Strategic Investment Decisions for Product Development Projects - An Option-Game Approach

by

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Abstract

Gate-criteria have been identified as critical drivers of the success of a new product development (NPD) process. However, a major weakness of NPD projects is that gate-criteria are often inadequate for making go/kill decisions. The most commonly used financial gate-criterion, the net present value (NPV) method, is insufficient when a project involves uncertainty. Alternatively, the real-option valuation method is also inadequate when a strategic decision involves the actions of competitors. In this research, I first develop an option-game valuation framework that explicitly incorporates product diffusion when dealing with an American investment option in a finite project life. The results of both simultaneous and sequential investment decisions are considered in each scenario of a duopolistic game. I introduce this approach as a gate-criterion to evaluate a new product development project in a fast-paced industry while considering potential managerial flexibility and market competition. As an option-game approach provides the possibility of a go/wait decision, the decision to delay represents an additional resource of value. Secondly, I further develop the option-game valuation framework with Bayesian analysis by explicitly involving technical risk and the 3-player-game in an NPD project. Volatilities from the initially uncertain market can be diminished as decision makers get to know more about customer requirements and preferences, while uncertainties about technical requirements are reduced through updated information about product performance. In addition, the option-game mechanism includes (inverse) measures of product differentiation to describe whether two goods are homogeneous, substituted, or independent, and to what degree. Moreover, the distribution of product correction is used to describe the level of the additional correction costs in a project. I introduce this approach as a gate-criterion to evaluate a new project at the gate and sub-gates of the development stages in the NPD process. The results present important implications: when demand is high, the project initiates "go" action if at least one competitor has a high unit variable cost in competing with a highly comparable product or simply if the target market is highly uncertain. When demand is low, the project may take "go" action only if the firm has a cost advantage. By using these models, industry players can make strategic decisions in a project assessment at the decision points of the development stages.

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Chapter 1 Introduction

1.1 Motivation and Research Issues

The project selection and portfolio choices that managers make are one of the most critical decisions in any business. Academic and industry participants rank new product project selection as one of the key issues in the new product development (NPD) process of high-tech companies (Scott, 2000).

However, the majority of businesses surveyed in Cooper and Edgett's study (2012) indicated that they lacked a fact-based and objective approach to decision-making at their gates of the NPD process. For example, before Microsoft agreed to acquire the handset and services business of Nokia in 2013, Nokia's global market share had been in a meltdown since 2009 (Steinbock, 2013). Analysts pointed out that Nokia's failure mainly resulted from its lack of response in growth and flexibility in the US and emerging markets (Steinbock, 2013). In addition, in 2012, three of Japan's consumer electronics giants (Sony, Sharp, and Panasonic) showed significant losses "from huge investments in the wrong technologies to a reluctance to exit loss-making businesses" (Tabuchi, 2012). Moreover, Cooper (2008) further mentioned that there are "too many projects in the pipeline" in the NPD process. Accordingly, my research has been motivated by the need for more effective criteria for product selection decisions.

Companies have recognized that the choice of products in their portfolios is a central factor influencing their chance of success (Miguel, 2008; Cooper et al., 1997).

Therefore, portfolio management for new product and R&D spending has gained tremendous attention over the decades (Miguel, 2008; Cooper et al., 1997, 2001; Scott, 2000). Portfolio management is defined as a process in which projects for new product development, including both potential new projects and existing projects, are continually evaluated, selected and prioritized (Cooper et al., 1997). As NPD is widely regarded as a vital source of competitive advantage (Bessant & Francis, 1997), the product development process from idea to launch consists of multiple phases, such as the project screening, monitoring, and progression frameworks of Cooper's stage-gate approach, in which a stage-gate process is a conceptual and operational blueprint for managing an NPD process (Cooper, 2008).

Since it is important that the selected projects are consistent with a business's strategy (Cooper et al., 1997), both academic and industry experts rank strategic planning for technology products as the top issue for NPD project success (Scott, 2000). In order to firmly link project selection and R&D spending to a business's strategy, one strategic technique is the strategic buckets method (Cooper et al., 1997). In this method, projects are classified into "buckets" and then project candidates within each bucket are rank-ordered by scoring models or financial criteria. The active projects within each bucket are prioritized based on limited allocated resources, then moved to the next stage for further investigation. The individual projects proceed to the subsequent development process on an ongoing basis through the stage-gate process. In this process, each stage of development is preceded by a "gate." At each gate, go/kill decisions are made to manage the risks of new products and to serve as quality-control checkpoints to continue moving the right projects forward (Cooper & Edgett, 2012; Cooper, 2008; Carbonell-Foulquié et al., 2004).

Effective portfolio decisions for NPD projects are a major challenge if the organization is to stay in business. To help companies make effective decisions about project selection, practitioners and researchers have proposed many mathematical approaches such as mathematical programming models, net present value (NPV), scoring models, and multi-attribute approaches. Due to the mathematical complexity of these models, only a few are actually being used (Meade & Presley, 2002). Of the various portfolio management methods, the ones most commonly used in R&D project selection are the financial criteria methods such as NPV and internal rate of return (IRR) (Meade & Presley, 2002). According to IRI's collected questionnaires (Cooper et al., 2001), a total of 40.4 percent of businesses rely on financial criteria as their dominant portfolio method, yet those businesses end up with the worst and poorest performing portfolios. The main reason for the poor performance of financial criteria methods is that prioritization decisions are made in the early stages of a project when the financial data are least accurate (Cooper et al., 2001).

In order to gain detailed insight into NPD projects, a method for strategic decision-making primarily needs to measure and define the performance of the NPD. As most firms' ultimate objective is financial success (Griffin & Page, 1996), the standard financial analysis methods for NPD projects are either the return on investment (ROI) method or the net present value (NPV) method (Ulrich & Eppinger, 2004; Speirs, 2008). The former, which evaluates the efficiency of the investment, is calculated as the return of an investment divided by the cost of the investment. The latter, which measures the present value of the project, is converted from the expected net cash flow from each period estimated from various variables, as shown in Fig. 1.1. The primary role influencers for this method are R&D, production, customers, marketing research, sales, and advertising.

Managers make strategic decisions according to the innovativeness of the product, market targeting, the number of competitors, and the marketability of the product (Hultink et al., 1997). Across a firm's total set of product development projects, success needs to be measured and achieved for each of the independent multidimensional product development outcomes, including consumer-based success, financial success, and technical or process-based success (Griffin & Page, 1996; Craig & Hart, 1992; Griffin & Page, 1993; Hart, 1993). Accordingly, the primary role factors and influencers in product management (Fig. 1.1) need to be considered in an interrelated manner.

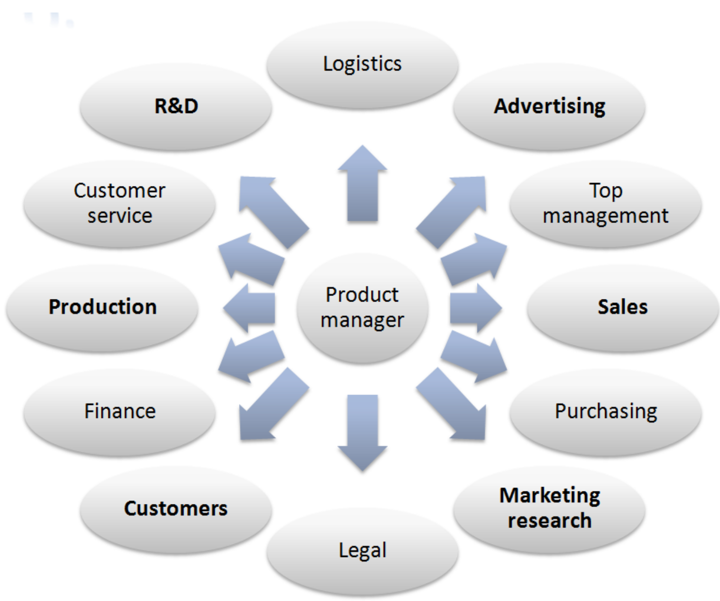

Fig. 1.1 Product management: primary role influencers (Gorchels, 2000)

However, in the increasing demand for better products launched more frequently and aimed at ever-narrowed customer segments (Holman et al., 2003), the standard NPV method for strategic decision-making in NPD projects fails not only to capture managerial flexibility (Harper, 2011), but also to consider new information about the markets and the actions of competitors. To resolve the above issues, this study proposes a promising quantitative integrated framework for decision-making.

1.2 Problem Statement

Go/kill criteria are the heart of project selection decisions because they determine whether a development project is allowed to continue through the development process (Carbonell et al., 2004). A wrong decision can lead to wasted resources and losses of strategic and market position (Meade & Presley, 2002). Despite the significance of go/kill criteria, the question of how to use them effectively is an area that has not yet been addressed sufficiently. In particular, financial criteria are rarely used to evaluate new products at the beginning of the NPD process (e.g., the idea screening and concept test stages) because the projected financial data at the early stages of a project are limited and inaccurate (Hart et al., 2003; Carbonell et al., 2004). Accordingly, the go/kill criteria for the NPD process are critical features. However, in Cooper's study (1995), the management of many of the participating companies admitted that they had no criteria for making the go/kill decision in their new product process. The formal gate-criteria that are used most often are scoring methods and conventional financial measures such as NPV, IRR, or ROI (Miguel, 2008; Carbonell et al., 2004; Cooper et al., 2001). Yet those conventional financial methods give inadequate measurements when projects are accompanied by risk and uncertainty (Meade & Presley, 2002; Scott, 2000; Sommer &

Loch, 2004). As a result, there is no comprehensive, cohesive, and rational alternative to traditional financial techniques for businesses that are faced specifically with products that have a rapidly changing, shorter life cycle or with new product projects that are competitive and risky.

The standard financial analysis measures (e.g., NPV) for NPD projects fail to account for all the opportunities and situations in a fast-changing environment. Specifically, these methods suffer from three main problems that are summarized in Fig. 1.2 and stated as follows.

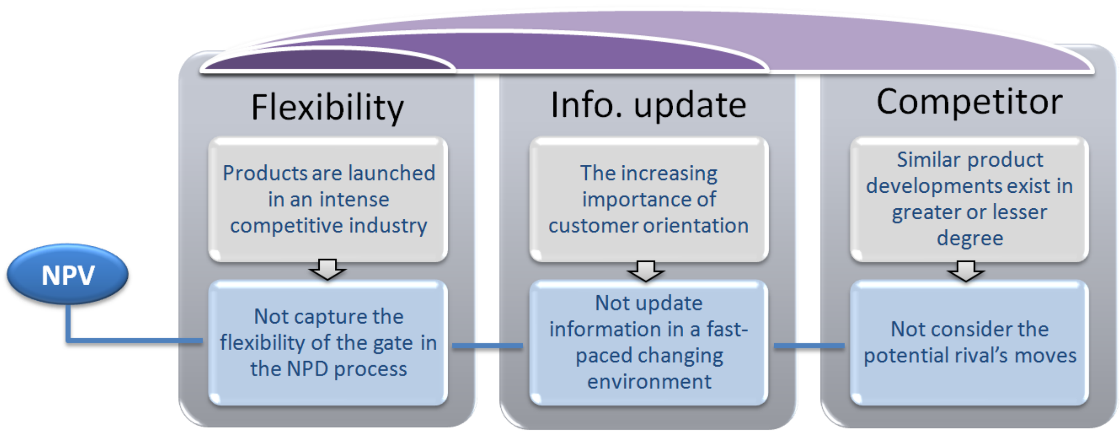

Fig. 1.2 Problem definitions

- *The NPV method cannot capture managerial flexibility in strategic decision-making at the gates in the NPD process.*

In the current marketplace, products are launched more frequently than in the past and are aimed at ever-narrower customer segments (Holman et al., 2003). Therefore, it is important for businesses to have the managerial flexibility (Holman et al., 2003) and the speed (McDaniel & Kolari, 1987; Miles et al., 1978) to change their products and markets in response to changing environmental conditions.

- *The NPV method does not consider new information about the targeted market and the actions of competitors.*

The standard NPV method for strategic decisions in NPD projects fails not only to capture managerial flexibility, but also to consider new information related to markets and competitors. In the traditional real-option framework, the new information is subjectively included in the analysis; however, methods for incorporating the arrival of new information into an option's value are still underdeveloped (Artmann, 2009; Sundaresan, 2000; Martzoukos & Trigeorgis, 2001; Herath & Park, 2001; Miller & Park, 2005). While voice-of-the-customer input has been identified as one of the drivers of success in the NPD process (Cooper & Edgett, 2012; Calantone et al., 1995), the major project selection criteria should involve developing an understanding of customer requirements (Scott, 2000; Bessant & Francis, 1997; Griffin & Hauser, 1996).

In addition, because "similar product developments exist in greater or lesser degree in almost all product areas" (Smith, 1995), the competitor's involvement in a dynamic setting could influence one firm's output choice in the target market. Hence, in the competitive marketplace, the real-option valuation methods fall short in resolving the dilemma when the moves of a rival are involved (Ferreira et al., 2009). Moreover, as the project success needs to be measured and achieved in multiple dimensions (Griffin & Page, 1996), the primary role influencers in product management need to be considered in an interrelated manner. Hence, other concepts and methods that have been developed for solving these problems, such as the game theory approach, might be applicable to new product development and allow decision makers to integrate new or updated information into product development projects.

- *NPD projects are rarely killed at gates after the idea screening* (Jenner, 2007).

Without a practical valuation approach, firms in fast-paced industries are known for rushing investments to pre-empt market shares (Smit & Trigeorgis, 2007). Fearing that competitors' growth will outpace their own, managers are too eager to invest excess cash in new capacities (Ferreira et al., 2009; Faughnder, 2012; Carson, 2007). And while both researchers and practitioners agree on the significance of gate-criteria (Carbonell-Foulquié et al., 2004; Agan, 2010), gates are rated as one of the weakest areas in product development (Cooper, 2008; Cooper, Edgett, & Kleinschmidt, 2002, 2005). Only 33 percent of firms have rigorous gates throughout the NPD process (Cooper, Edgett, & Kleinschmidt, 2002, 2005). In too many companies, gates either do not exist or are not effective, allowing numerous bad projects to proceed (Cooper, 2008; Jenner, 2007; Cooper & Edgett, 2012). Therefore, a practical and quantitative framework is urgently needed, especially in fast-paced industries.

The decision problem involves questions from two perspectives: questions about project investment and managerial decisions and questions about collecting and integrating new information. These questions include the following: What is the value of flexibility in a product development project in response to the changing environmental conditions of a competitor's moves and updated market information? How does Bayesian analysis affect the project value and the strategic decisions? Should the current project proceed to the next stage? How does this information impact a company's investment and managerial decisions?

1.3 Research Objective

The proposed problem in this research focuses on decision-making under market uncertainty and intense competition in an NPD project. I intend to value managerial flexibility, especially on the gate-criteria of individual project assessment and particularly for the gates of development phase in the NPD process. Specifically, the objectives of this research are:

- To quantify an integrated framework and to provide a measure of and criteria for product development performance considering the multiple dimensions of product development.
- To determine the investment and managerial decisions at the gate by valuing flexibility in an NPD project in response to changing environmental conditions of a competitor's moves and updated market information, while maximizing the expected economic returns.
- To assess updated information in a product development project and explore how it impacts a company's investment decisions and its competitive advantages.

As illustrated in Fig. 1.3, three main issues have been proposed. Regarding primary role influencers on strategic decisions in NPD projects, I will consider market demand and moves of competitors. Annual market demand in a potential segmented market is variable and may change during the initial NPD process. However, the uncertainty of market demand can be reduced by acquiring additional information via deriving a general Bayesian updating formulation during the development process to update initial forecasts

(Artmann, 2009). In addition, the actions of competitors could damage the value of the product development projects before they enter the market. Therefore, the payoff matrix of option-game is derived for the moves of a competitor in a comparable NPD project and incorporated with a general Bayesian updating formulation of market demand information.

In this approach, I present – to the best of my knowledge – the first decision model for gate-criteria that integrates an option-game framework with statistical decision theory in the form of Bayesian analysis in an NPD project.

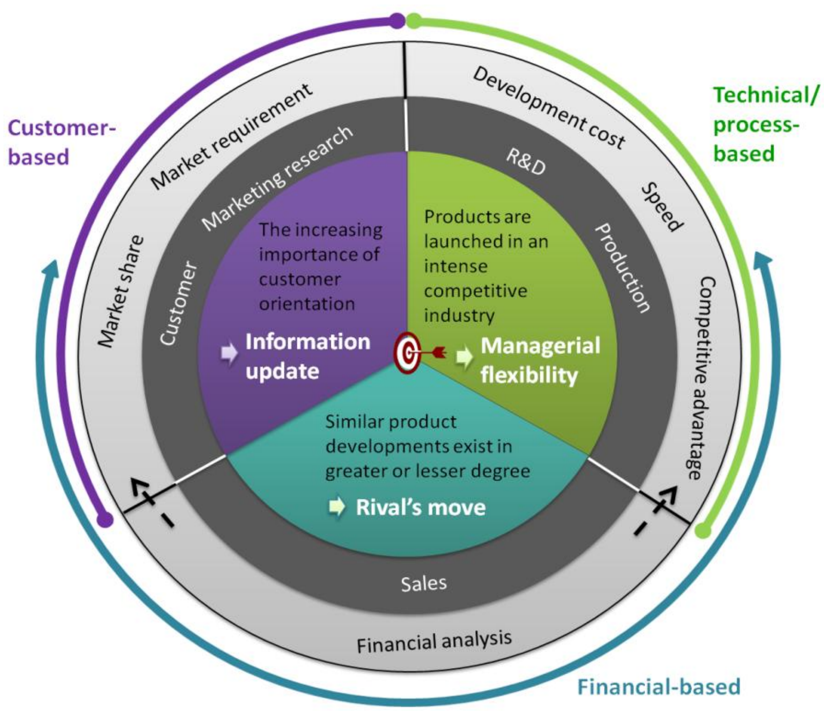

Fig. 1.3 Schematic diagram of research

With the described model and analysis, this research contributes to developing the decision models of the gate-criteria in the NPD process by deriving an option-game framework with a method for updating information. It also provides a practical and quantitative measure of product development performance from multidimensional perspectives that will help product development teams make investment and managerial decisions in NPD projects. Hence, this research further enhances the basis for decisions for NPD projects in response to changing environmental conditions, managerial flexibility, the competitor's moves, and updated market information.

The remainder of the dissertation is structured as follows: In chapter 2, I review the relevant literature. Chapter 3 develops an option-game valuation framework that explicitly incorporates a product life cycle (product diffusion) when dealing with an American investment option in a finite project life. In addition, the results of both potential simultaneous and sequential investment decisions are considered in each scenario of a duopolistic game. I introduce this approach as a gate-criterion to evaluate a new project in the NPD process with potential managerial flexibility and a competitor in fast-paced industries. In chapter 4, I develop a discrete option-game valuation framework that explicitly incorporates statistical decision theory in the form of Bayesian analysis. In addition, I include an inverse measure of product differentiation in the option-game mechanism to describe whether two goods are homogeneous, substituted, or independent, and to what degree. I introduce this approach as the gate-criteria to evaluate a new project at the gate and sub-gates of development stages in the NPD process. In chapter 5, I extend the option-game valuation framework with Bayesian analysis that is developed in chapter 4 by explicitly involving technical risk and 3-player-games in an NPD project. Finally, chapter 6 summarizes the main findings and provides possible extensions of the developed models for future research.

Chapter 2 Literature Review

For decades, practitioners and academics have studied the factors related to product development success (Craig & Hart, 1992; Griffin, 1997; Griffin & Page, 1993, 1996; Hart, 1993; Hart et al., 2003; McDaniel & Kolari, 1987). However, different strategies produce different levels of dependence upon new product development (Griffin, 1997; Griffin & Page, 1993, 1996; Hart, 1993). These differences mean that one set of measures of overall success is unlikely to be suitable across firms with different strategies (Griffin & Page, 1996). Instead of determining the factors of product development success, in this research, I focus on assessing flexibility of an individual project in an NPD process under changing environmental conditions.

This research framework is based on previously developed concepts which are not comprehensively linked. To build this link between flexibility and its related system attributes, the following literature review is split into four categories: new product development, real-option analysis, the option-game approach, and decision models with information updating.

2.1 New Product Development

New product development is widely regarded as a vital source of competitive advantage (Bessant & Francis, 1997). A product development process from idea to launch consists of multiple phases, such as the project screening, monitoring, and progression frameworks of Cooper's stage-gate approach, which is a conceptual and operational blueprint for managing the NPD process (Cooper, 2008). Nowadays, instead of a standardized mechanistic implementation process, there are many different versions to fit different business needs (Cooper, 2008). In an idea-to-launch product process, each stage has defined procedures and requires the gathering of relevant information. Following each stage is a "gate" where go/kill decisions are made to manage the risks of new products and to serve as a quality-control checkpoint to continue moving the right projects forward (Cooper & Edgett, 2012; Cooper, 2008; Carbonell-Foulquié et al., 2004).

In order to gain competitive advantages, companies must continuously introduce successful and innovative products into the market (Holman, Kaas & Keeling, 2003; Kaplan, 1954). However, the average success rate for NPD projects is not significantly high (Griffin, 1997). Companies have recognized that the choice of products in their portfolios is a central factor influencing their chance of success (Miguel, 2008; Cooper et al., 1997). Therefore, portfolio management for new product and R&D spending has gained tremendous attention over the decades (Miguel, 2008; Cooper et al., 1997, 2001; Scott, 2000). Portfolio management is defined as a process in which projects for product development, both new or potential projects and existing projects, are continually evaluated, selected and prioritized (Cooper et al., 1997). Nevertheless, a benchmarking study (Cooper et al., 1995) has identified portfolio management as the weakest area in managing new product development.

Effective portfolio decision for NPD projects is thus a major challenge if the organization is to stay in business. To help organizations make decisions about project selection, practitioners and researchers have proposed many mathematical approaches such as mathematical programming models, net present value (NPV), scoring models, and multi-attribute approaches. However, due to the mathematical complexity of these models, only a few are actually being used (Meade & Presley, 2002). Of various portfolio management methods, the most commonly used in R&D project selection are financial criteria (such as NPV and IRR) (Meade & Presley, 2002). Accordng to IRI's collected questionnaires (Cooper et al., 2001), a total of 40.4 percent of businesses rely on financial criteria as their dominant portfolio method, but those businesses end up with the worst and poorest performing portfolios. The main reason for the failure of financial criteria is that prioritization decisions are made in the early stage of a project, when the financial data are the least accurate (Cooper et al., 2001). In other words, the conventional financial criteria do not succeed at predicting the future financial success of a technology (Scott, 2000). As the initial NPD projects are risky and multidimensional in nature, decisions about these projects should consider strategic and multidimensional measures (Meade & Presley, 2002).

Moreover, both academic and industry experts have identified strategic planning for technology products as a significant issue for NPD project success (Scott, 2000), since it is important that the selected projects are consistent with a business's strategy (Cooper et al., 1997). A total of 26.6 percent of businesses use strategic approaches as the dominant portfolio method, making them the second most popular portfolio approach (Cooper et al., 2001). In order to firmly link project selection and R&D spending to a business's strategy, many companies use the strategic buckets method (Cooper et al., 1997). The strategic bucket approach allocates spending to different buckets or envelopes based on the business's strategy and strategic priorities across various dimensions (e.g., type of market, type of development, product line, and so on). After projects are classified into buckets, project candidates within each bucket are rank-ordered by scoring models or financial criteria. The active projects within each bucket are prioritized and allocated limited resources, then moved to the next stage for further investigation. The individual projects proceed to the subsequent development process on an ongoing basis through the stage-gate process with the gate-criteria of go/kill decisions.

Go/kill criteria are the heart of project selection decisions, determining whether a development project is allowed to continue through the development process (Carbonell et al., 2004). A wrong decision can lead to wasted resources and losses of strategic and market position (Meade & Presley, 2002). Despite the significance of go/kill criteria, however, methods for using them successfully have not yet been addressed sufficiently. In particular, financial criteria are rarely used to evaluate new products at the beginning of the NPD process (e.g., the idea screening and concept test stages), because the projected financial data in the early stages are limited and inaccurate (Hart et al., 2003; Carbonell et al., 2004). Accordingly, go/kill criteria for the NPD process are critical features. However, in Cooper et al.'s study (1995), the managers of many participating companies admitted that they had no criteria for making the go/kill decision in their new product processes. The formal gate-criteria that are used most often are scoring and conventional financial measures such as the NPV, IRR, or ROI (Miguel, 2008; Carbonell et al., 2004; Cooper et al., 2001). Yet those conventional financial methods give inadequate measurements when projects are accompanied by risk and uncertainty (Meade & Presley, 2002; Scott, 2000; Sommer & Loch, 2004).

Literature study has determined that the financial criteria for gate decisions after the screening and investigation stages will positively impact new product success (Carbonell et al., 2004; Hart et al., 2003). As different criteria can be used for projects from different buckets, it is not necessary to develop a universal criterion that fits all projects (Cooper et al., 1997). Nevertheless, the traditional valuation approach techniques, which assume at the outset that all future outcomes are fixed, are used widely in business (Krychowski & Quélin, 2010). The traditional valuation approach relies on a discounted cash flow series, assuming that the investment is an all-or-nothing strategy in which the net present worth or net present value (NPV) is considered as a project's expected future cash flow into the time value of money at time 0 with a risk-adjusted discount rate (today's dollars). The main problem with this approach is that it underestimates the flexibility value of a project and assumes that all outcomes are static and all decisions made are irrevocable (Mun, 2006). As a result, there is no comprehensive, cohesive, and rational alternative to traditional financial techniques for businesses that are faced specifically with rapidly changing, shorter product life cycles or competitive and risky new product projects.

2.2 Real-Option Analysis

A real-option approach, building upon traditional discounted cash flow analysis, gives decision makers a set of options without committing them to one particular decision. The real-option approach considers flexibility in decision-making, and the flexibility can be viewed as options or investment opportunities available to the company (Antikarov et al., 2001). Therefore, the real-option approach allows managers to build options into products and projects in the real world (Mun, 2006; Harper, 2011) and increases the overall understanding of the investment decision, especially in areas of uncertainty (Michailidis, 2006).

Cooper (2008) explains that the stage-gate process of an NPD project is very similar to that of buying a series of options on an investment: as each stage of the development process costs more than the preceding one, the initial amount of cost is analogous to the purchase of an option, and the decision of whether or not to continue investing in the project is made at the gate (maturity), while new information is gathered during the stage. Indeed, the flexibility of the real-option approach corresponds to the structure of the NPD process, allowing developers to build options into products and projects (Mun, 2006). In the following sections, I provide a short introduction to the real-option method and its applications in NPD projects.

2.2.1 Common real-option

Real-option theory originates from methodologies developed in the field of financial analysis (Black & Scholes, 1973), but there are key differences between financial options and real-option (Mun, 2006) as listed in Fig. 2.1. In addition, management can benefit from different types of real-option, which are primarily classified by sources of managerial flexibility, as shown in Table 2.1 (Smit & Trigeorgis, 2004; Chevalier-Roignant & Trigeorgis, 2011). In dynamic decision-making, the manager's actions depend on all information available at time 0 as well as all new information revealed between times 0 and T (Guthrie, 2009). As a result, in a product developer's cost modeling, the value of future decisions can be explicitly incorporated into calculations of expected returns from a project (Harper, 2011; Guthrie, 2009). In other words, incorporating flexible options into the project plan can increase the financial performance of the project over its entire life cycle (Harper, 2011).

Financial options	Real-option
• Short maturity, usually in months. • Underlying variable driving its value is equity price or price of a financial asset. • Cannot control option value by manipulating stock prices. • Values are usually small. • Competitive or market effects are irrelevant to its value and pricing. • Have been around and traded for more than three decades. • Usually solved using closed-form partial differential equations and simulation/ variance reduction techniques for exotic options. • Marketable and traded security with comparables and pricing info. • Management assumptions and actions have no bearing on valuation.	• Longer maturity, usually in years. • Underlying variables are free cash flows, which in turn are driven by competition, demand, management. • Can increase strategic option value by management decisions and flexibility. • Major million and billion dollar decisions. • Competition and market drive the value of a strategic option. • A recent development in corporate finance within the last decade. • Usually solved using closed-form equations and binomial lattices with simulation of the underlying variables, not on the option analysis. • Not traded and proprietary in nature, with no market comparables. • Management assumptions and actions drive the value of a real-option.

Fig. 2.1 Financial options versus real-option methods (Mun, 2006)

2.2.2 Basic option valuation

Many numerical analysis techniques to value options take advantage of risk-neutral valuation. In general, numerical techniques for option valuation can be classified into two types (Smit & Trigeorgis, 2004):

- Approximating the underlying stochastic processes: The first category includes the Monte Carlo simulation used by Boyle (1977) and various lattice approaches, such as Cox, Ross, and Rubinstein's (1979) standard binomial lattice method and Trigeorgis's (1991) log-transformed binomial approach. These methods are generally more intuitive, and the latter methods are particularly well suited to valuing complex projects with multiple embedded real-option methods, a series of investment outlays, dividend-like effects, and option interactions.

- Approximating the resulting partial differential equations: Examples of the second category include numerical integration and the implicit or explicit finite-difference schemes used by Brennen (1979), Brennen and Schwartz (1978), and Majd and Pindyck (1987).

Table 2.1 Common real-option (Chevalier-Roignant & Trigeorgis, 2011)

Real-option type	Description	Relevant industry
Deferral or waiting option	Management can wait before making the investment to see how the market unfolds.	Resource extraction industries, real-estate development, capital-intensive industries.
Staging or time-to-build option	When a managerial decision takes time or is done in stages, management can default if market prospects prove worse than expected.	Technology-based firms (R&D), long development capital intensive industries (e.g., electric utilities), startup ventures.
Expand or expend option	If the project turns out better than expected, management can spend more to expand the project scale or it can extend the project's useful life.	Natural-resource industries (e.g., mining), real-estate development.
Contract or abandon option	If the market prospects are worse than expected, managers can contract or abandon it for salvage.	Capital-intensive industries (e.g., airplane manufacturers), new product introduction.
Switching option	Management can select among the best of several alternatives, e.g., inputs outputs or locations, under the prevalent market conditions.	Multinational firms with production facilities, in different currencies, platform strategy in the automotive sector.
Compound option	If investment takes place in stages, the first project can be value in view of the future growth options it creates.	High-tech, R&D, industries with multiple product generations, strategic acquisitions.

The two best-known option-pricing models are those of Black and Scholes (1973) and Cox, Ross, and Rubinstein (1979). Originally, these models were designed to price financial options, but they have been extended to valuing real-option models. The Black-

Scholes (BS) model involves advanced mathematics and notions of financial theory in continuous time. The continuous-time models assume instantaneous decision-making and are appealing because they help better identify the theoretical value drivers and examine the underlying trade-offs. On the other hand, the discrete-time multiplicative binomial model of Cox-Ross-Rubinstein (CRR) offers a more intuitive introduction to option pricing. Discrete-time models are generally better suited to handling practical or complex valuation problems (e.g., portfolios of real-option) and are easier to implement (Chevalier-Roignant & Trigeorgis, 2011).

2.2.3 The real-option approach in NPD projects

The real-option approach has gained attention in the area of product development projects (i.e., R&D project evaluation) since it can value managerial flexibility with respect to contingent multi-stages in high-tech projects and the market uncertainty inherent in the projects (Benninga & Tolkowsky, 2002; Loch & Bode-Greuel, 2001; Oriani & Sobrero, 2008; Huchzermeier & Loch, 2001; Santiago & Vakili, 2005).

Loch and Bode-Greuel (2001) demonstrated a quantitative evaluation of compound growth options in a large international pharmaceutical company using a decision tree to provide transparency about project value and strategic options. Lint and Pennings (2001) developed a real-option framework with market and technology uncertainty in a development project. They also demonstrated how any particular project in the R&D phase may be assigned within a 2 by 2 matrix of uncertainty versus R&D option value to allow managers to decide whether to speed up or delay the development process. Oriani and Sobrero (2008) provided new theoretical insights into the real-option logic and gave empirical evidence of the effect of market and technological uncertainty on the market valuation of a firm's R&D capital. Huchzermeier and Loch (2001) incorporated the operational sources of uncertainty into real-option value of managerial flexibility and introduced an improvement option to take corrective actions during the NPD process for the purpose of better product performance. Santiago and Vakili (2005) used the practical relevance of the improvement option to extend Huchzermeier and Loch's (2001) work to value a high-technology development project in the presence of technical uncertainties.

However, because "similar product developments exist in greater or lesser degree in almost all product areas" (Smith, 1995), a competitor's involvement in a dynamic setting could influence one firm's output choice in the target market. Real-option theory mainly considers single decision-maker problems which assume that firms are operating in a monopoly or perfect competition markets (Huisman et al., 2004). These traditional valuation methods fall short of resolving the dilemma when moves of competitors are involved in the competitive marketplace (Ferreira et al., 2009). An additional problem with these methods is the limited knowledge of how to evaluate projects and make critical go/kill decisions throughout the entire development process (Schmidt & Calantone, 1998; Carbonell-Foulquié, 2004).

2.3 The Option-Game Approach

The term "option-game" was developed by Smit and Trigeorgis (2006). Their theory combines real-option (which relies on the evolution of prices and demand) and game theory (which captures competitors' moves) to quantify the value of flexibility and commitment. As mentioned above, the traditional real-option valuations are inadequate when moves of competitors are involved (Ferreira et al., 2009). Nevertheless, the real-option approach has the potential to make a significant difference in the area of competition and strategy. Many researchers have dealt with the concepts of competitive and strategic options (Trigeorgis & Kasanen, 1991). Competitive investment strategy is based on the strategic or expanded NPV criterion that incorporates not only the direct cash-flow value and the flexibility or option value but also the strategic commitment value from competitive interaction. The first two studies dealing with real-option context in a duopoly were Smet's (1991) and Dixit and Pindyck's (1994). Their research has led to a number of studies combining real-option and game theory (Smit & Trigeorgis, 2006) in situations where several firms have the option to invest in the same project (Smet, 1991; Smit & Ankum, 1993; Smit & Trigeorgis, 1995; Chevalier-Roignant & Trigeorgis, 2011). In the following section, I provide a brief introduction to option-game and its applications.

2.3.1 An illustration of the option-game approach

Chevalier-Roignant and Trigeorgis (2011) provided a simple illustration of the logic behind option-game which is shown below. An option-game approach viewed in discrete time is an overlay of a binomial tree onto a payoff matrix. A binomial tree (Fig. 2.2) is used to model the stochastic evolution of project value (V), while two-by-two matrices are used to capture the competitive iterations among players. In the binomial tree, each scenario at the end of the node corresponds to the cumulative risk-neutral probability after two steps, where q_r is the risk-neutral probability of an upward per period.

Consider a duopoly consisting of Firms i and j sharing a European option to invest in an emerging market within two years. Both firms can invest, wait and invest later (at maturity in time 2), or let the option expire. If neither invests now, at the end node in time 2, the firm's strategic choices (represented in two-by-two payoff matrices) are either to invest or not to invest (abandon). At maturity, both Firms *i* and *j* can invest, both can abandon, or only one can invest (potentially involving a coordination problem). The basic structure of this option-game in discrete-time is depicted in Fig. 2.3. Once the binomial tree charts the evolution of potential demand scenarios until maturity (time 2) in each end node, a two-by-two payoff matrix depicts the resulting competitive interaction. The resulting equilibrium outcome (*) and corresponding player payoffs can be anticipated for each of the three payoff matrices. Once the equilibrium (*) strategic option values are obtained in each end state (C^{*++}, C^{*+-}, C^{*--}), working the tree backward enables the firm to assess the value that each strategy creates under rivalry. This analysis reveals the benefits to each player of pursuing a given strategy and enables management to determine how these benefits might change if certain key variables, such as growth or volatility, change.

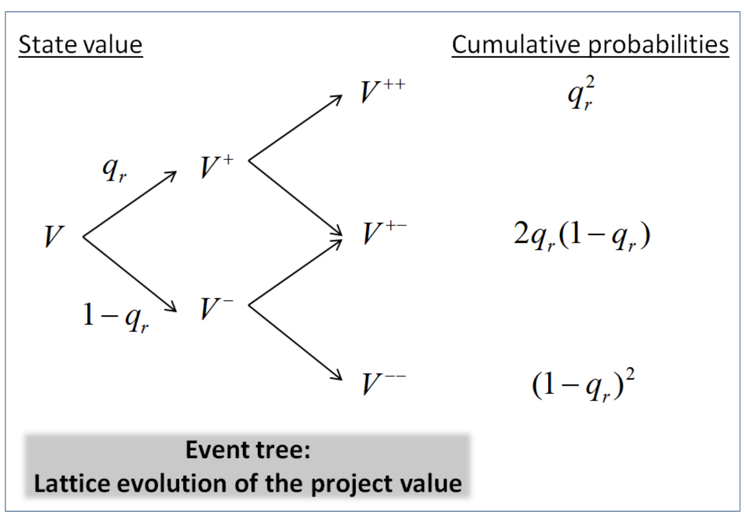

Fig. 2.2 Binomial tree representing evolution of market uncertainty and associated probabilities (Chevalier-Roignant & Trigeorgis, 2011)

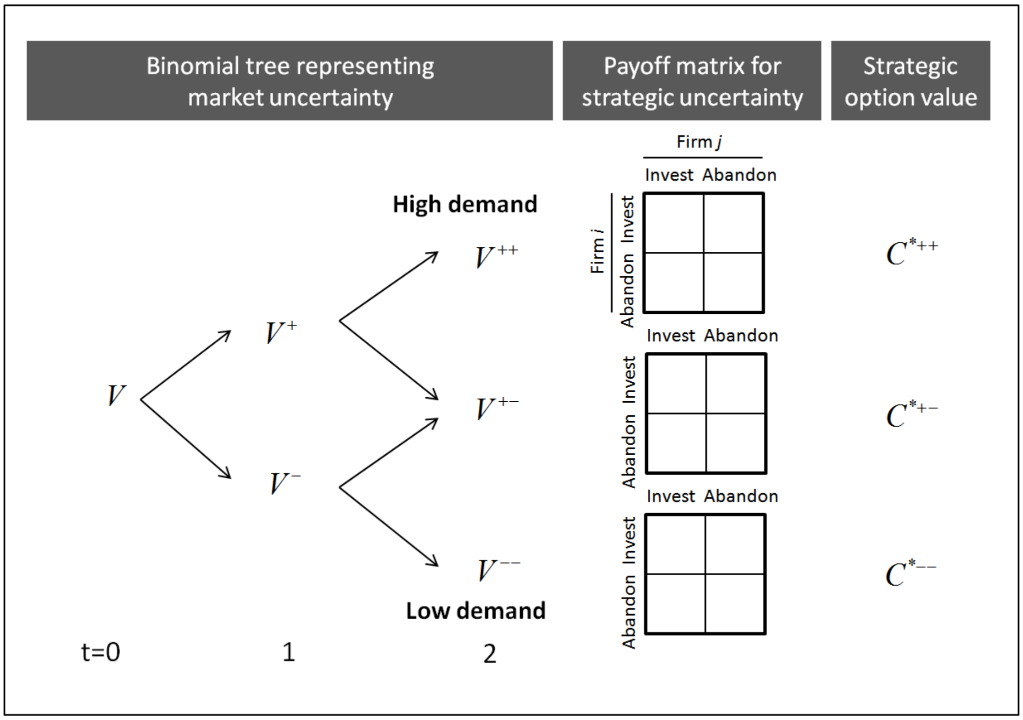

Fig. 2.3 Structure of an option-game approach involving both market (demand) and strategic (rival) uncertainty (Chevalier-Roignant & Trigeorgis, 2011)

2.3.2 Applications

The real-option approach with a game theoretic concept has gained attention in the area of strategic investment (Huisman, 2001; Egami, 2010; Beveridge & Joshi, 2011; Huisman et al., 2004; Smit & Trigeorgis, 2007; Smit & Trigeorgis, 2009; Martzoukos & Zacharias, 2012), since it can quantify the value of flexibility and commitment, allowing decision makers to make rational choices (Ferreira et al., 2009).

Smit and Trigeorgis (2009) applied the option-game methodology to the case of evaluating airport infrastructure expansion investments. They proposed important advantages of a binomial-tree option-game, such as the transparency and tractability of value movement dynamics; the modularity to embed strategic interactions, restrictions, and other features in a realistic setting; and the intuitiveness and accessibility of the methodological logic. Ferreira et al. (2009) illustrated that the option-game is suited for competing in capital-intensive industries, using a simplified example of a mining company considering whether or not to add new capacity in the face of demand and competitive uncertainties, and analyzed four scenarios arising from their decisions to invest now or wait. Martzoukos & Zacharias (2012) demonstrated to decision makers a method for deciding on the best action strategy and the amount of effort in a competition situation, a decision which is heavily dependent on the effectiveness of R&D investments, their cost, and the degree of coordination that is optimal for the two firms.

However, with the increasing importance of customer orientation (Sun, 2006) in the current fast-changing marketplace, if managers do not have updated information on market requirements and foresight of market demand, this lack of information will significantly affect strategic decisions as well as the sales of new products (Kahn, 2002; Artmann, 2009).

2.4 Decision Models with Information Updating

Because voice-of-the-customer input has been identified as one of the drivers of success in the NPD process (Cooper & Edgett, 2012; Calantone et al., 1995), the major project selection criteria should involve developing an understanding of customer requirements (Scott, 2000; Bessant & Francis, 1997; Griffin & Hauser, 1996). Due to shorter product life cycles in fast-paced industries, it is not necessary to wait for perfect information at the pre-defined gate for decision-making. Stages can be overlapped in a stage-gate process by using spiral development, allowing product development to continuously incorporate valuable customer feedback into the product design during the

NPD process until the final product is closer to customers' ideal (Cooper, 2008). The data obtained from customer feedback allows decision makers to estimate the potential market share of each concept and to select an optimal product investment. Without updated information on market requirements and foresight of market demand, the sales of new products will be significantly affected (Kahn, 2002; Artmann, 2009). However, a common problem is that companies collect data on customer interest before the start of development activities and generally do not update the data (von Hippel, 1992; Artmann, 2009). Hence, problems arise if the customers' needs change (Bhattacharya et al., 1998). Researchers have developed numerous models for decision-making that allow managerial flexibility for responding to new information in certain environments, permitting management to refine its information over time and adjust its initial decisions (Artmann, 2009; Loch & Terwiesch, 2005).

2.4.1 Information generation and updating

Gathering high-quality data involves direct contact with customers and experience with the use environment of the product. The most common means of generating market information are the traditional market research methods (Lynn et al., 1999; Zahay et al., 2004). Three methods are commonly used: interviews, focus groups, and observing the product in use (Ulrich & Eppinger, 2004).

Depending on the issue being studied, the level of uncertainty about demand and the methods for reducing uncertainty can be modeled in different approaches. There are three major updating methods applied to decision models: time series analysis, Markov-modulated forecast updates, and Bayesian analysis (Sethi et al., 2005).

2.4.2 Basic ideas of Bayesian analysis

Bayesian analysis is a statistical decision theory developed by Thomas Bayes (1764). It is a popular method in the field of statistical decision theory, which is concerned with the problem of making decisions based on statistical knowledge about uncertain quantities. The decision maker's challenge is to estimate an objective probability model with critical parameters. Using statistical sample data from experiments or market research about the unknown parameters, the Bayesian method combines the sample data with initial information about the problem, allowing the decision maker to obtain the posterior distribution of parameters. Hence, the objective probability model can be updated. Because they are easily interpreted and suitable for practical applications, the Bayesian methods have been used by researchers in various disciplines and different applications over the last decade.

2.4.3 The real-option approach with information updating

In the traditional real-option framework, new information is subjectively included in the analysis; however, methods incorporating the arrival of new information into an option's value are still underdeveloped (Sundaresan, 2000; De Weck et al., 2007; Halpern, 2003; Martzoukos & Trigeorgis, 2001). Several researchers have observed the traditional real-option framework and attempted to combine Bayesian analysis with real-option (Herath & Park, 2001; Huchzermeier & Loch, 2001; Santiago & Vakili, 2005; Miller & Park, 2005; Armstrong et al., 2005; Grenadier & Malenko, 2010) and Bayesian learning with the binomial lattice model (Guidolin & Timmermann, 2003; Guidolin & Timmermann, 2007).

Herath and Park (2001) were the first to introduce Bayesian analysis combined with real-option. They developed a simple valuation framework based on the concept of the expected value of perfect information (EVPI) of real-option and sampling information. In their approach, they studied investment decisions where management has the option to defer a project until more information becomes available. Miller and Park (2005) indicated that reducing uncertainty in real-option theory has traditionally been regarded as a passive process. In contrast, they quantified information acquisition by merging statistical Bayesian perspective with the real-option framework to improve decision-making and modeled a contingent multi-stage investment scenario in which the initial estimates of the expected future cash flows are updated during the management phase of the project. They identified a key threshold which defines when the firm's prior decision should be reversed based on observed sample results.

Armstrong et al. (2005) presented a primary practical application of a framework that combines Bayesian analysis with a real-option approach. They studied the option value of acquiring additional information in a project for enhancing oil field production. They assumed that the two sources of uncertainty, the underlying oil prices and the characteristics of the reservoir, were bivariate normal distribution by using a Monte Carlo simulation. Grenadier and Malenko (2010) augmented the standard Brownian uncertainty driving traditional real-option models with additional Bayesian uncertainty over distinguishing between the temporary and permanent nature of past cash flow shocks. Artmann (2009) derived the Bayesian updating formulation for an update of the market requirement distribution that allows for managerial flexibility in a situation where product performance is uncertain.

2.5 Summary of the Literature

A common problem with NPD processes is that projects are rarely killed at gates after the stage of idea screening (Jenner, 2007). Additionally, Anderson (2008) pointed out that the most significant challenge in managing current product development is the overall integration of strategy, process, the measurement of performance, and continuous improvement. As shown by the above review of the relevant literatures about flexibility in NPD projects, the option-game approach, and decision models with information updating, managers need a comprehensive quantitative model to improve decision-making about the gate-criteria of NPD projects (Fig. 2.4). Cooper (2008) explained that the stage-gate process of an NPD project is very similar to that of buying a series of options on an investment. On the other hand, Huchzermeier and Loch (2001) proposed an insightful framework of managerial flexibility in an NPD project, in which the product's developer considers an improvement option to take corrective actions during the NPD process. In contrast to traditional real-option methods which regard uncertainty reduction as a passive process (Miller & Park, 2005), Artmann (2009) extended the work of Huchzermeier and Loch (2001) by deriving the Bayesian updating formulation for the market requirement distribution and integrating this mechanism into a real-option framework. Moreover, Chevalier-Roignant and Trigeorgis (2011) studied and illustrated the option-game framework, which allows decision makers to make rational choices between alternative investment strategies (Ferreira et al., 2009), combining real-option models (which rely on the evolution of prices and demand) and game theory (which captures competitors' moves).

The above four areas make the option-game framework well suited for NPD projects as well as for a base case demonstrating the decision models of the gate-criteria with information updating under competitive environments. The current option-game models are not considered Bayesian learning analysis. Therefore, I introduce an option-game valuation framework with Bayesian analysis as a gate-criterion of a new project in the NPD process. By gathering new information about potential markets, project payoff, and the rivals' actions, a decision maker can use this integrated approach to make the proper strategic decisions in the NPD process.

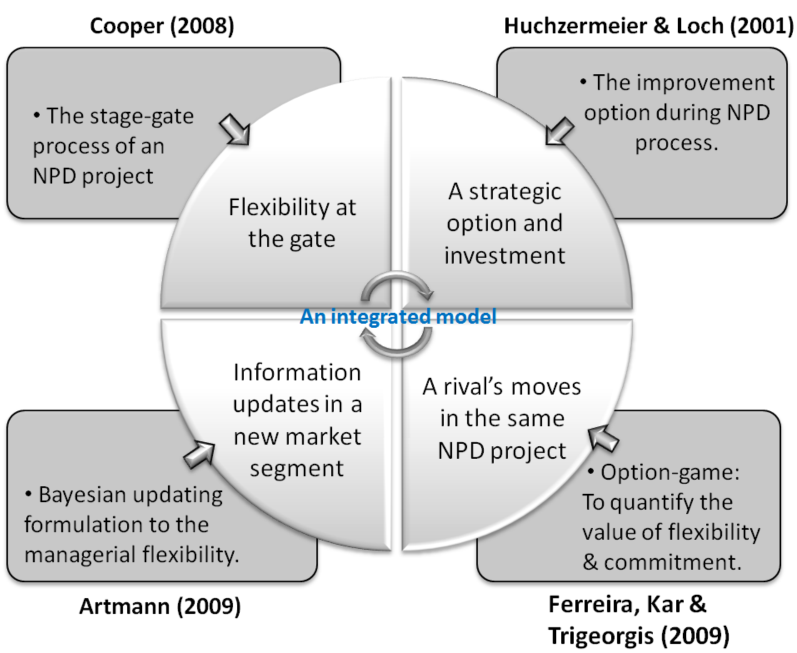

Fig. 2.4 Summary of the literature

Chapter 3 Assessing Investment Flexibility in a New Product Development Project: An Option-Game Approach with Product Diffusion

Abstract

Project selection of new products is a vital issue in the new product development (NPD) process of high-tech companies. A major problem with project selection is the inadequacy of using gate-criteria to make the go/kill decisions. The most common financial gate-criterion, the net present value (NPV), is insufficient when a project has a high degree of uncertainty, resulting in killing potential projects unnecessarily. In this chapter, I develop an option-game valuation framework that explicitly incorporates product diffusion when dealing with an American investment option in a finite project life. In addition, the results of both potential simultaneous and sequential investment decisions are considered in each scenario of the duopolistic game. I introduce this approach as the gate-criterion to evaluate a new project in the NPD process with potential managerial flexibility and a competitor in fast-paced industries. As an option-game approach provides a go/wait decision, it shows that the decision to delay represents an additional resource of value. The results provide important implications for strategic project selection when investigating an NPD project during the product development process. By using this approach, industry players can make strategic decisions in a

project assessment and plan the optimal annual production capacity at the outset of the product development stage.

Keywords: option-game, product diffusion, gate-criteria, new product development, Cournot duopoly competition, sequential investment

3.1 Background

According to Scott (2000), academic and industry participants rank new product selection as one of the most critical issues in the NPD process of high-tech companies. Indeed, the project selection and portfolio choices that managers make will guide businesses' new product efforts either toward or away from their organizational goals.

3.1.1 Issues in the new product development

In order to gain competitive advantages, companies must continually introduce successful and innovative products into the market (Holman, Kaas, & Keeling, 2003; Kaplan, 1954). However, the average success rate for NPD projects is not significantly high (Griffin, 1997). Companies have recognized that the choice of products in their portfolios is a central factor influencing their chance of success (Miguel, 2008; Cooper et al., 1997). Therefore, portfolio management for new product and R&D spending has gained tremendous attention over the decades (Miguel, 2008; Cooper et al., 1997, 2001; Scott, 2000). Portfolio management is defined as a process in which projects for product development, both new or potential projects and existing projects, are continually evaluated, selected and prioritized (Cooper et al., 1997). Nevertheless, a benchmarking study (Cooper et al., 1995) has identified portfolio management as the weakest area in managing new product development.

Effective portfolio decision for NPD projects is thus a major challenge if the organization is to stay in business. To help organizations make decisions about project selection, practitioners and researchers have proposed many mathematical approaches such as mathematical programming models, net present value (NPV), scoring models, and multi-attribute approaches. However, due to the mathematical complexity of these models, only a few are actually being used (Meade & Presley, 2002). Of various portfolio management methods, the most commonly used in R&D project selection are financial criteria (such as NPV and IRR) (Meade & Presley, 2002). According to IRI's collected questionnaires (Cooper et al., 2001), a total of 40.4 percent of businesses rely on financial criteria as the dominant portfolio method, but those businesses end up with the worst and poorest performing portfolios. The main reason for the failure of financial criteria is that prioritization decisions are made in the early stages of a project when the financial data are the least accurate (Cooper et al., 2001). In other words, the conventional financial criteria do not succeed at predicting the future financial success of a technology (Scott, 2000). As R&D projects are risky and multidimensional in nature, decisions about these projects should consider strategic and multidimensional measures (Meade & Presley, 2002).

Moreover, both academic and industry experts have identified strategic planning for technology products as a significant issue for NPD project success (Scott, 2000), since it is important that the selected projects are consistent with a business's strategy (Cooper et al., 1997). A total of 26.6 percent of businesses use strategic approaches as the dominant portfolio method, making them the second most popular portfolio approach (Cooper et al., 2001). In order to firmly link project selection and R&D spending to a business's strategy, many companies use the strategic buckets method (Cooper et al., 1997). The strategic buckets approach allocates spending to different buckets or envelopes based on business strategy and strategic priorities across various dimensions (e.g., type of market, type of development, product line, and so on). After projects are classified into buckets, project candidates within each bucket are rank-ordered by scoring models or financial criteria. The active projects within each bucket are prioritized based on limited allocated resources, and then moved to the next stage for further investigation. The individual projects proceed to the subsequent development process on an ongoing basis through the stage-gate process with the gate-criteria of go/kill decisions.

3.1.2 The go/kill gate-criteria in the NPD process

Go/kill criteria are the heart of project selection decisions, determining whether a development project is allowed to continue through the development process (Carbonell et al., 2004). A wrong decision can lead to wasted resources and losses of strategic and market position (Meade & Presley, 2002). Despite the significance of go/kill criteria, methods for using them successfully are an area that is not yet addressed sufficiently. In particular, financial criteria are rarely used to evaluate new products at the beginning of the NPD process (e.g., the idea screening and concept test stages), because the projected financial data in the early stages is inadequate and inaccurate (Hart et al., 2003; Carbonell et al., 2004). Accordingly, go/kill criteria for the NPD process are critical features. However, in Cooper et al.'s study (1995), the managers of many participating companies admitted that they had no criteria for making the go/kill decisions in their new product processes. The formal gate-criteria that are used most often are scoring measures and conventional financial measures such as NPV, IRR, or ROI (Miguel, 2008; Carbonell et al., 2004; Cooper et al., 2001). Yet those conventional financial methods give inadequate measurements when projects are accompanied by risk and uncertainty (Meade & Presley, 2002; Scott, 2000; Sommer & Loch, 2004). As a result, there is no comprehensive, cohesive, and rational alternative to traditional financial techniques for businesses that are faced specifically with rapidly changing, shorter product life cycles or competitive and risky new product projects.

3.1.3 The scope of this chapter

Literature study has determined that the financial criteria for gate decisions after the screening stage will have a positive impact on new product success (Carbonell et al., 2004; Hart et al., 2003). This chapter focuses on the gate-criteria of individual project assessment, specifically for the gate of development stage in the NPD process (the bold gate in Fig. 3.1), which is the first gate after the process of screening and project investigation. As different criteria can be used for projects from different buckets, it is not necessary to develop a universal criterion that fits all the projects (Cooper et al., 1997). Hence, I am interested in designing a criterion specifically for the buckets of new product projects in the dimensions of high risk, shorter product life cycle, and a rapidly changing and competitive marketplace—the circumstances in which the conventional financial criteria are the most unsuitable (Meade & Presley, 2002; Scott, 2000; Sommer & Loch, 2004). Consequently, I introduce a discrete option-game framework with the concept of product diffusion as the gate-criterion of the development stage. Product developers can assess an NPD project with potential managerial flexibility and a competitor within a finite project life. The term "option-game" has recently been introduced by Smit and Trigeorgis (2006). The option-game concept combines real-option (which relies on the evolution of prices and demand) and game theory (which captures competitors' moves). A real-option approach with game theoretic concept has gained increasing interest in the area of strategic investment (Huisman, 2001; Huisman et al., 2004; Smit & Trigeorgis, 2007, 2009), since this approach allows decision makers to make rational choices by quantifying flexibility and commitment (Ferreira, Kar, & Trigeorgis, 2009).

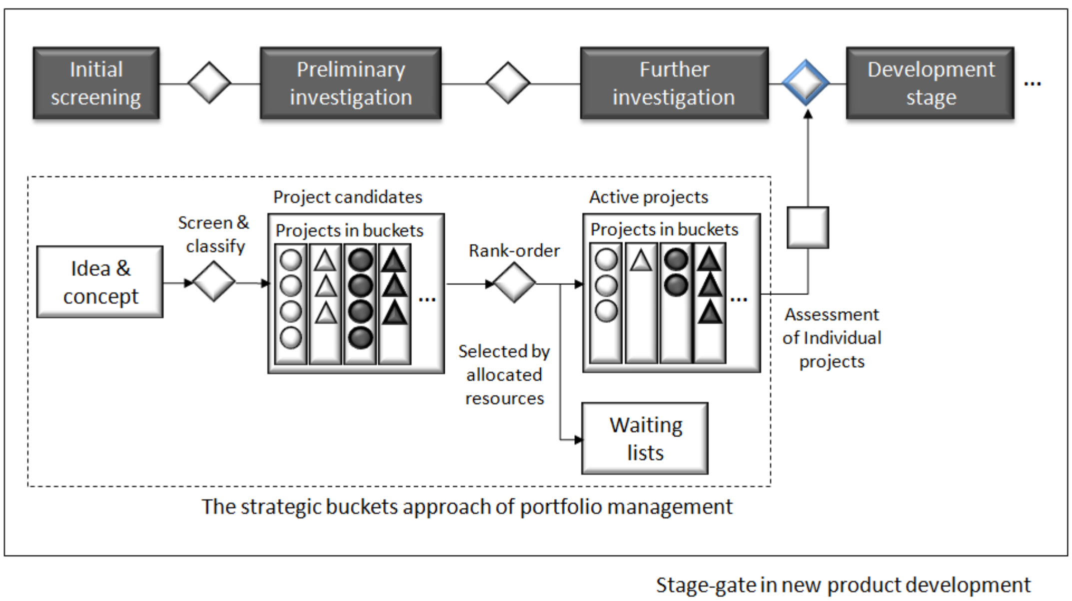

Fig. 3.1 The strategic buckets approach in the NPD process

My model structure builds upon an extended and modified version of the model developed by Ferreira, Kar, and Trigeorgis (2009). While their method considers adding a capacity option with a constant expected growth rate for demand or price in a numerical example (Ferreira, Kar, & Trigeorgis, 2009), I integrate product adoption rates with the product life cycle (Rogers, 1995; Bollen, 1999) into an option-game framework for evaluating an NPD project. I further develop a formal mathematical option-game framework in a discrete-time analysis when dealing with an American investment option in a finite project life. In contrast to the discrete option-game models using a European option by Chevalier-Roignant and Trigeorgis (2011), I consider the results of both potential simultaneous and sequential investment decisions in each scenario of the duopolistic game, and project service life is set as finite years. Therefore, I propose the gate-criterion of individual project assessment for the gate of development stage in the NPD process. Moreover, this technique can also be used to compute optimal selection of the planned production capacity. In summary, the strategic buckets approach in the early stages of the NPD process (Fig. 3.1) links business strategy and project portfolios (Cooper et al., 1997). With an option-game framework in the gate-criterion of the project development stage, this approach allows further inspection and examination of the individual projects in the development process.

As this research builds on proposed concepts in areas that have not yet been fully developed, the relevant literature concepts have been reviewed and discussed above. The remaining chapter is organized as follows. In section 3.2, I define the model description and develop this work by using an extended version of the proposed model structure for my valuation model. The concept of product diffusion is integrated into a valuation model that allows determining the value of a project in a finite project life cycle. In section 3.3, I illustrate the differences of demand structures by comparing the results of assuming a constant annual growth rate with the results of integrating product diffusion into the demand binomial lattice. I also provide a case study to demonstrate the model and compare the results with a benchmark, using NPV, the common and widely used conventional financial method in gate-criteria, as the benchmark. In section 3.4, I further validate this valuation model against the benchmark and discuss the results. Section 3.5 includes a summary of the results and concluding remarks.

3.2 Model Development

As I focus on individual project assessment at the gate-criterion of the development stage, I will assume that the projects have already been roughly screened and initially selected through the strategic buckets approach in the early stages of the NPD process as shown in Fig. 3.1. I am specifically interested in evaluating the buckets of projects with the following characteristics and dimensions: (1) managerial flexibility is expected for the risky and market-uncertain project; (2) there is a potential competitor for the same new project; (3) the new project is in a short product life cycle.

Consider two firms (Firms i and j) in a duopoly sharing an option to invest in an NPD project. Suppose that the firms are dealing with a delay investment option because of the highly uncertain market. For now, this project is proceeding at the gate of development stage in the NPD process. The gate decision of the development stage depends mainly on the expected performance and expected project value from the future periods (Fig. 3.1). In other words, the gate of development stage determines whether the firm will invest in the project at the stage of development. For the purpose of simplicity in calculation of the time horizon, the beginning development stage is set as time $t = 0$, which is the same as the gate of development stage, as shown in Fig. 3.2.

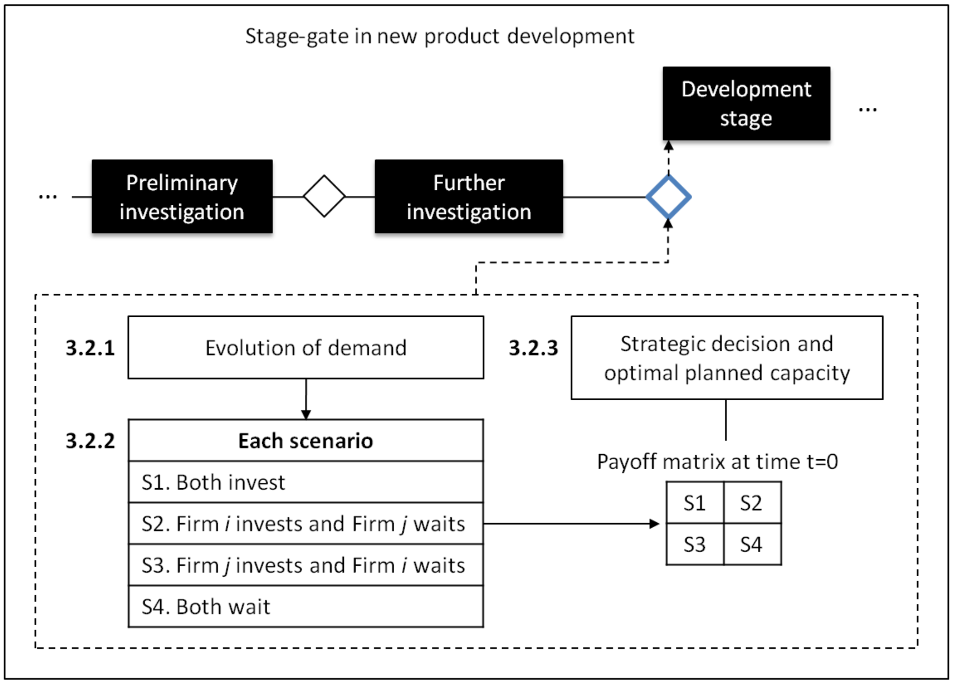

Fig. 3.2 The structure of model development

In addition, to simplify the NPD process, the later gates and stages of testing and production are not demonstrated. Hence, once the fixed investment cost is invested at the outset of the development stage, the cash flows will begin in the following period. Suppose that these two firms are active in the market now and behave rationally by selecting the profit-maximizing outputs. The main sources of uncertainty here are the market demand and the decisions of the rival.

According to the business strategy in the categorized buckets of projects, suppose that the firms' roles and sequences are not determined a priori. Hence, different combinations of actions may give further insights and help determine the values of potential decisions. In addition, suppose that one of the firms has a cost advantage (unit variable costs $c_i \neq c_j$). Due to the considerations of the product life cycle, reduced fixed investment cost over time, and asymmetric unit variable costs, the firms are also not sufficiently distinct. There is a trade-off between commitment and flexibility. When there is a first-mover advantage for the product life cycle after the new product is introduced to the market, both firms will want to invest as the leader to grasp this advantage. However, the fixed investment cost is reduced each year, where I_0 is the current fixed investment cost and λ is the annual reduced rate over time. Besides, an NPD project normally faces large demand uncertainty. Hence, there is also an incentive to delay until the market becomes larger and the fixed investment cost is lower (making the investment at time t before maturity T).

The duopolists have a finite planning horizon and can choose to invest before maturity T. For the purpose of clearly demonstrating insights into different possible scenarios, suppose that the option will expire in two years ($T = 2$), both firms make their decisions on an annual basis ($\Delta t = 1$), and the project will operate for a finite service life of N years. Both firms face the same interest rate r and risk free rate r_f. The main issues for the option holder are to make the strategic decision and to compute the optimal planned capacity at the gate of development stage in the NPD process (Fig. 3.2). To do so, the evolution of demand over the next two years is illustrated by a basic binomial lattice combined with the concept of product life cycle in section 3.2.1. Based on the demand evolution and the probabilities of upward and downward of each period in demand, I further determine the payoff values for the scenarios in a payoff matrix of time $t = 0$ in section 3.2.2. Each scenario at time $t = 0$ is considered with different combinations of potential decisions. The maximization of payoffs in each combination of decisions and the optimal payoff in each scenario are obtained by the Nash equilibrium with the best response analysis. Hence, the strategic decisions at time $t = 0$ and the optimal planned capacity are determined in section 3.2.3. Finally, I will compare this approach with a basic benchmark in section 3.3 and further discuss the results in section 3.4.

3.2.1 Demand evolution and the probabilities of upward in demand with product diffusion

A binomial lattice framework is used to represent the market demand uncertainty (Q) within T = 2 years. Based on experts' experience and a survey collection, the current demand is given as Q_0, its expected yearly growth rate is g, and its expected standard deviation is σ. Suppose that the decisions are made annually (i.e., Δt = 1); hence, the parameters of a binomial lattice (Luenberger, 1998) can be simplified as shown in equation (3.1).

· $u = e^{\sigma\sqrt{\Delta t}} = e^{\sigma}, d = 1/u$

· Risk-neutral probability of an upward:

$$q_r = \frac{(1+r_f)-d}{u-d}, \text{where } r_f : \text{risk-free rate} \qquad (3.1)$$

· The probability of an upward:

$$P = \frac{1}{2} + \frac{1}{2}(\frac{g}{\sigma})\sqrt{\Delta t} = \frac{1}{2} + \frac{1}{2}(\frac{g}{\sigma})$$

In order to reflect the changes of demand depending on when the new product is introduced to the market, the binomial lattice is combined with the concept of a product life cycle, where cumulative product diffusion (Rogers, 1995) can be used to estimate the relation of the market size in each period within a product life cycle. Hence, the demand structure at and after maturity will employ the concept of cumulative product diffusion, depending on when the product is introduced to the new market. The value of a cumulative normal distribution function of elapsed time can be applied to update the probability of a downward of the demand binomial lattice in each period (Bollen, 1999), indicating the probability of the expected non-growth in demand. In other words, during the earlier periods of a product life cycle, demand is expected to have a higher future market growth than during the later periods, i.e., the expected non-growth demand is lower in the earlier periods. Therefore, the updated probability of a downward in each period of the demand binomial lattice can be obtained by the average of the original probability of a downward at each period *1-P* and a cumulative normal distribution function of elapsed time *t* as $\Phi(x_t)$, expressed in equation (3.2).

$$1 - P_t = \frac{(1-P) + \Phi(x_t)}{2} \tag{3.2}$$

where $1-P$: the original probability of a downward in each period
$\Phi(x_t)$: a cumulative normal distribution of elapsed time t

Calculating equation (3.2) gives the updated probability of an upward at each period P_t in a demand binomial lattice. Assuming that the expected standard deviation σ in demand is the same over time, its expected yearly growth rate g_t at time *t* can be determined by putting P_t into equation (3.1) as expressed in equation (3.3).

$$g_t = 2\sigma(P_t - 0.5) \tag{3.3}$$

where P_t: the updated probability of an upward at time t

With the calculation of equations (3.1) to (3.3), the market structure can be framed. Before the option is expired, three possible structures of market patterns will be formed within two years. Suppose that the firms may invest at time *t* ($t \le 2$) and the annual profit grows at an expected growth rate g_t at time *t* with a risk-adjusted discount rate *r* ($r > g_t$). Hence, the total growth at maturity time 2 due to the three possible structures of market patterns is expressed in equation (3.4).

$$
\begin{cases}
G_0 = \frac{1+g_3}{1+r} + \frac{(1+g_3)(1+g_4)}{(1+r)^2} + ... + \frac{(1+g_3)...(1+g_N)}{(1+r)^{N-2}} \\
G_1 = \frac{1+g_3}{1+r} + \frac{(1+g_3)(1+g_4)}{(1+r)^2} + ... + \frac{(1+g_3)...(1+g_{N+1})}{(1+r)^{N-1}} \\
G_2 = \frac{1+g_3}{1+r} + \frac{(1+g_3)(1+g_4)}{(1+r)^2} + ... + \frac{(1+g_3)...(1+g_{N+2})}{(1+r)^{N}}
\end{cases}
\quad (3.4)
$$

where N : the project service life;
G_0 : either firm invests now $(t=0)$;
G_1 : no firms invest now, but either firm invests at time 1;
G_2 : no firms invest now or at time 1, but either firm invests at time 2

3.2.2 Payoff matrix of option-game at time *t* = 0

To determine market-clearing price and firm profits, a commonly used assumption in industry structure models is the linear (inverse) demand function (Chevalier-Roignant & Trigeorgis, 2011). Suppose that in the discrete-time model of Smit and Trigeorgis (2004) and Chevalier-Roignant and Trigeorgis (2011), the demand intercept in the linear market demand function follows a multiplicative binomial process as shown in equation (3.5).

$$
\tilde{p}_t = \tilde{a}_t - bQ = \tilde{a}_t - b(q_i + q_j) \quad (3.5)
$$

where $\tilde{a}_t, b$: constant parameters, $\tilde{a}_t, b > 0$;
Q : the total quantity will be supplied in the market;
$\tilde{a}_t$ follows a multiplicative binomial process

The intercept of demand function $\tilde{a}_t$ is followed by a stochastic binomial as shown in Fig. 3.3 for two periods: at each up move, $\tilde{a}_t$ is multiplied by u, while at each down move, it is multiplied by d from equation (3.1). When $\tilde{a}_t$ goes to time 1, it is noted as $\tilde{a}_1$, which indicates it could be either $\tilde{a}_u$ or $\tilde{a}_d$. Similarly, when $\tilde{a}_t$ goes to time 2, it is noted as $\tilde{a}_2$, which indicates it could be $\tilde{a}_{uu}$, $\tilde{a}_{ud}$, or $\tilde{a}_{dd}$.

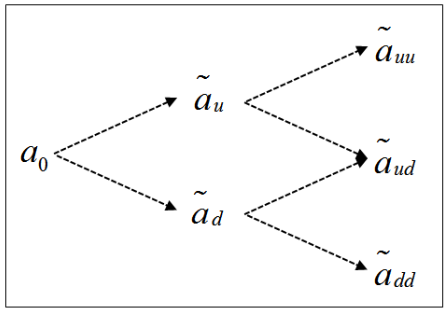

Fig. 3.3 Multiplicative binomial process followed by the intercept of demand $\tilde{a}_t$ at time t ($t \leq 2$)

I next determine the payoffs for both firms in each of the four scenarios from their decisions to invest or wait until maturity to decide, using a two-by-two matrix to capture the competitive interactions among players (Chevalier-Roignant & Trigeorgis, 2011). The payoff matrix for strategic decision at time t = 0 (the gate of development stage) is shown in Fig. 3.4.

S1: Simultaneous investment. If both firms invest simultaneously now, their payoff functions of scenario 1 in Fig. 3.4 can be described as the net present value (NPV) of a duopoly Cournot competition as expressed in equation (3.6).

$$\pi_h^{\mathrm{C}}(q_i, q_j) = \mathrm{NPV}_h^{\mathrm{C}} = -I_0 + E[V_{h0}^{\mathrm{C}}] \tag{3.6}$$

where I_0: current fixed investment cost; h = Firm i or j;
$E[V_{h0}^{\mathrm{C}}]$: expected present project value of duopoly Cournot

The expected present project value in equation (3.6) indicates the expected present values of the project cash flows, which can be calculated from the intermediate and terminal statuses in the demand binomial lattices. Since the option will expire in two years on the annual basis, the expected present project value is the sum of the expected present cash flows from the intermediate statuses of time 1 ($E[\tilde{A}^{\mathrm{C}}_{h1}]$) and the expected project value at the expiration (time 2) ($E[\tilde{V}^{\mathrm{C}}_{h2}]$) as shown in equation (3.7).

$$E[V^{\mathrm{C}}_{h0}] = (1+r)^{-1}E[\tilde{A}^{\mathrm{C}}_{h1}] + (1+r)^{-2}(1+G_0)E[\tilde{V}^{\mathrm{C}}_{h2}] \tag{3.7}$$

where $E[\tilde{A}^{\mathrm{C}}_{h1}] = P_1\tilde{A}^{\mathrm{C}}_{hu} + (1-P_1)\tilde{A}^{\mathrm{C}}_{hd}$;

$E[\tilde{V}^{\mathrm{C}}_{h2}] = P_1P_2\tilde{V}^{\mathrm{C}}_{huu} + [P_1(1-P_2) + P_2(1-P_1)]\tilde{V}^{\mathrm{C}}_{hud} + (1-P_1)(1-P_2)\tilde{V}^{\mathrm{C}}_{hdd}$;

P_t : probability of an upward at time t ($t = 1,2$)

		Firm *j*	
		Invest	**Wait**
Firm *i*	**Invest**	(S1) Simultaneous investment $\begin{bmatrix}\pi_i^{\mathrm{C}}(q_i,q_j)\\ \pi_j^{\mathrm{C}}(q_i,q_j)\end{bmatrix}$	(S2) Sequential investment $\begin{bmatrix}\pi_i^{\mathrm{L}}(q_i,q_j)\\ \pi_j^{\mathrm{F}}(q_i,q_j)\end{bmatrix}$
	Wait	(S3) Sequential investment $\begin{bmatrix}\pi_i^{\mathrm{F}}(q_i,q_j)\\ \pi_j^{\mathrm{L}}(q_i,q_j)\end{bmatrix}$	(S4) No investment (Both wait) $\begin{bmatrix}\pi_i^{\mathrm{W}}(q_i,q_j)\\ \pi_j^{\mathrm{W}}(q_i,q_j)\end{bmatrix}$

Fig. 3.4 Payoff matrix for strategic decision at time $t = 0$
(C: Cournot competition, L: leader, F: follower, W: wait)

The right two terms of equation (3.7) can be further defined by finding the differences between the market-clearing price and the firm's unit variable cost and then multiplying the number of the annual planned capacity, as expressed in equation (3.8). In equation (3.8), $\tilde{A}^{\mathrm{C}}_{h1}$ is the stochastic value of the cash flow at time 1 for Firm *h*. On the other hand, $\tilde{V}^{\mathrm{C}}_{h2}$ includes the stochastic cash flows at time 2 and for the remaining project life with the total annual growth rate G_0 at maturity.

$$\begin{cases} \tilde{A}_{h1}^{C} = (\tilde{p}_1 - c_h) q_h \\ \tilde{V}_{h2}^{C} = (\tilde{p}_2 - c_h) q_h (1 + G_0) \end{cases} \tag{3.8}$$

where c_h : unit variable cost of Firm h ($h =$ Firm i or j) ;

q_h : annual capacity of Firm h;

$\tilde{p}_1, \tilde{p}_2$: stochastic market clearing price at time 1, 2

Hence, both the expected value of cash flow at time 1 and the expected project value at time 2 for Firm *h* can be computed from their values at each status in Fig. 3.3 with their corresponding probabilities from equation (3.2), given by equation (3.9).

$$E[\tilde{A}_{h1}^{C}] = q_h [P_1 (\tilde{p}_u - c_h) + (1 - P_1)(\tilde{p}_d - c_h)]$$
$$E[\tilde{V}_{h2}^{C}] = q_h (1 + G_0) \{P_1 P_2 (\tilde{p}_{uu} - c_h) + [P_1 (1 - P_2) + P_2 (1 - P_1)](\tilde{p}_{ud} - c_h) + (1 - P_1)(1 - P_2)(\tilde{p}_{dd} - c_h)\}$$

(3.9)

By combining equations (3.6) to (3.9) with the linear (inverse) demand function, the payoff functions of scenario 3.1 in Fig. 3.4 can be rewritten as in equation (3.10).

$$\pi_h^C (q_i, q_j) = -I_0 + (1 + r)^{-1} E[\tilde{A}_{h1}^{C}] + (1 + r)^{-2} (1 + G_0) E[\tilde{V}_{h2}^{C}]$$
$$= -I_0 + (1 + r)^{-1} q_h [P_1 (\tilde{\alpha}_u - \tilde{\alpha}_d) + (\tilde{\alpha}_d - b q_h - b q_{h'} - c_h)] +$$
$$(1 + r)^{-2} q_h (1 + G_0) \{P_1 P_2 \tilde{\alpha}_{uu} + [P_1 (1 - P_2) + P_2 (1 - P_1)] \tilde{\alpha}_{ud} + (1 - P_1)(1 - P_2) \tilde{\alpha}_{dd} - b q_h - b q_{h'} - c_h\}$$

(3.10)

where $q_{h'}$: capacity of Firm h's competitor

S2: Sequential investment (Firm *i* invests and Firm *j* waits). In the second scenario of Fig. 3.4, Firm *i* invests now and Firm *j* waits: this scenario makes Firm *i* the leader when Firm *j* invests at time 1 or 2, or makes Firm *i* a monopolist if Firm *j* eventually abandons the project at time 2. Hence, each of the three possible cases will be discussed individually below. Accordingly, the payoff functions of scenario 2 will select the maximization of these three possible cases.

- ***Case 1: When Firm i invests now, Firm j invests at time 2.*** In this case, the payoff function of Firm *i* will comprise the expected monopolistic profits for the first two periods $E[\,(E[\tilde{A}_{i1}^{\mathrm{M}}], E[\tilde{A}_{i2}^{\mathrm{M}}])$ and the expected duopolistic profits for the remaining project service life ($E[\tilde{V}_{i2}^{\mathrm{C}}]$) as expressed in equation (3.11).

$$\pi_i^{\mathrm{L}}(q_i, q_j) = -I_0 + E[\tilde{A}_{i1}^{\mathrm{M}}](1+r)^{-1} + E[\tilde{A}_{i2}^{\mathrm{M}}](1+r)^{-2} + E[\tilde{V}_{i2}^{\mathrm{C}}](1+r)^{-2} G_0 \tag{3.11}$$

$$\text{where L: leader; M: monopoly; } E[\tilde{A}_{i1}^{\mathrm{M}}] = P_1 \tilde{A}_{iu}^{\mathrm{M}} + (1-P_1)\tilde{A}_{id}^{\mathrm{M}};$$
$$E[\tilde{A}_{i2}^{\mathrm{M}}] = P_1 P_2 \tilde{A}_{iuu}^{\mathrm{M}} + [P_1(1-P_2) + P_2(1-P_1)]\tilde{A}_{iud}^{\mathrm{M}} + (1-P_1)(1-P_2)\tilde{A}_{idd}^{\mathrm{M}};$$
$$E[\tilde{V}_{i2}^{\mathrm{C}}] = P_1 P_2 \tilde{V}_{iuu}^{\mathrm{C}} + [P_1(1-P_2) + P_2(1-P_1)]\tilde{V}_{iud}^{\mathrm{C}} + (1-P_1)(1-P_2)\tilde{V}_{idd}^{\mathrm{C}}$$

On the other hand, the current payoff function of Firm *j* describes the fixed investment cost of time 2 and the current values of gains from the duopolistic profits after time 2 (depending on the product diffusion rate in demand) as shown in equation (3.12). The term $E[\tilde{V}_{j2}^{\mathrm{C}}]$ in equation (3.12) is the expected profit of Firm *j* at time 2 with the corresponding probabilities.

$$\pi_{j(2)}^{\mathrm{F}}(q_i, q_j) = -I_2(1+r)^{-2} + (1+r)^{-2} G_0 E[\tilde{V}_{j2}^{\mathrm{C}}] \tag{3.12}$$

$$\text{where } E[\tilde{V}_{j2}^{\mathrm{C}}] = P_1 P_2 \tilde{V}_{juu}^{\mathrm{C}} + [P_1(1-P_2) + P_2(1-P_1)]\tilde{V}_{jud}^{\mathrm{C}} + (1-P_1)(1-P_2)\tilde{V}_{jdd}^{\mathrm{C}};$$
$$\pi_{j(2)}^{\mathrm{F}}: \text{current profit function of Firm } j \text{ when it is a follower at time 2;}$$
$$I_2: \text{the fixed investment cost at time 2}, I_2 = (1-\lambda)^2 I_0$$

- ***Case 2: When Firm i invests now, Firm j abandons at time 2.*** In this case, Firm *i* will simply gain the monopolistic profits during its product service life and Firm *j*'s payoff value is 0 as shown in equation (3.13). Term $E[\tilde{V}_{i2}^{\mathrm{M}}]$ in equation (3.13) is the expected monopolistic project value of Firm i at time 2 with the corresponding probabilities.

$$\begin{cases} \pi_i^{\mathrm{M}}(q_i, q_j) = -I_0 + (1+r)^{-1} E[\tilde{A}_{i1}^{\mathrm{M}}] + (1+r)^{-2}(1+G_0) E[\tilde{V}_{i2}^{\mathrm{M}}] \\ \pi_j(q_i, q_j) = 0 \end{cases} \tag{3.13}$$

$$where\ E[\tilde{V}_{i2}^{\mathrm{M}}] = P_1 P_2 \tilde{V}_{iuu}^{\mathrm{M}} + [P_1(1-P_2) + P_2(1-P_1)]\tilde{V}_{iud}^{\mathrm{M}} + (1-P_1)(1-P_2)\tilde{V}_{idd}^{\mathrm{M}}$$

- ***Case 3: When Firm i invests now, Firm j invests at time 1.*** In this case, the payoff function of Firm i will comprise the expected monopolistic profit in the first period and the expected duopolistic profits for the remaining project service life as shown in equation (3.14).

$$\pi_i^{\mathrm{L}}(q_i, q_j) = -I_0 + E[\tilde{A}_{i1}^{\mathrm{M}}](1+r)^{-1} + E[\tilde{V}_{i2}^{\mathrm{C}}](1+r)^{-2}(1+G_0) \tag{3.14}$$

On the other hand, the current payoff function of Firm j describes the fixed investment cost of time 1 and the gains from the expected duopolistic profits after time 1 (depending on the product diffusion rate in demand), as shown in equation (3.15).

$$\pi_{j(1)}^{\mathrm{F}}(q_i, q_j) = -I_1(1+r)^{-1} + E[\tilde{V}_{j2}^{\mathrm{C}}](1+r)^{-2}(1+G_0) \tag{3.15}$$

where I_1 : the fixed investment cost of time 1, $I_1 = (1-\lambda)I_0$;
$\pi_{j(1)}^{\mathrm{F}}$: current profit function of Firm j when it is a follower at time 1

Of all the above three cases in scenario 2, Firm i has a fixed setting to invest at time 0, but Firm j instead has three possible moves. Since Firm i has only one move, the payoff functions of scenario 2 will thus mainly depend on Firm j's decision. The maximization of these three possible moves from Firm j's decision can be expressed by equation (3.16), which combines equations (3.12), (3.13) and (3.15).

$$\begin{cases} \text{Firm } i: \pi_i^{\text{L}}(\pi_j^{\text{F*}}(q_i, q_j)) \\ \text{Firm } j: \pi_j^{\text{F*}}(q_i, q_j) = \max[\pi_{j(1)}^{\text{F}}(q_i, q_j), \pi_{j(2)}^{\text{F}}(q_i, q_j), 0] \end{cases} \tag{3.16}$$

S3: Sequential investment (Firm *j* invests and Firm *i* waits). In the third scenario of Fig. 3.4, Firm *j* invests now and Firm *i* waits. This scenario allows Firm *j* to be a leader if Firm *i* invests at time 1 or 2, or to be a monopolist if Firm *i* eventually abandons the project at time 2. Scenario 3 is the same concept as scenario 2 but with the firms having opposite roles. Hence, Firm *j* has only one move, so the payoff functions of scenarios 3 will mainly depend on Firm *i*'s decision. Similarly, the payoff functions of scenario 3 can be written to maximize the three possible moves from Firm *i*'s decision as expressed in equation (3.17).

$$\begin{cases} \text{Firm } i: \pi_i^{\text{F*}}(q_i, q_j) = \max[\pi_{i(1)}^{\text{F}}(q_i, q_j), \pi_{i(2)}^{\text{F}}(q_i, q_j), 0] \\ \text{Firm } j: \pi_j^{\text{L}}(\pi_i^{\text{F*}}(q_i, q_j)) \end{cases} \tag{3.17}$$

S4: No investment (both wait). If both firms wait now, their payoff functions can be viewed as the present value of a shared American call option with three possible investment actions within two periods: invest at time 1, invest at time 2, or abandon at time 2. With the evolution of the demand binomial tree, I can value each strategy between the firm and its rival by working the tree backward (Chevalier-Roignant & Trigeorgis, 2011). At maturity, there is a two-by-two payoff matrix in each of the terminal statuses as shown in Fig. 3.5. When firms decide to invest or abandon the project at time 2, there are three combined strategies: simultaneous investment, monopoly investment, and no investment. Simultaneous investment means that if both invest at time 2, a Cournot duopoly game is formed and their stochastic payoff functions can be expressed as shown in equation (3.18). Monopoly investment means that only one of them invests at time 2, so that the investing firm gains the stochastic monopolistic investment and its rival's value is zero as shown in equation (3.19). No investment gives both firms zero value since they abandon the project simultaneously at time 2.

Firm *i* / **Firm *j***	**Invest**	**Abandon**
Invest	(1) Simultaneous investment $\begin{bmatrix}\tilde{C}_{i2}(q_i,q_j)\\ \tilde{C}_{j2}(q_i,q_j)\end{bmatrix}$	(2) Monopoly investment $\begin{bmatrix}\tilde{M}_{i2}(q_i,q_j)\\ 0\end{bmatrix}$
Abandon	(3) Monopoly investment $\begin{bmatrix}0\\ \tilde{M}_{j2}(q_i,q_j)\end{bmatrix}$	(4) No investment (Abandon) $\begin{bmatrix}0\\ 0\end{bmatrix}$

Fig. 3.5 Payoff matrix for strategic investment decision at time t = 2

$$\tilde{C}_{h2}(q_i,q_j) = -I_2 + \tilde{V}_{h2}^{\mathrm{C}} G_2 \tag{3.18}$$

$$\text{where } \tilde{V}_{h2}^{\mathrm{C}} = -bq_h^2 + (\tilde{\alpha}_2 - bq_{h'} - c_h)q_h$$

$$\tilde{M}_{h2}(q_i,q_j) = -I_2 + \tilde{V}_{h2}^{\mathrm{M}} G_2 \tag{3.19}$$

$$\text{where } \tilde{V}_{h2}^{\mathrm{M}} = -bq_h^2 + (\tilde{\alpha}_2 - c_h)q_h$$

Thus, the resulting equilibrium outcomes in the end statuses can be obtained from the payoff matrices of time 2 by applying the Nash equilibrium with the best response analysis, where the competitive outcomes at time 2 in each status are noted as $\left[\tilde{X}_{i2}(q_i^*,q_j^*),\tilde{X}_{j2}(q_i^*,q_j^*)\right]$.

Next, working in the previous period (time 1) of the binomial tree, there is a payoff matrix in each of the intermediate statuses as shown in Fig. 3.6. When the firms decide to invest or wait at time 1, there are three combined strategies: simultaneous investment, sequential investment, and no investment. Simultaneous investment means that if both invest at time 1, a Cournot duopoly game is formed and their stochastic payoff functions can be expressed in equation (3.20).

$$\tilde{C}_{h1}(q_i, q_j) = -I_1 + (1+r)^{-1}(1+G_1)E[\tilde{V}^{C}_{h2}] \tag{3.20}$$

where $E[\tilde{V}^{C}_{h2}] = P_2(\tilde{V}^{C}_{h2}) + (1-P_2)(\tilde{V}^{C}_{h2'})$;

$\tilde{V}^{C}_{h2} = -bq_h^2 + (\tilde{a}_2 - bq_{h'} - c_h)q_h$;

2 : the up move at time 2; $2'$: the down move at time 2

		Firm *j*	
		Invest	**Wait**
Firm *i*	**Invest**	(1) Simultaneous investment $\begin{bmatrix} \tilde{C}_{i1}(q_i, q_j) \\ \tilde{C}_{j1}(q_i, q_j) \end{bmatrix}$	(2) Sequential investment $\begin{bmatrix} \tilde{L}_{i1}(q_i, q_j) \\ \tilde{F}_{j1}(q_i, q_j) \end{bmatrix}$
	Wait	(3) Sequential investment $\begin{bmatrix} \tilde{F}_{i1}(q_i, q_j) \\ \tilde{L}_{j1}(q_i, q_j) \end{bmatrix}$	(4) No investment (Both wait) $\begin{bmatrix} \tilde{W}_{i1}(q_i, q_j) \\ \tilde{W}_{j1}(q_i, q_j) \end{bmatrix}$

Fig. 3.6 Payoff matrix for strategic investment decision at time $t = 1$

Sequential investment means that if one of the firms invests at time 1, the other waits, comprising two possible cases: actual sequential investment and monopoly investment, as shown in Fig. 3.6. If it is an actual sequential investment, one invests at time 1 and the other invests at time 2. If it is a monopoly investment, one of them invests at time 1 and gains the monopoly. Its rival abandons the project at time 2 with zero value. The payoff functions will be the maximum for sequential investment. Equation (3.21) describes the payoff functions of sequential investment by maximizing the above two cases for scenarios 2 and 3 in Fig. 3.6, respectively. No investment means that if both firms wait at time 1, their payoff functions can be computed as the option value from the optimal matrix outcome of time 2 with the risk neutral probability q_r, as expressed in equation (3.22).

$$\begin{cases} \text{Scenario 2: } (\tilde{L}_{i1}, \tilde{F}_{j1}) = \max[(\tilde{\pi}^{\mathrm{L}}_{i1}, \tilde{\pi}^{\mathrm{F}}_{j(2)}), (\tilde{\pi}^{\mathrm{M}}_{i1}, 0)] \\ \text{Scenario 3: } (\tilde{F}_{i1}, \tilde{L}_{j1}) = \max[(\tilde{\pi}^{\mathrm{F}}_{i(2)}, \tilde{\pi}^{\mathrm{L}}_{j1}), (0, \tilde{\pi}^{\mathrm{M}}_{j1})] \end{cases} \tag{3.21}$$

where $\tilde{\pi}^{\mathrm{L}}_{i1}, \tilde{\pi}^{\mathrm{L}}_{j1}$: payoff when Firm i, j is a leader at time 1;

$\tilde{\pi}^{\mathrm{F}}_{i(2)}, \tilde{\pi}^{\mathrm{F}}_{j(2)}$: payoff when Firm i, j is a follower at time 2

$$[\tilde{W}_{i1}(q_i, q_j), \tilde{W}_{j1}(q_i, q_j)] = \left[\frac{q_r \tilde{x}^*_{i2} + (1-q_r)\tilde{x}^*_{i2'}}{1+r_f}, \frac{q_r \tilde{x}^*_{j2} + (1-q_r)\tilde{x}^*_{j2'}}{1+r_f} \right] \tag{3.22}$$

where $\tilde{X}^*_{h2} = \tilde{X}_{h2}(q_i^*, q_j^*)$: equilibrium results at time 2 for Firm i or j

Therefore, the resulting equilibrium outcome in each intermediate status can be obtained from the payoff matrices of time 1 by applying the Nash equilibrium with the best response analysis, where the competitive outcomes are noted as $\left[\tilde{X}_{i1}(q_i^*, q_j^*), \tilde{X}_{j1}(q_i^*, q_j^*)\right]$. Finally, the payoff functions of scenario 4 at time t = 0 in Fig. 3.4 are the competitive outcomes at intermediate statuses obtained from the payoff matrices of time 1 by applying the Nash equilibrium with the best response analysis, as shown in equation (3.23).

$$[\pi_i^{W}(q_i, q_j), \pi_j^{W}(q_i, q_j)] = [\ \frac{q_r \tilde{x}^*_{iu} + (1-q_r)\tilde{x}^*_{id}}{1+r_f}\ ,\ \frac{q_r \tilde{x}^*_{ju} + (1-q_r)\tilde{x}^*_{jd}}{1+r_f}\ ] \tag{3.23}$$

where $\tilde{X}^*_{h1} = \tilde{X}_{h1}(q_i^*, q_j^*)$: equilibrium results at time 1 of Firm h (time $\tilde{1} = u$ or d)

3.2.3 Strategic decisions and the planned capacity

The profit functions of both firms in each of the four scenarios at time t = 0 are derived and defined in section 3.2.2 above. One firm's output choice (q_h) is not the only factor that influences the product market price; the rival's choice ($q_{h'}$) also influences it. In order to find the equilibrium results of the payoff matrix at time t = 0, the Nash equilibrium outputs (q_i, q_j) are applied, where each firm's capacity choice is the best response to the other's optimal capacity decision (Chevalier-Roignant & Trigeorgis, 2011). Therefore, one firm's optimal capacity can be determined by taking the first-order condition for the firm's profit maximization and the rival's capacity choice as given. The details of Nash equilibrium outputs for the four scenarios are derived separately in Appendix A and summarized in the payoff matrix shown in Fig. 3.7. Finally, the resulting equilibrium for the gate decision of the development stage can be obtained from the payoff matrix at time t = 0 (Fig. 3.7) by applying the Nash equilibrium with the best response analysis, where the competitive outcomes are noted as $[X_i\,(q_i^*, q_j^*), X_j\,(q_i^*, q_j^*)]$ with the optimal capacity (q_i^*, q_j^*) .

Firm *i* \ Firm *j*	**Invest**	**Wait**
Invest	(S1) Simultaneous investment $\begin{bmatrix}\pi_i^{\mathrm{C}}(q_i^*,q_j^*)\\ \pi_j^{\mathrm{C}}(q_i^*,q_j^*)\end{bmatrix}$	(S2) Sequential investment $\begin{bmatrix}\pi_i^{\mathrm{L}}(\pi_j^{\mathrm{F}}(q_i,q_j^{**}))\\ \pi_j^{\mathrm{F}}(q_i,q_j^{**})\end{bmatrix}$
Wait	(S3) Sequential investment $\begin{bmatrix}\pi_i^{\mathrm{F}}(q_i^{**},q_j)\\ \pi_j^{\mathrm{L}}(\pi_i^{\mathrm{F}}(q_i^{**},q_j))\end{bmatrix}$	(S4) No investment (Both wait) $\begin{bmatrix}\pi_i^{\mathrm{W}}(q_i^*,q_j^*)\\ \pi_j^{\mathrm{W}}(q_i^*,q_j^*)\end{bmatrix}$

Fig. 3.7 Profit maximization for each strategic investment decision at time $t = 0$

3.2.4 Benchmark: the NPV approach

Suppose the two firms are competing in the target marketplace and Firm *i*'s and *j*'s unit variable costs c_i and c_j are constant ($c_i, c_j > 0, c_i \neq c_j$). In the settings of the benchmark, the demand will have the constant expected growth rate *g*. In addition, the profit of Firm *i* is based on its market share of the overall product quantity in the target market. To earn the maximum overall profit, the industry chooses to produce the output that equals their average marginal cost to marginal revenue (Chevalier-Roignant & Trigeorgis, 2011). Therefore, the equilibrium quantity produced in the industry is shown in equation (3.24) and Appendix A.

$$Q = \frac{a_0 - \bar{c}}{2b} \tag{3.24}$$

$$\text{where } \bar{c} : \text{average marginal cost} = (c_i + c_j)/2$$

The capacity of Firm *i* is computed by its estimated market share ω of the total supply quantities in the industry and represents the degree of dominance that Firm *i* has within the particular market. To simplify the definition, the market share is estimated by the unit variable costs from both firms (c_i, c_j). As I assume that there is only one competitor, the rival's unit variable cost directly influences Firm *i*'s market share as expressed in equation (3.25). Finally, the resulting equilibrium profit of Firm *i* by the NPV approach can be expressed in equation (3.26) and is provided in Appendix A.

$$\omega = \frac{c_j}{c_i + c_j} \tag{3.25}$$

$$\text{NPV}_{i0} = -I_0 + \frac{G\omega(a_0 - \bar{c})(a_0 + \bar{c} - 2c_i)}{4b} \tag{3.26}$$

$$\text{where } G = \sum_{m=1}^{N} \left(\frac{1+g}{1+r}\right)^m$$

3.3 Case Study

In this section, a numerical example is demonstrated with the analysis and comparison of a project with single output. The market demand follows a binomial lattice with the product life cycle as defined in section 3.2.1. The illustrations of a binomial lattice integrated with product diffusion and the relevant market structure patterns are presented in section 3.3.1. Accordingly, the scenarios of payoff matrices in the option-game framework are calculated and shown in Section 3.3.2. I further compare my approach to a benchmark and observe the results of the strategic decision and the quantity of the planned capacity. I chose NPV as the benchmark because it is the most common and widely used conventional financial method in gate-criteria. In addition, further sensitivity analyses of the project payoffs and the option values are studied based on the assumptions of the parameters in section 3.3.3.

Suppose Firm *i* is assessing an individual project at gate-decision of the development stage in the NPD process, where all the individual projects have been screened and investigated through the strategic buckets approach in the early stages (as described in section 3.2). Some portions of the buckets are the projects with the specific dimensions of high risk, uncertain market, short life cycle, a potential competitor, and a rapidly changing environment. Firm *i* will need to evaluate these categories of projects in the gate decision before proceeding to the product development stage. The questions for Firm *i* are how to evaluate this project at this gate-decision, whether this project should proceed to the next stage, and if so, what the optimal quantity of planned capacity will be.

Firm *i* and its rival (Firm *j*) are in a duopoly and share a delay option to invest in an NPD project where the option will expire in two years ($T = 2$). Both firms make their decisions on an annual basis ($\Delta t = 1$), and the project will operate for a finite service life of $N = 4$ years with the same interest rate $r = 12\%$ and risk free rate $r_f = 5\%$. The current demand is given as $Q_0 = 750$, with an expected yearly growth rate of $g = 8\%$ and an expected standard deviation of $\sigma = 50\%$. Both firms have the same current fixed investment cost (I_0 = \$34,500), which would be reduced 15% each year (i.e., I_1 = \$29,325; I_2 = \$24,926.25). Firm *i* has a cost advantage where Firm *i*'s unit variable cost (c_i = \$10) is less than Firm *j*'s (c_j = \$15). The current (inverse) demand function is given as $p_0 = 50 - 0.05Q$. Suppose that the firms' roles and sequences are not determined a priori because of the business strategy in the categorized buckets of projects. Moreover, due to the considerations of the product life cycle, reduced fixed investment cost over time, and asymmetric unit variable costs, the firms are also not sufficiently distinct.

Hence, mixed strategies may give further insights and help determine the values of potential decisions.

3.3.1 Demand structure patterns with product diffusion

With the above given information (g = 8%, σ = 50%, r_f = 5%, T = 2, Δt = 1), I can calculate the parameters of the binomial lattice into equation (3.1) and obtain the following: u = 1.6487, d = 0.6065, q_r = 0.4255, 1-q_r = 0.5745, P = 0.58, and 1-P = 0.42. The concept of product life cycle is integrated into the binomial lattice depending on when the new product is introduced to the market. There are three integrated demand structures considered when the project diffusion is incorporated with the binomial lattice: (1) if either firm invests now, (2) if the project is first invested at time 1, and (3) if the project is first invested at time 2.

In the first demand structure, the upward probabilities in the first period and second period can be computed from equation (3.2) as 0.71 and 0.54, respectively. The remaining two-year product life after maturity will have the growth rates of -0.13 and -0.21 for years 3 and 4, respectively, from equation (3.3). Fig. 3.8 shows the demand binomial lattice with product diffusion of N = 4 years product life cycle and the cumulative probabilities of demand at time 2 in the first demand structure, where the cumulative demand indicates demand at and after time 2 at each end status for the observation of the total future demand distribution.

To compare the demand distribution of a binomial lattice with product diffusion to that of a standard one, I assume the standard binomial lattice follows a constant growth rate (g = 8%) in a finite project life. Fig. 3.9 shows that the demand values at each end status of the standard method are slightly overestimated without considering product diffusion. In addition, when product diffusion is considered, if the product is introduced to market next period, the probability of the upward status at maturity is increased. Moreover, the expected demand at time 2 is computed as 3,141.06 units, which is about 10.65 percent lower than that of the standard method. The main reason for the difference is that the standard binomial lattice is assumed to have a constant annual growth rate. In contrast, when using the product diffusion concept, the annual growth rate will be re-calculated based on the different market structure patterns.

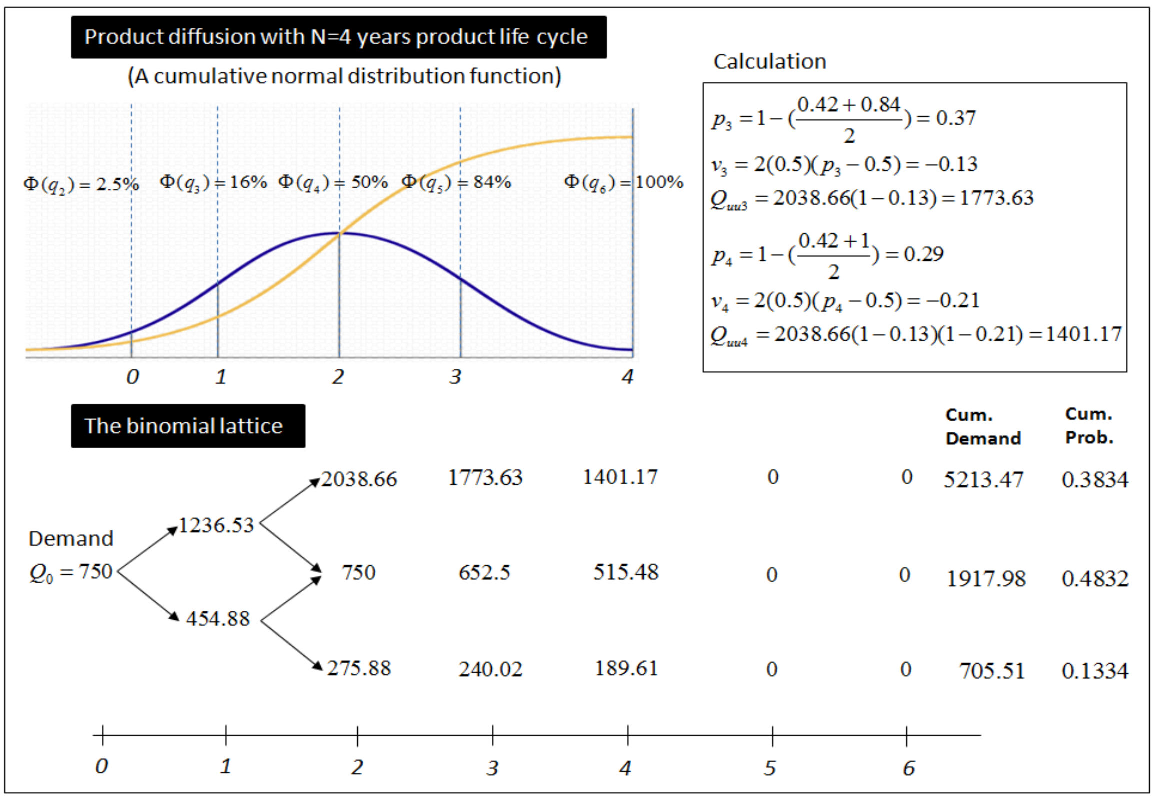

Fig. 3.8 The binomial lattice with product diffusion of N = 4 product life cycle
(The first demand structure pattern: if either firm invests now)

The binomial lattices with product diffusion and the demand probability distributions at time 2 for the second and third demand structure patterns are shown in

Appendix B1. Overall, the demand distribution will be affected by when the new product is introduced to the market (for all three demand structures). In other words, if either of the firms invests in the project in the early periods, the demand distribution at maturity will not be optimistic. Furthermore, in all three demand structures, the expected demands at maturity of my approach are 10.65%, 3.06%, and 8.35% lower than those of standard ones (in the order of the demand structure), due to the consideration of product diffusion. In summary, the demand distribution at $T = 2$ and the annual growth rate after maturity can be overestimated without integrating the concept of product diffusion into a demand binomial lattice.

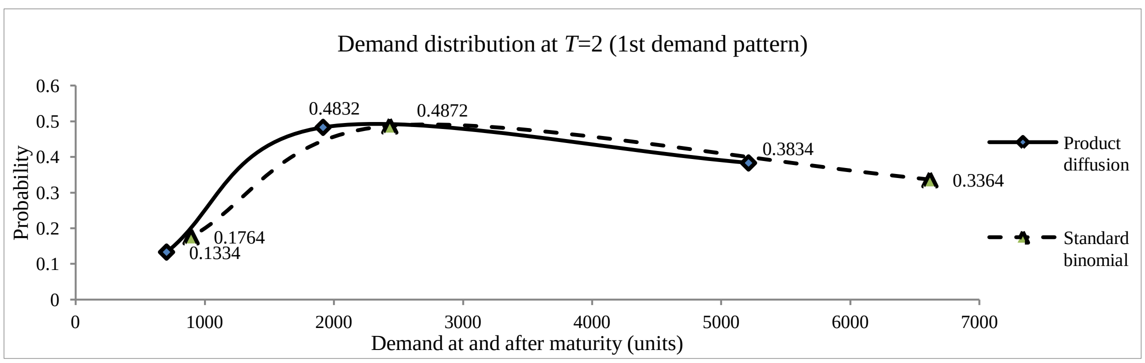

Fig. 3.9 Demand distribution at $T = 2$
(The first demand structure pattern: if either firm invests now)

3.3.2 Strategic decisions and the optimal planned capacity

Appendix B2 shows the calculations in each scenario and the payoff matrices in the intermediate and terminal statuses. The results are summarized in Table 3.1. Applying the Nash equilibrium concept, the payoff matrix at time $t = 0$ can be obtained from combining the four scenarios of Appendix B2. In Table 3.1, both firms will gain negative payoffs if they invest simultaneously. The optimal strategic decision will be for both firms to wait. The second best outcome will be for either firm to take the action opposite of the rival's to gain the monopoly profit. Hence, based on these competitive outcomes, the firms should not both invest at the same time now, but carefully observe the rival's move. The optimal planned capacities in each scenario are shown in Table 3.2.

Table 3.1 Payoff matrix at time $t = 0$

π_i, π_j		Firm *j*			
		Invest		Wait	
Firm *i*	Invest	-\$4,583.59	-\$16,028.75	\$17,220.72	\$0.00
	Wait	\$0.00	\$9,136.94	\$17,178.73	\$9,147.47

Table 3.2 The optimal planned capacity

q_i, q_j		Firm *j*			
		Invest		Wait	
Firm *i*	Invest	467	367	614	0
	Wait	0	564	873	773

In order to compare the results to a benchmark, I use the NPV approach, the common and widely used conventional financial method in gate-criteria. Appendix B3 shows the details of the calculation of NPV. The result of NPV is -\$17,022.6 with an average annual planned capacity of 225 units. Hence, by this gate-criterion, the negative value of NPV makes the current project a kill/no go decision. Based on the NPV criterion, the project should be abandoned, but the option-game approach assesses the value of a project's flexibility and suggests putting the project on a waiting list (Fig. 3.1) to see if any new information appears.

3.3.3 Sensitivity analyses

As a numerical example has been demonstrated, in this section, further sensitivity analyses of the project payoffs and the option values are studied based on the assumptions of the parameters (the expected growth rate g, the expected standard deviation σ, the unit variable costs c_i, c_j, and the project service life N). All other parameters are the defaults from section 3.3.2. The results of the sensitivity analyses in each of the four parameters are shown in Appendix B4. Overall, the results show that the payoffs and option values of Firm i in each scenario become larger when increasing the value of the parameter. In scenario 2 (Firm i invests and Firm j waits at time $t = 0$), with the growing standard deviation, or project service life, Firm i may gain a lower payoff from the next period of competitive outcome at time 1, since Firm j may change its investment decisions due to the increasing option value. Therefore, even though Firm i has the cost advantage (i.e., unit variable cost), their project profits and/or option values could be influenced and partitioned by Firm j's investment decision when the project variability or product service life is high.

3.3.4 Interpretation of the results

This case study shows that the integration of product diffusion into a binomial lattice of demand influences the demand distribution at $T = 2$, the probability of an upward in demand, and the annual growth rate when compared to a standard one (with a constant growth rate in a finite project life). The results and implications are consistent with Bollen's study (1999). For the gate-criterion, this approach suggests that the firms should not invest simultaneously now, but carefully observe the rival's move as long as there is still value in the decision to wait. While the conventional NPV criterion gives a kill/no go decision for this project, this approach allows for a “wait-and-see” action. Therefore, instead of abandoning a project based on a kill/no go decision, this approach determines that the project is worth re-investigating in the next round of periods. On the other hand, the optimal planned capacities in each of the four scenarios can be obtained by the Nash equilibrium, which can provide a more strategic preliminary planned capacity for the scale of the new product development than that of the NPV approach with an average annual planned capacity. The sensitivity analyses show that in scenario 2, option values and project payoffs of Firm *i* can be partitioned by its rival when either the parameter of project variability or product service life is high. As a numerical example cannot generalize the results, the next section provides further validation and discussion.

3.4 Validation and Discussion

The option value approach incorporates potential flexibility, which the NPV approach does not consider. In this section, I use my approach to verify the value of managerial flexibility in a project. I also discuss the research limitations and possibilities for future research.

3.4.1 Validation

The academic literature has confirmed the value of flexibility, which the NPV approach lacks. Hence, I mainly focus on the value of flexibility provided by the option-game technique. It has been proved that the optimal exercise policy for the owner of an American call option is to hold the option until maturity (Hull, 2008). Accordingly, since the delay option in this model can be viewed as an American investment option, I will validate this model as a European option at maturity for the sake of simplicity.

Moreover, Chevalier-Roignant and Trigeorgis (2011) have illustrated the investment decisions of a European option at maturity in an asymmetric Cournot duopoly. They conclude that both firms invest simultaneously as an asymmetric Cournot when demand is high; a low-cost firm invests as monopoly but a high-cost firm does not when demand is in the intermediate; no one invests when demand is low. From their findings, I can employ these sets of investment decisions in each status of maturity as a priori for the two-year binomial tree as shown in Fig. 3.10.

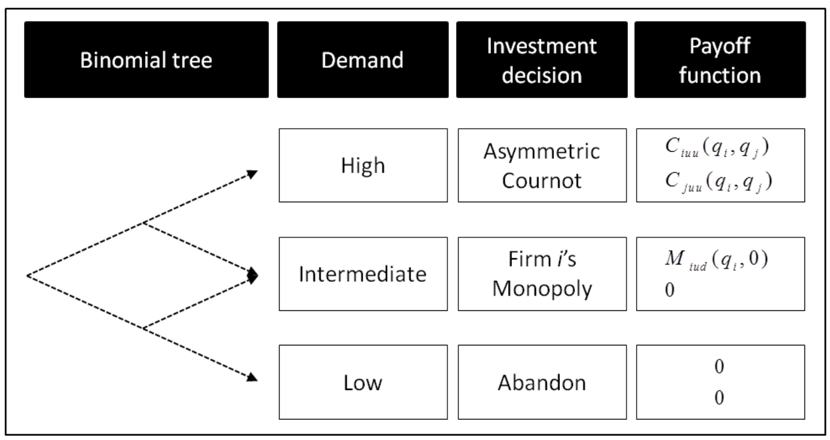

Fig. 3.10 Investment decisions and payoffs at maturity in an asymmetric Cournot duopoly (Chevalier-Roignant & Trigeorgis, 2011)

Consequently, with these payoff functions in each status at maturity (Fig. 3.10), I can compute their option value, which is also called strategic net present value (SNPV), at time $t = 0$. When NPV is subtracted from the value of SNPV, the option premium is obtained. In this way, I can demonstrate the value of managerial flexibility via the option-game approach. More specifically, option premium is used as an indicator in the option-game approach to measure the exclusive strategic value of flexibility, which the NPV method lacks.

Before calculating the option value, Firm i's resulting equilibrium profit needs to be determined. The details of calculation of resulting equilibrium profits are provided in Appendix C. The project service life is assumed to be N = 4 years. Hence, the equilibrium profits of asymmetric Cournot and monopoly for Firm i are shown in equations (3.27) and (3.28), respectively. With equations (3.27) and (3.28) and the risk-neutral probability, the present value (t = 0) of the strategic investment option for Firm i can be computed as expressed in equation (3.29). Finally, option premium (OP) is obtained with equation (3.29), subtracting the value of NPV, as expressed in equation (3.30).

$$\tilde{C}_{iuu}(q_i, q_j) = -I_2 + \frac{(\tilde{a}_{uu} - 2c_i + c_j)^2 G_2}{9b} \tag{3.27}$$

$$\widetilde{M}_{iud}(q_i, q_j) = -I_2 + \frac{(\tilde{a}_{ud} - c_i)^2 G_2}{4b} \tag{3.28}$$

$$\text{SNPV}_{i00} = \frac{\tilde{C}_{iuu} q_r^2 + 2\tilde{M}_{iud} q_r (1 - q_r)}{(1 + r_f)^2} \tag{3.29}$$

$$\begin{aligned} \text{OP}_{i00} &= \text{SNPV}_{i00} - \text{NPV}_{i00} \\ &= \frac{\tilde{C}_{iuu} q_r^2 + 2\tilde{M}_{iud} q_r (1 - q_r)}{(1 + r_f)^2} + I_0 - \frac{G\omega(a_0 - \bar{c})(a_0 + \bar{c} - 2c_i)}{4b} \end{aligned} \tag{3.30}$$

As the value of option premium can be influenced by multiple parameters, further sensitivity analyses can provide the trends with specific parameters (the expected standard deviation of demand σ, the expected yearly growth rate g, the ratio of firms' unit costs β_{vc}, and the annual reduced rate of the fixed investment cost λ). All other parameters are set as the defaults from the previous section. The results show that the expected standard deviation of demand (σ) is the most critical parameter in the option premium. As shown in Fig. 3.11, option premium grows dramatically with the increasing value of σ.

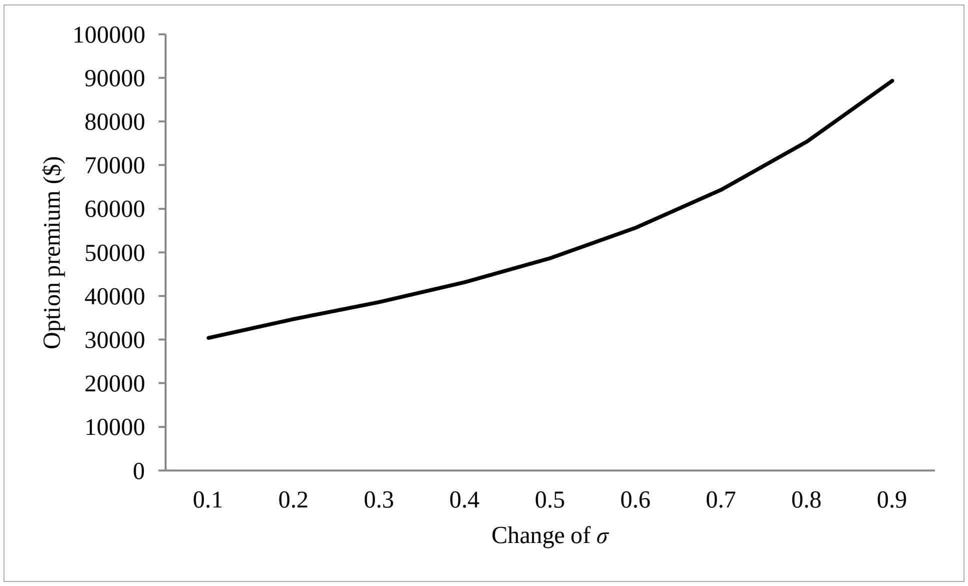

Fig. 3.11 Sensitivity analysis of option premium by changing the expected standard deviation of demand σ

On the other hand, increasing either the expected yearly growth rate (g) or the ratio of the firms' unit costs (β_{vc}) increases option premium only slightly, as shown in Figs. 3.12 and 3.13, respectively. It is noted that when Firm j's unit variable cost is much greater than Firm i's, the ratio of β_{vc} is larger. Hence, Firm i can take more cost advantage.

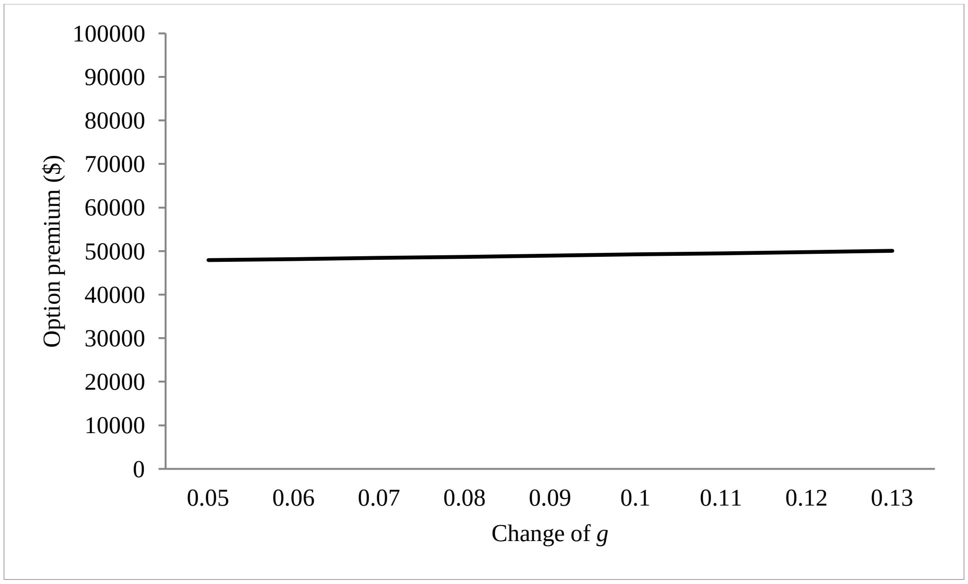

Fig. 3.12 Sensitivity analysis of option premium by changing the expected yearly growth rate *g*

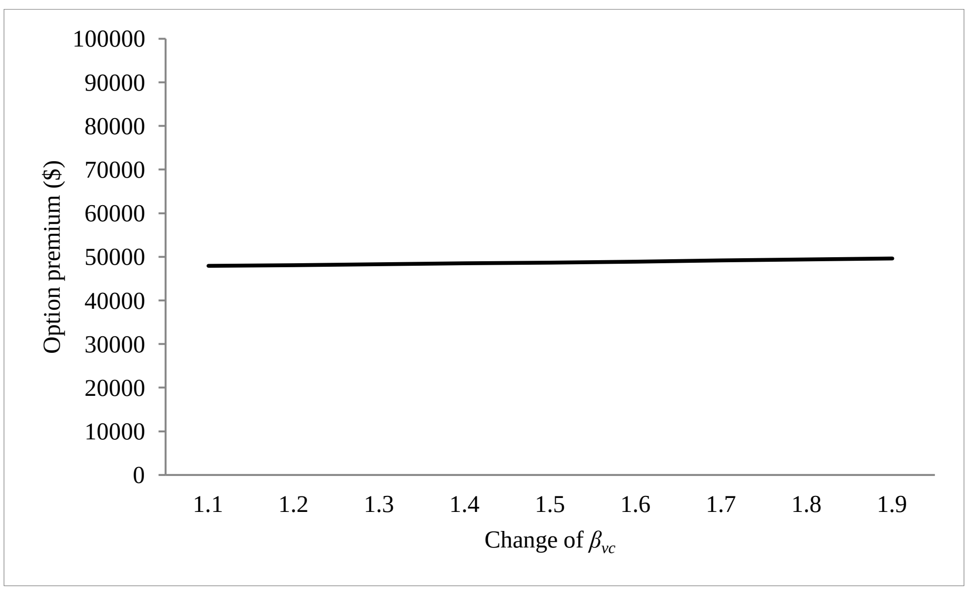

Fig. 3.13 Sensitivity analysis of option premium by changing the ratio of firms' unit costs β_{vc}

The last parameter, λ, is defined as the annual reduced rate of the fixed investment cost. It has an upward trend on option premium when the fixed investment cost drops greatly over time. Therefore, a rising reduced rate of λ will also positively impact option premium as shown in Fig. 3.14.

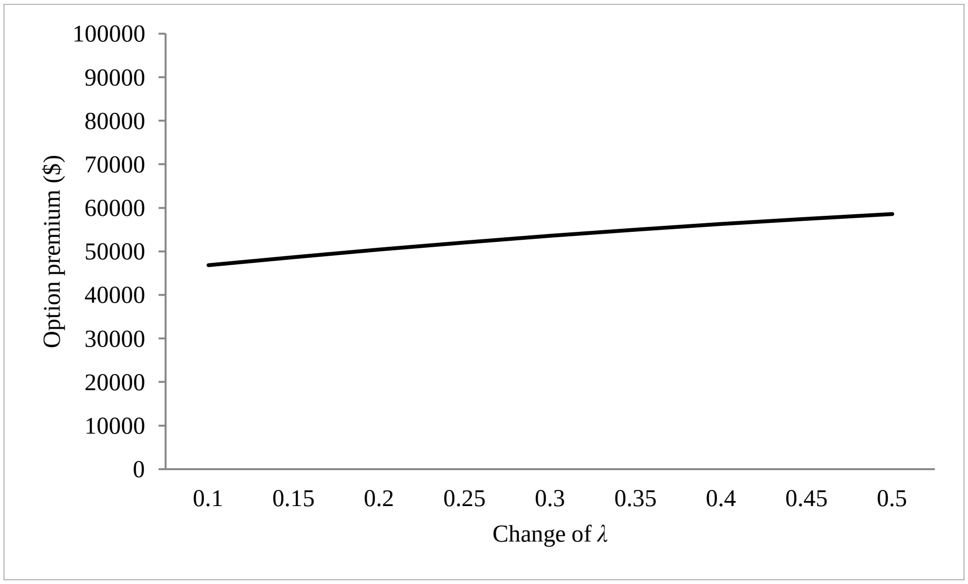

Fig. 3.14 Sensitivity analysis of option premium by changing the annual reduced rate of the fixed investment cost λ

In summary, option premium is used as an indicator in the option-game approach to measure the exclusive strategic value of flexibility, which the NPV method lacks. The results of sensitivity analyses imply that option premium is positively influenced by the dimensions and characteristics in the buckets of projects in the area of interest. Particularly, the high risk and uncertain projects in the market have higher value of flexibility in this approach, while the NPV method does not consider the uncertainty. Moreover, the above results of the demonstrated option premium are based on the assumption of a European option. An American option is generally more valuable than a European option, since it can be exercised at any time before maturity. Therefore, the

American investment option in this approach can provide an equivalent or even better option premium.

3.4.2 Limitations and possible extensions

As I focus on individual project assessment at gate-criterion of the development stage in the NPD process (Fig. 3.2), this gate criterion will determine whether the project goes to the active development level in the next stage of development. When the market condition of the project is highly uncertain, the option-game approach can assess the value of flexibility, which is inadequately assessed in the NPV method. While the NPV criterion offers a go/kill decision, the option-game approach instead provides a go/wait decision. The decision to wait is especially significant for risky projects. Both passive and active strategies can be used in a delay option (Mun, 2006). In the passive wait-and-see strategy, the project will go to the waiting list. Meanwhile, the firms wait and gather new information, and the project will be re-investigated in the next round of periods. Alternatively, they may also use an active market research strategy. Instead of waiting until the next period, firms may budget more for marketing in order to collect information. The maximum value to spend on marketing information is the value of option premium.

The gate-criteria for projects are multidimensional in the NPD process. Especially in the early and middle stages, the financial data are inadequate and inaccurate. Multiple qualitative and quantitative factors are not considered thoroughly in this option-game framework, such as gathering new information, technical success rate, product quality, periodic linking to business strategy, etc. Hence, most companies use other supportive methods in conjunction with financial models in their management (Cooper et al., 2001), such as scoring models and QFD (quality function deployment). Most importantly, unlike the conventional financial methods, the option-game approach provides a project evaluation of managerial flexibility. Combined with other standard approaches, the gate-criteria for project assessment can become more comprehensive.

3.5 Summary and Conclusion

In this chapter, I develop an option-game framework for the gate-criterion of a project in the NPD process for which the market demand is uncertain and the new product is in a short life cycle. The decision to delay adds flexibility, allowing firms to use a passive wait-and-see strategy or an active market research strategy while delaying. The standard conventional financial method in gate-criteria, NPV, is inadequate when projects face uncertainty. Hence, while the NPV criterion offers a go/kill decision, the option-game approach instead provides a go/wait decision.

The results of sensitivity analyses of option premium imply that option premium is positively influenced by the dimensions and characteristics of the project buckets on which I focused. Predominantly, high risk and uncertain projects have a higher value of flexibility.

To consider a short product life cycle, I integrate product adoption rates (Rogers, 1995; Bollen, 1999) into the option-game framework for evaluating an NPD project. I further develop the formal mathematical option-game framework in the discrete-time analysis when dealing with an American investment option in a finite project life. In this model, I consider the results of both simultaneous and sequential investment decisions in each scenario of the duopolistic game. Moreover, I can also use this technique to compute the optimal selection of the planned production capacity. The optimal planned capacities in each of the four scenarios can be obtained by the Nash equilibrium, which can provide a more strategic preliminary planned capacity for the scale of the new product development.

The strategic buckets approach in the early stages of the NPD process links the business strategy and the portfolios (Cooper et al., 1997). The option-game framework in the gate-criterion of the development stage allows further inspection and examination of the individual projects in the development process. Most importantly, in contrast to the commonly used financial methods, the option-game approach provides a project evaluation of managerial flexibility. Many companies use other supportive methods in conjunction with financial models in their management (Cooper et al., 2001), such as scoring models and QFD. Combined with other standard approaches, the gate-criteria for project assessment become more comprehensive.

Chapter 4 Assessing Managerial Flexibility in a New Product Development Project: An Option-Game Approach in a Duopoly with Bayesian Analysis

Abstract

Effective gates are central to the success of an idea-to-launch product development process. The most common financial gate-criterion, the net present value (NPV) method, is insufficient when the success of a project is uncertain. Alternatively, the real-option valuation is inadequate when a strategic decision is affected by the moves of the competition. In this chapter, I develop the idea for a discrete option-game valuation framework that explicitly incorporates statistical decision theory in the form of Bayesian analysis. The high volatility in an initially uncertain market is diminished via consumer information updates and by understanding the requirements and preferences of the customers. In addition, an inverse measure of product differentiation is included in the option-game mechanism to describe whether two goods are homogeneous, substituted, or independent, and to what degree. I introduce this approach as a gate-criterion to evaluate a new project at the gates of the development stages in a new product development (NPD) process. In a highly uncertain target market, evidence of high demand warrants a "go" action, especially when a firm has the cost advantage in competing with its rival's highly comparable product. This research has important implications for stage-gate

management when investigating an NPD project in the duopoly game during the product development process. By this approach, industry players can make the proper strategic decisions in a project assessment at the gates of the development stages.

Keywords: option-game, asymmetric duopoly, Cournot competition, product differentiation, gate-criteria, new product development, Bayesian analysis

4.1 Background

Effective gates are central to the success of an idea-to-launch product development process. Yet the majority of the businesses in Cooper and Edgett's study (2012) indicated that they lacked a fact-based and objective approach to decision-making at the gates of the new product development (NPD) process.

4.1.1 New product development (NPD)

NPD is widely regarded as a vital source of competitive advantage (Bessant & Francis, 1997). An NPD process from idea to launch consists of multiple stages, such as the project screening, monitoring, and progression frameworks of Cooper's stage-gate approach. A stage-gate process is a conceptual and operational blueprint for managing the NPD process (Cooper, 2008). Nowadays, instead of a standardized mechanistic implementation process, there are many different versions to fit different business needs (Cooper, 2008). In an idea-to-launch product process, each stage has defined procedures and requires the gathering of relevant information. Following each stage is a "gate" where go/kill decisions are made to manage the risks of new products and to serve as a quality-control checkpoint to continue moving the right projects forward (Cooper & Edgett, 2012; Cooper, 2008; Carbonell-Foulquié et al., 2004).

Cooper (2008) explains the stage-gate process as being very similar to that of buying a series of options on an investment: as each stage costs more than the preceding one, the initial amount of cost is analogous to the purchase of an option. Then the decision of whether or not to continue investing in the project is made at the gate (maturity), while new information is gathered during the stage. Indeed, the flexibility of the real-option approach corresponds to the structure of the NPD process, allowing developers to build options into products and projects during decision-making, especially in areas of uncertainty (Mun, 2006). Huchzermeier and Loch (2001) incorporated the operational sources of uncertainty with real-option value of managerial flexibility and introduced an improvement option to take corrective actions during the NPD process for the purpose of better product performance. However, a major problem with this approach is the limited knowledge of evaluating projects and the difficulty of making critical go/kill decisions throughout the entire development process (Schmidt & Calantone, 1998; Carbonell-Foulquié et al., 2004), especially in a rapidly changing and competitive environment.

4.1.2 Problem statement

Though both researchers and practitioners agree on the significance of gate-criteria (Carbonell-Foulquié et al., 2004; Agan, 2010), gates are rated as one of the weakest areas in product development (Cooper, 2008; Cooper, Edgett, & Kleinschmidt, 2002, 2005). Only 33 percent of firms have rigorous gates throughout the NPD process (Cooper, Edgett, & Kleinschmidt, 2002, 2005). In too many companies, gates either do not exist or are not effective, allowing numerous bad projects to proceed (Cooper, 2008; Jenner, 2007; Cooper & Edgett, 2012). In addition, almost two-thirds of the respondents in

Cooper and Edgett's study (2012) indicated that gatekeepers' contributions were of low quality. With a lack of robust and transparent decision-making criteria, gatekeepers often implement stage-gate decisions with the naive belief that using opinion and even personal agenda is effective (Cooper, 2008).

Moreover, since voice-of-the-customer input is identified as one of the drivers of success in an NPD process (Cooper & Edgett, 2012; Calantone et al., 1995), the criteria in a project assessment should involve the understanding of customer needs (Scott, 2000; Bessant & Francis, 1997; Griffin & Hauser, 1996). Due to shorter product life cycles in fast-paced industries, it is not necessary to wait for perfect information at the pre-defined gate for decision-making. Stages can be overlapped in a stage-gate process by using spiral development, allowing product development to continuously incorporate valuable customer feedback into product design during an NPD process until the final product is closer to customers' ideal (Cooper, 2008). In contrast to traditional uncertainty reduction methods in real-option theory, which are a passive process (Miller & Park, 2005), Artmann (2009) derived the Bayesian updating formulation for the market requirement distribution and integrated this mechanism into a real-option framework. In addition to the problem of predicting product demand, decision makers must also consider what competing companies are doing. Because "similar product developments exist in greater or lesser degrees in almost all product areas" (Smith, 1995), the competitor's involvement in a dynamic setting could influence one firm's output choice in the target market. Hence, in a competitive marketplace, the real-option valuation methods fall short in resolving the dilemma when the moves of a rival are involved (Ferreira et al., 2009). Recently, however, Smit and Trigeorgis (2006) introduced the concept of "option-game," combining real-option (which relies on the evolution of prices and demand) and game theory (which captures the moves of competitors) to quantify the value of flexibility and commitment.

4.1.3 The scope of this chapter

Owing to "too many projects in the pipeline" (Cooper, 2008), I am interested in decision-making at the gates of an NPD process, particularly involving new information from a competitor's interactions and from the requirements and preferences of the customers. Ronkainen (1985) pointed out that the go/kill decision-making at each gate should vary across product development stages. Moreover, Cooper (2008) indicated that most contributions to higher success rates are from the front end of stage-gate decision-making, where serious financial commitments are started during the go-to-development stages. Therefore, this chapter focuses specifically on the outset of the development stages and the iterated sub-decisions of prototyping and testing within the development stages as shown in Fig. 4.1.

In contrast to the assumptions in chapter 3, I assume that a new project is competing with a latent product to an inverse measure of product differentiation in the market at the outset of the development stages. During the sub-decision gates of development (Fig. 4.1), two kinds of new information about market risks are considered: a parameter of one competitor's (inverse) product differentiation and the requirements and preferences of the customers. In other words, one competitor may invest in a related project during the development stages, when information about the degree of (inverse) product differentiation might be unknown or uncertain at the outset. While I assumed product homogeneity in chapter 3, I relax this assumption here and assume that the firms are producing differentiated goods. Two products from two firms are differentiated when there are actual substitute products but not perfect substitutes (Motta, 2004). In addition, realizing the increasing importance of customer orientation (Sun, 2006), companies target a new project at a certain domain of market segmentation, according to the requirements and preferences of the customers. Yet prediction of customers' requirements is difficult because customers do not necessarily realize what their future needs are in the early stages of product development (Artmann, 2009), making it difficult for producers to estimate the nature of market demand (Smith, 1995).

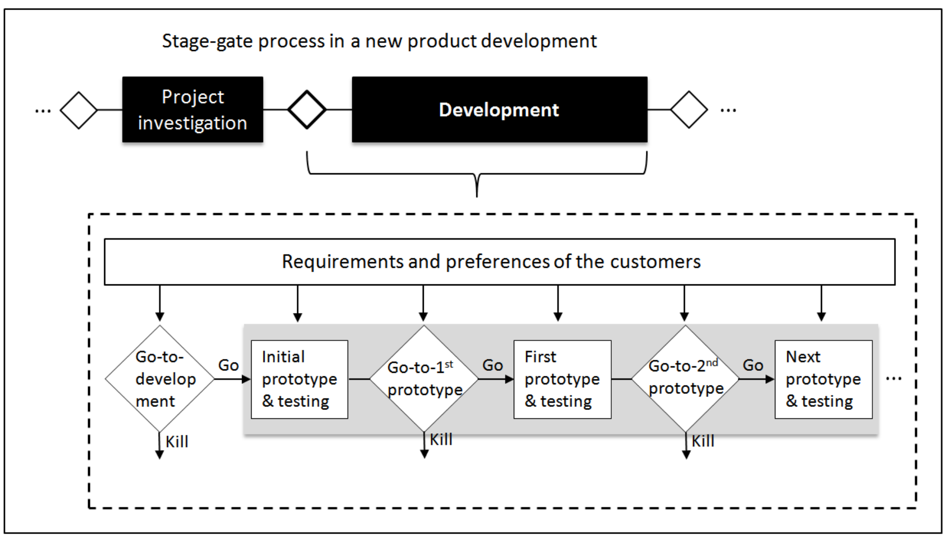

Fig. 4.1 Decision-making during the stages of product development

As time progresses during the stages of development (Fig. 4.1), variations in demand can be diminished by effective use of updated information about the requirements and preferences of customers. In addition, managerial flexibility should be considered when a latent product with a certain degree of (inverse) product differentiation is present in the future competing market. Consequently, considering the above two factors, I propose a discrete option-game valuation framework that explicitly incorporates statistical decision theory in the form of Bayesian analysis in an NPD project. In view of the fact that projects are rarely killed at gates after the stage of idea screening (Jenner, 2007), I introduce this approach as a rigorous gate-criterion to evaluate a new project during the stages of development (Fig. 4.1). As Anderson (2008) pointed out, successful management of current product development requires the overall integration of strategy, process, measurement of performance, and continuous improvement. Therefore, this product development process is discussed in the context of strategic portfolio management. Hence, this method is based on the strategic buckets method for NPD projects and is tailored for products in the dimensions of high variability in the initial markets and uncertainties about latent and competitive products.

As this research builds on concepts that have been previously proposed but not fully developed, the relevant literature concepts have been reviewed and discussed above. The remaining parts of this chapter are organized as follows. In section 4.2, I define the model description and develop this work by using an extended version of the former structure for my valuation model. The theory of Bayesian analysis is integrated with a valuation model that allows updating the variability of a target market. In addition, a latent rival's product development in a certain degree of (inverse) product differentiation is considered in the option-game approach. In section 4.3, I provide a case study to demonstrate the model and compare the results with two benchmarks. The first benchmark is the NPV method, used to represent the actions of go/kill at the outset of development stages and the action of go for the remaining NPD process to highlight the many industrial problems. The second benchmark is based on Artmann's study (2009), in which a real-option framework is incorporated with Bayesian analysis. In section 4.4, I further validate my valuation model against the benchmarks and discuss the results. Section 4.5 summarizes the results and concludes the chapter.

4.2 Model Development

Suppose that projects are initially screened and selected through the strategic buckets approach in the early stages of the NPD process. I am interested in the assessment of individual projects at the gate and sub-gates of the development as shown in Fig. 4.1. Specifically, I focus on evaluating the buckets of projects with the following characteristics and dimensions: (1) managerial flexibility, expected for market-uncertain projects, (2) potential competing products from rivals in certain degrees of (inverse) product differentiation, (3) new projects with a short life cycle, and (4) high variability in the target market, mainly from high diversity or differences in initial customer requirements.

Because the NPD process is a conceptual blueprint with pre-defined stages of idea-to-launch development and because different products have different development processes (Cooper, 2008), I summarize the basic concept of an NPD process here. Fig. 4.2 shows the scope of the NPD process that I will discuss. The gate of go-to-development with an initial development cost (I_0) is the starting point ($t = 0$) in cash flow. The next is the development stage, consisting of multiple sub-gates for product prototype development. To simplify the prototype process, I set two sub-gates during the development stage (Fig. 4.2) with the first and second advanced development costs (I_1 and I_2). In the remainder of this chapter, the term "development stages" will refer to this entire step of the development process, including the two sub-gates.

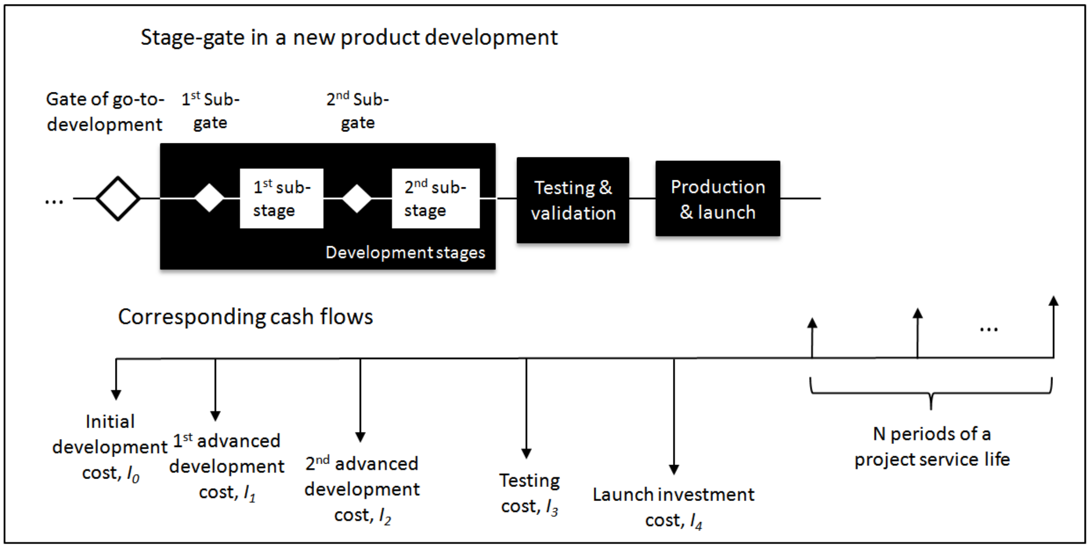

Fig. 4.2 Product development process and the corresponding cash flows

Following the development stages, the next two stages of testing/validation and production/launch have a testing cost (I_3) and a launch investment cost (I_4), respectively. Thereafter, products are sent to market, and the annual profit occurs one period after launch with N periods of project service life. For the purpose of simplifying the symbols of the model, I demonstrate that the time intervals of the cash flows are equivalent in the time horizon (Fig. 4.2). Note that different time intervals of the cash flows will be demonstrated in the next section with a case study.

In this chapter, I focus on assessment of an individual project at the gate of go-to-development and on the two sub-gates of the development stages in the context of a potential competitor and updated customer requirements, thereby implementing a rigorous evaluation method but retaining the value of flexibility for the ongoing NPD projects as shown in Fig. 4.3.

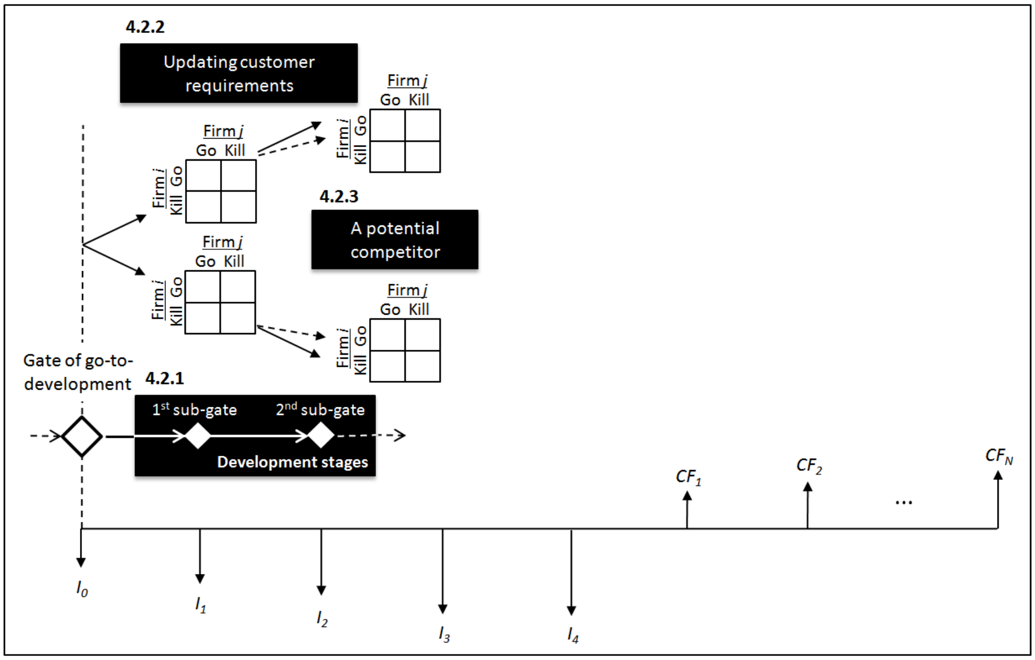

Fig. 4.3 The concept of model structure

To achieve these goals, in section 4.2.1, the evolution of demand is illustrated by a basic binomial lattice combined with the concept of a product life cycle (as shown in chapter 3). I define the linkage of market demand and the distribution of customer requirements and preferences. Hence, I base the NPV method (benchmark A) on these settings, taking the actions of go/kill at the gate of go-to-development and the action of go at the sub-gates of the development stages. In section 4.2.2, I demonstrate how new information about the requirements and preferences of the customers can be updated with statistical decision theory in the form of Bayesian analysis until the first sub-gate of the development stages is reached, thus diminishing the variation of market demand. Therefore, the real-option framework with Bayesian analysis (benchmark B), taking the actions of go/kill at the first sub-gate, will be defined under these settings. Section 4.2.3 considers managerial flexibility with a latent product with a certain degree of (inverse) product differentiation, representing the discrete option-game valuation framework. Finally, I compare this approach to two basic benchmarks and further discuss the results in sections 4.3 and 4.4.

4.2.1 Demand evolution and the probabilities of upward in demand

A binomial lattice framework is used to represent the market demand uncertainty (Q) within four periods as shown in Fig. 4.4. The binomial model is multiplicative in nature, and thus demand is always positive. Since the percentage changes in the demand over short intervals of time are normally distributed (Luenberger, 1998; Park, 2011), I can define the normal random variable y with expected yearly growth rate g and volatility yearly growth rate σ, i.e., $y \sim N(g, \sigma^2)$. The parameters of a binomial lattice from Luenberger (1998) are shown in equation (4.1).

· $u = e^{\sigma\sqrt{\Delta t}}, d = 1/u$

· Risk-neutral probability of an upward:

$$q_r = \frac{(1+r_f)-d}{u-d}, \text{where } r_f \text{:risk-free rate} \tag{4.1}$$

· The probability of an upward:

$$P = \frac{1}{2} + \frac{1}{2}\left(\frac{g}{\sigma}\right)\sqrt{\Delta t}$$

On the other hand, suppose the market research contains information on market performance requirements and customer requirements and preferences. The former represents the expected product performance from the customers, which is assumed to be normally distributed in Artmann (2009). The latter indicates the firm's knowledge of customer preferences, such as customer life-stage, accumulation of product knowledge, change in financial resources, consumption experience, etc. (Sun, 2006). As Edwards and Allenby (2003) proposed a multivariate normal distribution for analyzing multiple binomial response data arising in the study of consumer surveys, it is reasonable to assume that the overall data of customer preferences is also normally distributed. Hence, the linear combination of the above two components is normally distributed. Consequently, I can assume that the random variable of customer requirements and preferences x is normally distributed with mean μ_x and variance $\xi_x{}^2$, i.e., $x \sim N(\mu_x, \xi_x^2)$.

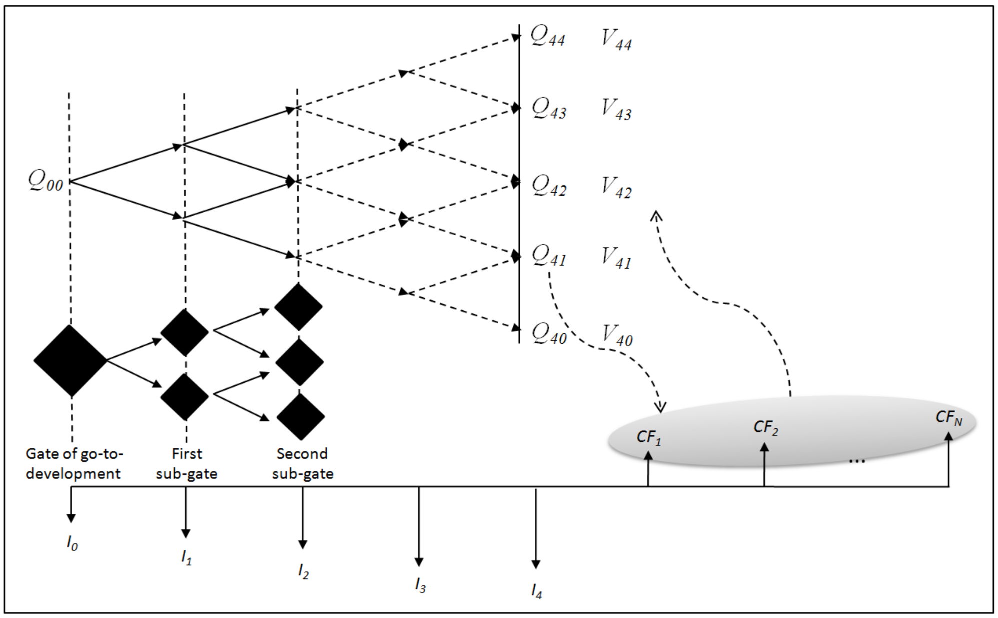

Fig. 4.4 Demand binomial lattice and the decision gate and sub-gates

Moreover, Smith (1995) pointed out that "lack of homogeneity on the demand side may be based upon different customs, desires for variety, or desires for exclusiveness, or may arise from basic differences in user needs." Therefore, I can assume that the factor of customer requirements and preferences x plays a key role on the demand side. The random variable x, customer requirements and preferences, can be defined as the joint index transforming from the entire weighted customer responses, because a formal treatment of the transformation from consumer questionnaires to the statistical relationship is outside the realm of this research (Edwards & Allenby, 2003; Kamakura et al., 2003). Therefore, I emphasize the relationship of customer requirements and preferences on the demand side: larger variability in the index of customer requirements and preferences can indicate greater volatility of the growth rate in demand. Accordingly, I can say that there is a positive correlation between customer requirements and preferences *x* and the percentage changes in the demand *y*, as expressed in equation (4.2).

$$y = \gamma x + \varepsilon \sim N(\gamma\mu_x + \varepsilon, \gamma^2\xi_x^2) \quad (4.2)$$

where y : the percentage changes in the demand, $y \sim N(g, \sigma^2)$;
γ: the correlation coefficient, $0 < \gamma < 1; \varepsilon \in R$;
x : customer requirements and preferences, $x \sim N(\mu_x, \xi_x^2)$

Suppose that the correlation coefficient γ in equation (4.2) is estimated by the weighted ratios of the factors that affect demand. Suppose further that the correlation coefficient is a constant. Based on the initial market research and past project experience, the current demand is given as Q_{00}. To determine market-clearing price and the firm profits, industry structure models commonly assume a linear (inverse) demand function (Chevalier-Roignant & Trigeorgis, 2011). Suppose that, based on the discrete-time model of Smit and Trigeorgis (2004) and Chevalier-Roignant and Trigeorgis (2011), the demand intercept in the linear market demand function follows a multiplicative binomial process as shown in equation (4.3).

$$\tilde{p}_t = \tilde{a}_t - bQ = \tilde{a}_t - b(q_i + q_j) \quad (4.3)$$

where $\tilde{a}_t, b$: constant parameters, $a_t, b > 0$;

Q: the total quantity that will be supplied in the market;

$\tilde{a}_t$ follows a multiplicative binomial process

The intercept of demand function $\tilde{a}_t$ is followed by a stochastic binomial as shown in Fig. 4.5 for four periods: at each up move, $\tilde{a}_t$ is multiplied by *u*, while at each down move it is multiplied by *d* from equation (4.1). When $\tilde{a}_t$ goes to time 1, it is noted as $\tilde{a}_1$, which indicates it could be either $\tilde{a}_{11}$ or $\tilde{a}_{10}$. Similarly, when $\tilde{a}_t$ goes to time 2, it is noted as $\tilde{a}_2$, which indicates it could be $\tilde{a}_{22}$, $\tilde{a}_{21}$, or $\tilde{a}_{20}$. The same concepts are used for the notations at times 3 and 4.

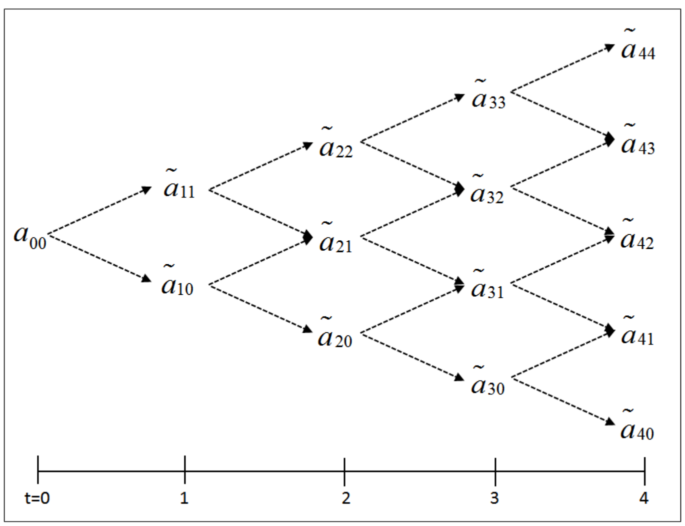

Fig. 4.5 Multiplicative binomial process followed by the intercept of demand $\tilde{a}_t$ at time t ($t \leq 4$)

The expected intercept of demand at time 2, $\tilde{\tilde{a}}_2$, can be computed by the intercepts of demand at time 4, multiplying by the corresponding cumulative probabilities from equation (4.1). Similarly, the expected intercept of demand at time 0, $\bar{a}_{00}$, can be obtained by the same procedures which are shown in equation (4.4).

$$\tilde{\tilde{a}}_2 : \begin{cases} \tilde{\tilde{a}}_{22} = P^2 \tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2 \tilde{a}_{42} \\ \tilde{\tilde{a}}_{21} = P^2 \tilde{a}_{43} + 2P(1-P)\tilde{a}_{42} + (1-P)^2 \tilde{a}_{41} \\ \tilde{\tilde{a}}_{20} = P^2 \tilde{a}_{42} + 2P(1-P)\tilde{a}_{41} + (1-P)^2 \tilde{a}_{40} \end{cases}$$
$$a_0 : \bar{a}_{00} = P^2 \tilde{\tilde{a}}_{22} + 2P(1-P)\tilde{\tilde{a}}_{21} + (1-P)^2 \tilde{\tilde{a}}_{20} \tag{4.4}$$

Suppose two firms are competing in the target marketplace, where Firm *i*'s and Firm *j*'s unit variable costs c_i and c_j are constant ($c_i, c_j > 0, c_i \neq c_j$). Hence, the project values at time 4 (Fig. 4.4) can be computed from the future expected cash flows. The market-clearing price is calculated based on a linear (inverse) demand function from equation (4.3) with an average unit variable cost in the different statuses of the binomial lattice. As shown in Fig. 4.4, suppose the product is planned to be launched at time 5, with a project service life of *N* years. The demand after time 4 in the binomial lattice will follow the annual expected growth rates according to the product life cycle. The annual profit after time 4 in the binomial lattice grows at an annual expected growth rate g_{4+m} at time 4+*m* (*m* = 1, 2,…,*N*) with a risk-adjusted discount rate *r* ($r > g_{4+m}$). Hence, based on chapter 3, the total future growth of the project value at time 4, G_4, can be expressed as shown in equation (4.5).

$$G_4 = \frac{1+g_5}{1+r} + \frac{(1+g_5)(1+g_6)}{(1+r)^2} + ... + \frac{(1+g_5)...(1+g_{N+4})}{(1+r)^N} \tag{4.5}$$

Therefore, with these settings, the profit function of Firm *i* by benchmark A at the second sub-gate (time 2) can be expressed in equation (4.6) as shown in Fig. 4.4 (also provided in Appendix A).

$$ {}^{\mathrm{A}}_{i2} = -I_{S2} + \frac{G_4 \omega}{(1+r)^2}[-bQ^2 - c_i Q + \tilde{\tilde{a}}_2 Q] \tag{4.6} $$

where $I_{S2} = I_2 + \frac{I_3}{(1+r)^1} + \frac{I_4}{(1+r)^2}$, r : interest rate; A : benchmark A;

I_2 : second advanced development cost, I_3 : testing cost, I_4 : launch investment cost

The profit function of Firm *i* by benchmark A in equation (4.6) is an absolute fraction of all sales in the market. Hence, the capacity of Firm *i* is computed by its estimated market share ω of the total supplied quantities in the industry, representing the degree of dominance that Firm *i* has within the particular market. According to the possible factors that determine the estimated market share in Harper (2011), I define the estimated market share ω as expressed in equation (4.7) and Appendix A by the unit variable costs (c_i, c_j), and the parameter of the (inverse) product differentiation τ of both firms. As I assume that there is only one competitor, the rival's unit variable cost directly influences Firm *i*'s market share. The parameter of the (inverse) product differentiation τ of two products from two firms consists of product functions and positions, Harper's (2011) comparative dominance of the developer's brand over competitors, comparative performance of the developer's product over competitors, and historical values for the developer's comparable products. If $\tau = 0$, then both products are independent. If $\tau = 1$, then both products can be viewed as homogenous products.

$$ \omega = \frac{c_i(1-\tau) + c_j}{c_i + c_j} \tag{4.7} $$

where τ : a parameter of the (inverse) product differentiation, $0 \le \tau \le 1$

Consequently, the profit function of Firm *i* by benchmark A at the gate of go-to-development in Fig. 4.4 can be rewritten from equation (4.6) with two forward periods, as expressed in equation (4.8).

$$\pi_{i00}^{\mathrm{A}} = -I + \frac{G_4\omega}{(1+r)^4}[-bQ^2 - c_iQ + \bar{a}_{00}Q] \tag{4.8}$$

where $I = I_0 + \frac{I_1}{(1+r)^1} + \frac{I_{S2}}{(1+r)^2}$,

I_1 : first advanced development cost, I_0 : initial development cost

Under these settings in benchmark A, the profit of Firm *i* is based on its market share of overall product quantity in the target market. To earn the maximum overall profit, the industry chooses to produce the output that equals their average marginal cost to marginal revenue (Chevalier-Roignant & Trigeorgis, 2011). Therefore, the equilibrium quantity produced in the industry is shown in equation (4.9) and Appendix A.

$$Q = \frac{\bar{a}_{00} - \bar{c}}{2b} \tag{4.9}$$

where $\bar{c}$: average marginal cost $= \frac{1}{2}(c_i + c_j)$

Finally, the resulting equilibrium profit of Firm *i* by benchmark A can be expressed in equation (4.10) and Appendix A.

$$\mathrm{NPV}_{i00} = -I + \frac{G_4\omega}{(1+r)^4}\frac{(\bar{a}_{00} - \bar{c})(\bar{a}_{00} + \bar{c} - 2c_i)}{4b} \tag{4.10}$$

4.2.2 Demand variance update: Bayesian analysis

The purpose of obtaining updated information about customer requirements and preferences is to diminish the variation of market demand at the first sub-gate of the development stages. Hence, suppose that the initial target group of the customers has a specified value of mean, while firms are uncertain about the true variance of customer requirements and preferences.

Customer requirements and preferences x (defined in section 4.2.1) follows a normal distribution with known mean μ_x ($\mu \in R$) and unknown variance ξ_x^2 ($\xi_x > 0$), i.e., $f(x|\mu_x) = N(\mu_x,\xi_x^2)$. Since ξ_x^2 is unknown, suppose that the prior distribution of ξ_x^2, i.e., $g(\xi_x^2)$, is inverse gamma distributed, $IG(\alpha,\beta)$ (where $\alpha,\beta > 0$). According to Artmann's (2009) proof, therefore, customer requirements and preferences at time 0, based on the prior information, is t distribution noted as $m(x) = St(x|\mu_x,(\alpha\beta)^{-1},2\alpha)$.

In order to determine the posterior predictive distribution of the customer requirements and preferences, I need to determine the posterior distribution of the unknown variance ξ_x^2 first, as dealt with in sample observations. As shown in Raiffa and Schlaifer (1961) and Artmann (2009), after the update with actual data $z = x_1,\ldots,x_{nx}$, which denotes a random sample from n_x independent observations of customer requirements and preferences, the posterior distribution of ξ_x^2 is given by $g(\xi_x^2|z) = IG(\xi_x^2|\alpha',\beta')$. The values of α', β' are shown in equation (4.11).

$$\alpha' = \alpha + \frac{n_x}{2} \text{ and } \beta' = [\frac{1}{\beta} + \frac{1}{2}\sum_{i=1}^{n_x}(x_i - \mu_x)^2]^{-1} \tag{4.11}$$

n_x : number of the random samples of customer requirements and preferences

With the update to the posterior distribution of ξ_x^2, given the actual sample data $z = x_1,x_2,\ldots,x_{nx}$, based on Artmann (2009), customer requirements and preferences are then t distributed, i.e., $m(x|z) = St(x|\mu_x,(\alpha'\beta')^{-1},2\alpha+n_x)$ with degree of freedom $2\alpha+n_x$. As the number of degrees of freedom grows, the t-distribution approaches normal distribution. Hence, with the constant correlation coefficient γ, the percentage changes in the demand *y* in equation (4.2) can be updated as expressed in equation (4.12), as shown in Appendix A.

$$y^{'} = \gamma x^{'} + \varepsilon \approx N(\gamma\mu_x + \varepsilon, \gamma^2 \xi_x^{2'}) \tag{4.12}$$

where $y^{'}$: the updated percentage changes in the demand, $y^{'} \sim N(g, \sigma^{2'}); \varepsilon \in R$;
$x^{'}$: the updated customer requirements and preferences $\approx N(\mu_x, \xi_x^{2'})$ w/ $2\alpha + n_x > 30$;
$\xi_x^{2'} = (2\alpha + n_x)(\alpha^{'}\beta^{'})^{-1}(2\alpha + n_x - 2)^{-1}$

Therefore, as the volatility of the yearly growth rate is updated to $\sigma^{2'}$, the demand binomial lattice is re-structured after the first period, so that the new parameters of the binomial lattice can be recalculated from equation (4.1) as shown in equation (4.13).

· $u^{'} = e^{\sigma^{'}\sqrt{\Delta t}}, d^{'} = 1/u^{'}$
· The updated risk-neutral probability of an upward:

$$q_r^{'} = \frac{(1+r_f) - d^{'}}{u^{'} - d^{'}} \tag{4.13}$$

· The updated probability of an upward:

$$P^{'} = \frac{1}{2} + \frac{1}{2}(\frac{g}{\sigma^{'}})\sqrt{\Delta t}$$

where $\sigma^{2'} = \gamma^2(2\alpha + n_x)(\alpha^{'}\beta^{'})^{-1}(2\alpha + n_x - 2)^{-1}$

As a result, the real-option framework with Bayesian analysis (benchmark B) considers the actions of go/kill at the first sub-gate. Under these settings, the payoff function of benchmark B at the second sub-gate can be rewritten from equation (4.6) with the new updated parameters as expressed in equation (4.14). Accordingly, the resulting equilibrium profit of Firm *i* at the second sub-gate can be written as equation (4.15).

$${}^{B'}_{i2} = -I_{S2} + \frac{G_4^{'}\omega^{'}}{(1+r)^2}[-bQ^{2'} - c_i Q^{'} + \tilde{\tilde{a}}_2^{'} Q^{'}] \tag{4.14}$$

where B : benchmark B; $G_4^{'} = \frac{1+g_5^{'}}{1+r} + \frac{(1+g_5^{'})(1+g_6^{'})}{(1+r)^2} + ... + \frac{(1+g_5^{'})...(1+g_{N+4}^{'})}{(1+r)^N}$

$$\tilde{\pi}_{i2}^{B'} = -I_{S2} + \frac{G_4^{'}\omega^{'}}{(1+r)^2}\,\frac{(\tilde{\bar{a}}_2^{'} - \bar{c})(\tilde{\bar{a}}_2^{'} + \bar{c} - 2c_i)}{4b} \tag{4.15}$$

Finally, with the new information updated by Bayesian analysis, the strategic net present value (SNPV) of benchmark B at the first sub-gates of up and down statuses can be written as equation (4.16).

$$\begin{cases} \mathrm{SNPV}_{i11}^{B'} = \tilde{\pi}_{i11}^{B'} = \dfrac{q_r^{'}\max[0, \tilde{\pi}_{i22}^{B'}] + (1-q_r^{'})\max[0, \tilde{\pi}_{i21}^{B'}]}{1+r_f} \\ \mathrm{SNPV}_{i10}^{B'} = \tilde{\pi}_{i10}^{B'} = \dfrac{q_r^{'}\max[0, \tilde{\pi}_{i21}^{B'}] + (1-q_r^{'})\max[0, \tilde{\pi}_{i20}^{B'}]}{1+r_f} \end{cases} \tag{4.16}$$

4.2.3 Discrete option-game valuation

At the starting point (the gate of go-to-development), I consider managerial flexibility with a latent product in a certain degree τ of the (inverse) product differentiation in the following periods of the two sub-gates, representing a potential competitor's involvement in the target market (Fig. 4.3). The parameter τ has been defined as the degree of the (inverse) product differentiation between Firm *i* and a latent competitor, Firm *j*. From the first-order conditions of the consumer problem in the linear demand model (Motta, 2004), a linear (inverse) demand function with parameter τ can be written as shown in equation (4.17). If $\tau = 0$, then q_i and q_j are independent, meaning that both products maximize differentiation. If $0 < \tau < 1$, then q_i and q_j are substitutes. If $\tau = 1$, then q_i and q_j are perfect substitutes (homogenous products).

$$\tilde{p}_4 = \tilde{a}_4 - bq_i - b\tau q_j \tag{4.17}$$

where $\tilde{a}_4 > c_i, c_j; q_i, q_j$: quantities of Firm i' and j's products

Suppose that the two firms have different unit variable costs ($c_i \neq c_j$). Both firms face the same interest rate *r* and risk free rate r_f. Consider that both firms compete in quantities after product launch (i.e., Cournot competition), choosing q_i, q_j so as to maximize their profits. The profit function of Firm *i* at the second sub-gate can be expressed as shown in equation (4.18) and provided in Appendix A, where C is the symbol of Cournot competition.

$$\tilde{\pi}_{i2}^{\mathrm{C}} = -I_{S2} + \frac{G_4}{(1+r)^2}[-bq_i^2 + (\tilde{\tilde{a}}_2 - c_i)q_i - \tau b q_j q_i] \qquad (4.18)$$

By substituting the reaction functions (into each other), Firm *i*'s equilibrium quantity can be written as shown in equation (4.19) (Appendix A). Hence, Firm *i*'s resulting profit at the second sub-gate is derived in Appendix A and shown in equation (4.20).

$$q_i^{\mathrm{C}} = \frac{\tilde{\tilde{a}}_2 - 2c_i + c_j}{3b} \qquad (4.19)$$

$$\tilde{\pi}_{i2}^{\mathrm{C}} = -I_{S2} + \frac{G_4}{(1+r)^2}\left[\frac{(\tilde{\tilde{a}}_2 - 2c_i + c_j)^2}{9b}\right] \qquad (4.20)$$

On the other hand, if Firm *i* has a monopoly, the linear (inverse) demand function from equation (4.17) is rewritten as $\tilde{p}_4 = \tilde{a}_4 - bq_i$. Hence, based on Chevalier-Roignant and Trigeorgis (2011), Firm *i*'s equilibrium quantity and profit in monopoly at the second sub-gate can be expressed as shown in equations (4.21) and (4.22), respectively, where M is the symbol of monopoly.

$$q_i^{\mathrm{M}} = \frac{\tilde{\tilde{a}}_2 - c_i}{2b} \qquad (4.21)$$

$$\tilde{\pi}_{i2}^{\mathrm{M}} = -I_{S2} + \frac{G_4}{(1+r)^2}\left[\frac{(\tilde{a}_2 - c_i)^2}{4b}\right] \tag{4.22}$$

Therefore, the resulting equilibrium outcome at each status of the second sub-gate can be obtained from the duopolistic payoff matrices by applying the Nash equilibrium concept, in which the optimal competitive outcomes at each status of time 2 are noted as $(\tilde{X}_{i2}^{*}, \tilde{X}_{j2}^{*})$. The 2-player payoff matrices at the second sub-gate can be written as shown in equation (4.23). Accordingly, the strategic value of the option-game approach at the first sub-gate of Firm *i* can be obtained by the Nash equilibrium with the best response analysis, as expressed in equation (4.24), where OG is the symbol of option-game.

$$(\tilde{X}_{i2}^{*}, \tilde{X}_{j2}^{*}) = \begin{bmatrix} (\tilde{\pi}_{i2}^{\mathrm{C}}(q_i^*, q_j^*), \tilde{\pi}_{j2}^{\mathrm{C}}(q_i^*, q_j^*)) & (\tilde{\pi}_{i2}^{\mathrm{M}}(q_i^*), 0) \\ (0, \tilde{\pi}_{j2}^{\mathrm{M}}(q_j^*)) & (0, 0) \end{bmatrix} \tag{4.23}$$

$$\begin{cases} \mathrm{SNPV}_{i11}^{\mathrm{OG}} = \tilde{X}_{i11}^{*} + I_1 \\ \mathrm{SNPV}_{i10}^{\mathrm{OG}} = \tilde{X}_{i10}^{*} + I_1 \end{cases} \tag{4.24}$$

where $(\tilde{X}_{i1}^{*}, \tilde{X}_{j1}^{*}) = \begin{bmatrix} (\tilde{\pi}_{i1}^{\mathrm{C}}, \tilde{\pi}_{j1}^{\mathrm{C}}) & (\tilde{\pi}_{i1}^{\mathrm{M}}, 0) \\ (0, \tilde{\pi}_{j1}^{\mathrm{M}}) & (0, 0) \end{bmatrix}$

$$\tilde{\pi}_{i11}^{\mathrm{C}} = \frac{q_r(\tilde{X}_{i22}^{*}) + (1-q_r)(\tilde{X}_{i21}^{*})}{1+r_f} - I_1; \tilde{\pi}_{i10}^{\mathrm{C}} = \frac{q_r(\tilde{X}_{i21}^{*}) + (1-q_r)(\tilde{X}_{i20}^{*})}{1+r_f} - I_1$$

Finally, the strategic value of the option-game approach at the gate of go-to-development of Firm *i* can be obtained from the 2-player payoff matrix by the Nash equilibrium with the best response analysis, as expressed in equation (4.25).

$$\mathrm{SNPV}_{i00}^{\mathrm{OG}} = X_{i00}^{*} + I_0 \tag{4.25}$$

where X^*_{i00} : the competitive outcomes of Firm *i* at time 0;

$$(X^*_{i00}, X^*_{j00}) = \begin{bmatrix} (\pi^{C}_{i00}, \pi^{C}_{j00}) & (\pi^{M}_{i00}, 0) \\ (0, \pi^{M}_{j00}) & (0,0) \end{bmatrix}; \pi^{C}_{i00} = \frac{q_r(\tilde{X}^*_{i11}) + (1-q_r)(\tilde{X}^*_{i10})}{1+r_f} - I_0$$

As time goes to the first sub-gate, suppose that the distribution of customer requirements and preferences has been updated with the collected data (section 4.2.2), so the new strategic value of the option-game approach at the first sub-gate of Firm *i* can be obtained from the updated 2-player payoff matrices by the Nash equilibrium with the best response analysis, as shown in equation (4.26).

$$\begin{cases} \text{SNPV}^{\text{OG}'}_{i11} = \tilde{\pi}^{\text{OG}'}_{i11} = \tilde{X}^{*'}_{i11} + I_1 \\ \text{SNPV}^{\text{OG}'}_{i10} = \tilde{\pi}^{\text{OG}'}_{i10} = \tilde{X}^{*'}_{i10} + I_1 \end{cases} \tag{4.26}$$

where $\tilde{X}^{*'}_{i2}, \tilde{X}^{*'}_{i1}$: the updated competitive outcomes of Firm *i* at time 2 and 1;

$$(X^{*'}_{i1}, X^{*'}_{j1}) = \begin{bmatrix} (\tilde{\pi}^{C'}_{i1}, \tilde{\pi}^{C'}_{j1}) & (\tilde{\pi}^{M'}_{i1}, 0) \\ (0, \tilde{\pi}^{M'}_{j1}) & (0,0) \end{bmatrix}; \tilde{\pi}^{C'}_{i11} = \frac{q'_r(\tilde{X}^{*'}_{i22}) + (1-q'_r)(\tilde{X}^{*'}_{i21})}{1+r_f} - I_1$$

4.3 Case Study

In this section, I demonstrate a numerical example and analyze and compare a project by different approaches. At the starting point (the gate of go-to-development), Firm *i* considers managerial flexibility with a latent product in a certain degree of the (inverse) product differentiation τ at the future sub-gates of the development stages. I first compare this approach to benchmark A, the NPV method, which is the widely-used conventional financial method in gate-criterion, and observe its results for the strategic decisions and present payoff values at the starting point in section 4.3.1. Section 4.3.2 illustrates the update of customer requirements and preferences with the collected sample data, accordingly updating the demand, so that the market demand follows a binomial lattice with a short product life cycle. I then compare this approach to benchmark B, the real-option approach with Bayesian analysis, and observe the results of the strategic decisions and the payoff values at the first sub-gate of the development stages. Finally, a summary is in section 4.3.3.

Suppose that Firm *i* is assessing an individual project in the NPD process and that all the individual projects have been screened and preliminarily investigated through the strategic buckets approach in the early stages. Some portions of the buckets are the projects with the specific dimensions of an uncertain market, a short life cycle, one potential competitor, and a rapidly changing environment. Firm *i* will need to evaluate these categories of projects at the gate of go-to-development and at the sub-gates of the development stages, as shown in Fig. 4.6. The questions for Firm *i* are how to evaluate this project at these gate-decisions when there might be a latent competitor's product in the next decision point, and, should this project proceed to the next stage, how the decisions would change at the sub-gates based on the different approaches when the additional sample information is collected.

Fig. 4.6 shows this project's current and remaining gates and stages in the NPD process in the following sequence: the gate of go-to-development, the first and second sub-gates of development, the stage of testing and validation, and the stage of production and launch, with the corresponding costs of an initial development cost (I_0 = \$4,500), the first advanced development cost (I_{S1} = \$6,000), the second advanced development cost (I_a), the testing cost (I_b), and the launch investment cost (I_c). Assume that the sum of the values for the last three fixed costs is given at the second sub-gate as I_{S2} = \$25,000 (assuming the rival has the same fixed costs). Firm i and a rival (Firm j) in a duopoly may share an option to invest a similar NPD project with an initial parameter of the (inverse) product differentiation $\tau = 0.75$, where the option will be expired in six months ($T = 2/4$), which is at the second sub-gate of the development stages (Fig. 4.6). The project will operate for a finite service life of $N = 4$ years after product launch with the same interest rate $r = 12\%$, and a risk free rate of $r_f = 5\%$. Based on the initial market research and past experience, assume that customer requirements and preferences x is normally distributed with mean $\mu_x = 2\%$ and standard deviation $\xi_x = 62.5\%$. The current demand is given as $Q_{00} = 750$. With the estimated correlation coefficient $\gamma = 0.8$ and $\varepsilon = 0.064$, an expected yearly growth rate of $g = 8\%$ in demand and the expected standard deviation of $\sigma = 50\%$ are obtained from equation (4.2). Firm i has a cost advantage where Firm i's unit variable cost ($c_i = \$10$) is less than Firm j's ($c_j = \$12$). The current (inverse) demand function is given as $p_0 = 55 - 0.05Q$.

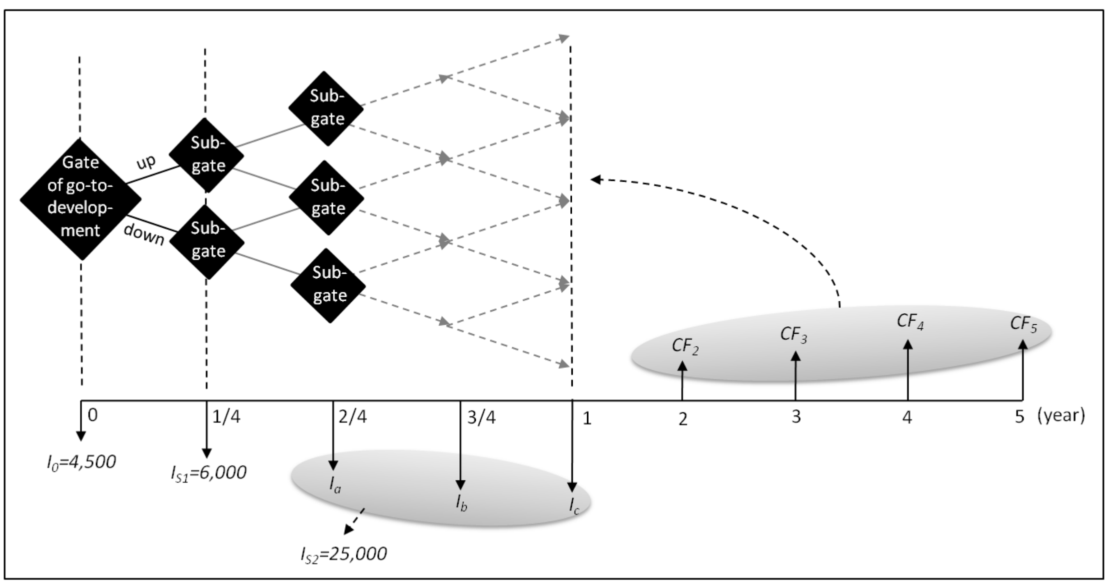

Fig. 4.6 Cash flows in this numerical example

4.3.1 Strategic decisions at the starting point (the gate of go-to-development)

With the above information (g = 8%, σ = 50%, r_f = 5%, T = 2/4, Δt = 1/4), I can calculate the parameters of the binomial lattice from equation (4.1) and obtain as the following: u = 1.2840, d = 0.7788, q_r = 0.5368, 1-q_r = 0.4632, P = 0.54, and 1-P = 0.46.

Appendix B shows the details of the calculations and Table 4.1 summarizes the current payoffs at the starting point (the gate of go-to-development). While benchmark A suggests the action of "kill" with a negative payoff value of $1,036.61, the option-game approach obtains a positive SNPV of $8,967.71. As the I_0 = $4,500, the option-game approach suggests an opposite action of "go." Hence, at the gate of go-to-development, with a high variability in demand, the option-game approach assesses the value of flexibility, an assessment which the NPV method lacks.

Table 4.1 The current payoffs at starting point of Firm *i* by benchmark A and my approach

	benchmark A: NPV method	**OG: Option-game**
Current payoff π_{00}	$\text{NPV}_{i00} = -\$1,036.61$	$\text{SNPV}_{i00}^{\text{OG}} = \$8,967.71$
Action taken	kill	go

4.3.2 Strategic decisions at the sub-gates with Bayesian analysis

Suppose that the project takes the action of "go" at the gate of go-to-development, and then the developer will collect actual samples for customer requirements and preferences. Suppose further that the project is targeted in a specified market with a known mean μ_x = 0.02, but the variance of customer requirements and preferences ξ_x, is unknown. The parameters of the prior distribution are given in Table 4.2.

Table 4.2 Parameters of the prior distribution of customer requirements and preferences

Parameter	**Value**
α	19.028
β	0.142
μ_x	0.020

Suppose the marketing department interviewed n_x = 8 potential key customers of the product. The results of the study show the samples with a spread of $\sum_{i=1}^{8}(x_i - 0.02)^2 = 0.30$. In addition, the parameter of the (inverse) product differentiation is updated and given as τ' = 0.9. Appendix B shows the details of the calculations by Bayesian analysis, and Table 4.3 summarizes the parameters of the posterior distribution. The posterior customer requirements and preferences is then *t* distribution, i.e., $m(x|z)$ = $St(x|0.02,0.3123,46.056)$ with expected value of $E(x|z)$ = 0.02, and the variance of $Var(x|z)$ = 0.3265. Fig. 4.7 shows the prior and posterior density distributions of customer requirements and preferences and Appendix B provides the mean and variance of the density distributions in this example.

Table 4.3 Parameters of the posterior distribution of customer requirements and preferences

Parameter	**Value**
α'	23.0280
β'	0.1390
ξ_x'	0.5714
σ'	0.4571

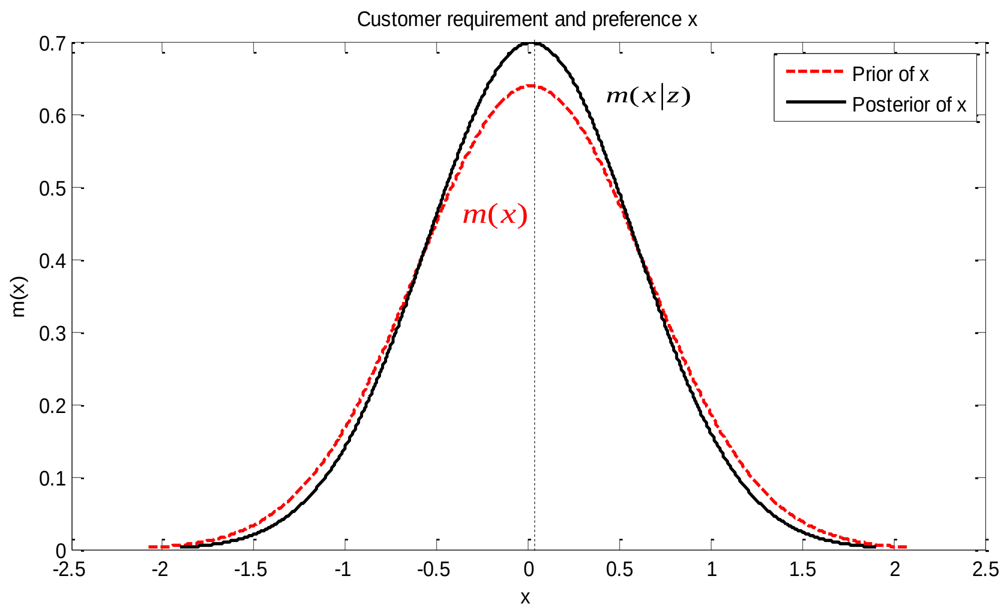

Fig. 4.7 Prior and posterior distributions of customer requirements and preferences *x*

Therefore, with the updated information (σ' = 45.71%), I can also update the parameters of the binomial lattice from equation (4.13) and obtain the following: u' = 1.2568, d' = 0.7957, q_r' = 0.5515, 1-q_r' = 0.4485, P' = 0.5438, and 1-P' = 0.4562. The binomial tree in demand at launch point (at year 1 in Fig. 4.6) can be described as a lognormal distribution. Based on Park (2011), the mean and variance of the demand distribution at t = 1 can be determined. Hence, the posterior demand is a lognormal distribution with the expected value of $E(Q_1|z)$ = 812.47 and the variance of $Var(Q_1|z)$ = 153,388.43. Fig. 4.8 shows the prior and posterior density distributions of demand at year 1 and Appendix B provides their mean and variance of density distributions in this example.

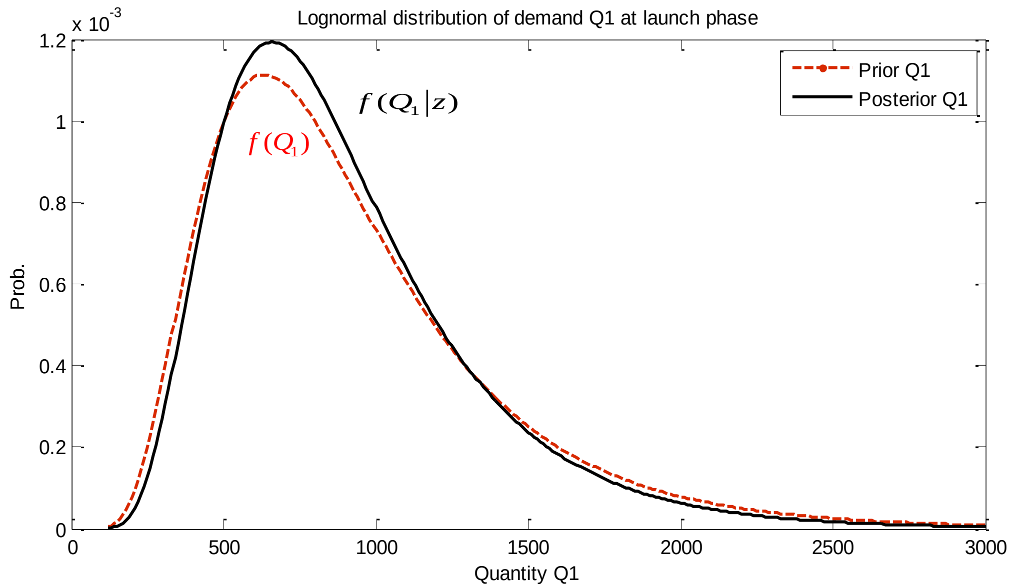

Fig. 4.8 Prior and posterior distributions of demand at product launch point Q_1 (at year 1)

Appendix B shows the details of the calculations after the information is updated and Table 4.4 summarizes the SNPVs at the first sub-gates of the development stages. At the sub-gate of the status of “11,” the SNPVs by benchmark B and this approach are \$9,711.40 and \$12,936.80, respectively. Since the first advanced development cost I_{S1} is \$6,000, benchmark B will suggest the action of “go.” However, the option-game approach will initiate the action of “go/kill,” since both firms face a Prisoner’s Dilemma, meaning that the maximum payoff for each firm is obtained only when their decisions are different. Hence, at this point, Firm *i* takes this project through further investigations and may re-evaluate it later by carefully observing its rival’s actions, and meanwhile looking for possibilities to lower costs. At the sub-gate of the status of “10,” both approaches suggest the same action of “kill” with zero value of the SNPVs.

Table 4.4 The SNPVs (first sub-gate) by benchmark B and my model after Bayesian analysis

	benchmark B: Real-option	**OG: Option-game**
Up node Payoff π_{11}	$\text{SNPV}_{i11}^{\text{B}'} = \$9,711.40$	$\text{SNPV}_{i11}^{\text{OG}'} = \$12,936.8$
Action taken	go	go/kill
Down node Payoff π_{10}	$\text{SNPV}_{i10}^{\text{B}'} = \$0$	$\text{SNPV}_{i10}^{\text{OG}'} = \$0$
Action taken	kill	kill

As a result, with the updated information by Bayesian analysis, the variability in customer requirements and preferences (Fig. 4.7) and in market demand (Fig. 4.8) are reduced. Hence, the payoff values at the sub-gates of the development stages by both approaches become smaller compared to the payoff values without an information update. With additional information about a latent competing product with a parameter of the (inverse) product differentiation τ' = 0.9, I can observe that the interaction of a rival's involvement could influence Firm *i*'s strategic decisions (Table 4.4).

4.3.3 Interpretation of the results

The option-game framework with Bayesian analysis is demonstrated as a gate-criterion of the development stages in the NPD process. First of all, I evaluate a project at the starting point (the gate of go-to-development). Benchmark A, the NPV method, is used to assess the project based on unchanged decisions in the future if the project is undertaken. In contrast, the option-game approach not only evaluates managerial flexibility but also considers a potential competitor in the future. Instead of assuming a homogenous competing product, I employ a parameter of the (inverse) product differentiation τ between Firm *i*'s and Firm *j*'s products. Even if the parameter of (inverse) product differentiation may be uncertain at the starting point, the initial guess value can also be used to estimate the corresponding payoff functions. I further discuss the parameter of (inverse) product differentiation in the next section.

When the project is accepted at the gate of go-to-development, given the high variability in the initial target market, additional market research may be needed to update information. The requirements and preferences of customers are an important indicator to estimate the target markets. Suppose that the distribution of customer requirements and preferences has a known mean but its variance is unknown. Using the actual collected samples, the distribution of customer requirements and preferences is updated by Bayesian analysis (Fig. 4.7). Accordingly, the volatility of the yearly growth rate in demand and the parameters of the demand binomial lattice are successively updated. Therefore, the structure of the demand binomial lattice is re-calculated, yielding a reduced variability compared to the initial estimator (Fig. 4.8).

The updated demand lattice is done by the first sub-gate of the development stages. As time goes to the first sub-gate, demand either goes up or down. Hence, the payoff value at the first up sub-gate of the development stages is reduced compared to the payoff value without an information update. Until the project reaches the first sub-gate, new information about a potential rival's product and the parameter of (inverse) product differentiation can be updated as well. The SNPVs will be influenced by the updated factor, depending on the degree of (inverse) product differentiation. In addition, I can observe that the interactions of a rival's involvement could influence Firm *i*'s strategic decisions. This case study shows that the option-game approach not only evaluates the managerial flexibility in a project at the gate of go-to-development, but also provides a rigorous evaluation method at the first sub-gate of the development stages after updating the information about demand by Bayesian analysis. As a numerical example cannot generalize the results, I further study and discuss validation in the next section.

4.4 Validation and Discussion

In this section, I validate this approach at the separate decision-gates (i.e., the gate of go-to-development and the first sub-gate of the development stages) in the NPD process. I also discuss the model properties, the model limitations, and possible extensions.

4.4.1 Validation

First, I verify the value of managerial flexibility in a project of this approach. Then I validate the SNPVs of benchmark B and this approach at the first sub-gate, which is after new information is updated by Bayesian analysis.

- *Strategic decisions at the gate of go-to-development*

First of all, I verify the value of managerial flexibility in a project in which the strategic present value of the option-game approach incorporates potential flexibility, a consideration which benchmark A (the NPV approach) lacks. With the current SNPV of the option-game approach subtracting the value of benchmark A, the option premium (OP) is obtained, so that I can demonstrate the value of managerial flexibility via the option-game approach. The present value (t = 0) of the strategic value in an asymmetric Cournot for Firm i is determined in equation (4.25). Hence, the option premium (OP) of Firm i can be obtained by equation (4.25), subtracting equation (4.10), as expressed in equation (4.27).

$$\mathrm{OP}_{i00} = \mathrm{SNPV}_{i00}^{\mathrm{OG}} - \mathrm{NPV}_{i00} \tag{4.27}$$

As the value of OP can be influenced by multiple parameters, further sensitivity analyses can provide the trends with specific parameters (the expected standard deviation in demand σ, a parameter of the (inverse) product differentiation τ, and the ratio of both unit variable costs β_{vc}). All other parameters are set as defaults from previous sections. The results illustrate that the expected standard deviation in demand (σ) is the most critical parameter to both NPV and SNPV of the option-game approach with a positive option premium, as shown in Fig. 4.9. While the project is killed by the NPV approach when NPV is negative, it is killed by the option-game approach when SNPV is less than I_0 = \$4,500. Based on the changes of the expected standard deviation in demand, Fig. 4.9 shows that the NPV approach could kill the potential projects.

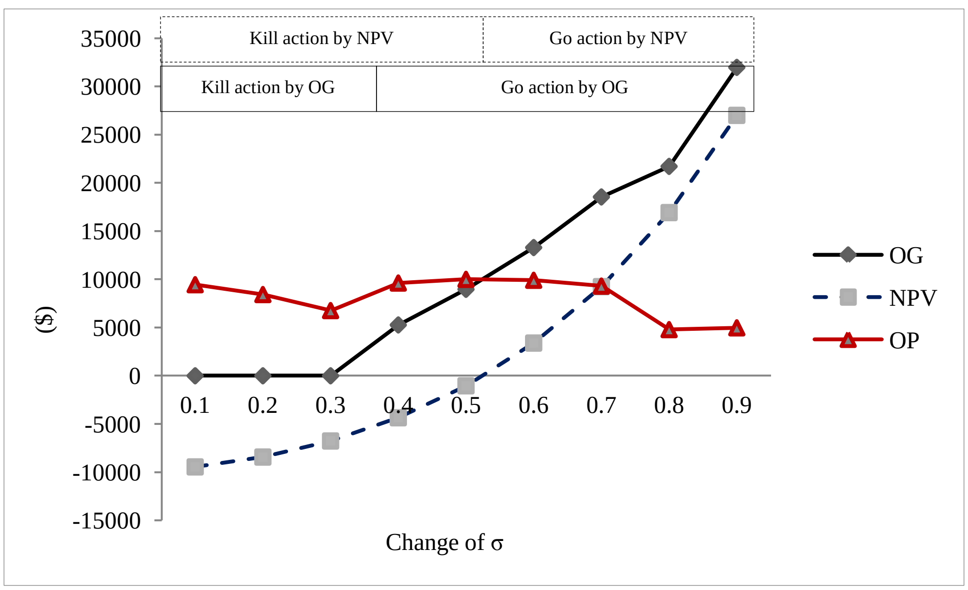

Fig. 4.9 Sensitivity analysis of SNPV of OG (the option-game approach), NPV (benchmark A), and OP (option premium) of Firm *i* by changing the expected standard deviation in demand σ

On the other hand, since a parameter of the (inverse) product differentiation τ is considered in the NPV method as one of the components of the market share, the (inverse) product differentiation influences the value of the NPV directly, as shown in Fig. 4.10. A higher value of the (inverse) product differentiation τ indicates that Firm *j*'s product is very similar to Firm *i*'s, and Firm *j* may not invest the project at the intermediate demand statuses. Hence, due to Firm *j*'s decision, the SNPV of Firm *i* after $\tau = 0.6$ increases, as shown in Fig. 4.10.

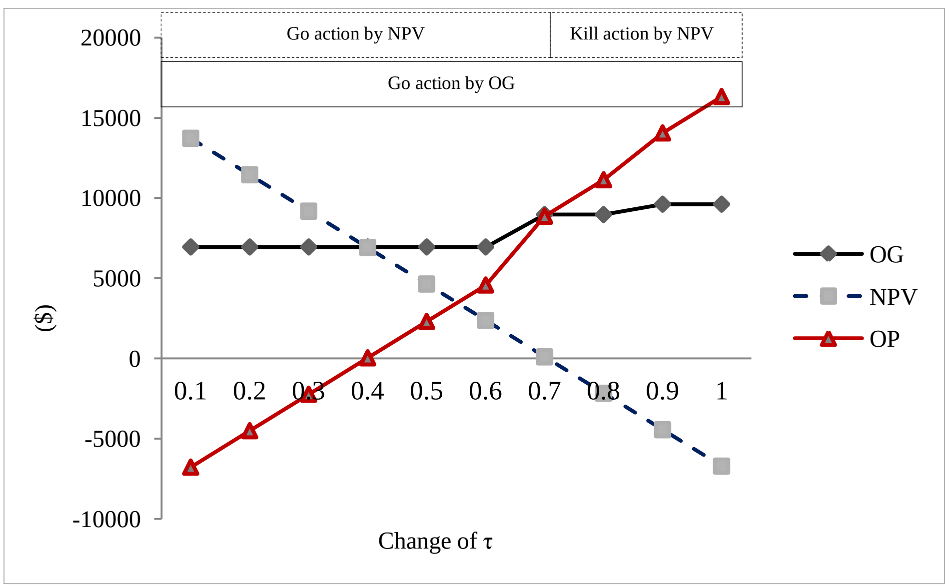

Fig. 4.10 Sensitivity analysis of SNPV of OG (the option-game approach), NPV (benchmark A), and OP (option premium) of Firm *i* by changing a parameter of the (inverse) product differentiation τ

The last parameter β_{vc}, is defined as Firm *j*'s unit variable cost divided by Firm *i*'s unit variable cost (i.e., $\beta_{vc} = c_j / c_i,\ c_i, c_j > 0$). In the settings of benchmark A, the profit of Firm *i* is an absolute fraction of the overall profits in the market when the firm chooses to produce the output that equals the average marginal cost to marginal revenue in the industry. Increasing the rival's unit variable cost leads to a larger average marginal cost, accordingly diminishing the overall profits in the market. Meanwhile, the market share of Firm *i* will rise directly. This result explains why the NPV grows in a curve trend with an increasing value of β_{vc}, as shown in Fig. 4.11. On the other hand, when the rival's marginal cost is very low, Firm *i* will kill the project by the option-game approach. When the parameter β_{vc} increases, Firm *i* gets the cost advantage and may earn more profit than its rival. Hence, the SNPV of the option-game approach goes up with an increasing value of β_{vc}. When Firm *j* has a very high marginal cost, Firm *j* will kill the project and Firm *i* can gain the monopolistic profit as shown in Fig. 4.11.

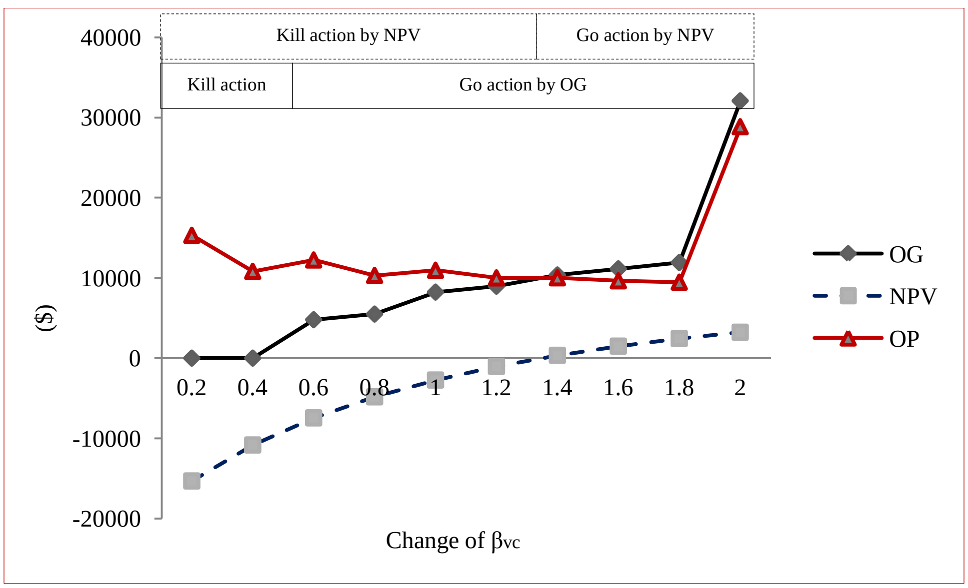

Fig. 4.11 Sensitivity analysis of SNPV of OG (the option-game approach), NPV (benchmark A), and OP (option premium) of Firm *i* by changing the ratio of unit costs β_{vc}

In summary, I observe the sensitivity analyses of benchmark A (the NPV approach), SNPV of the option-game approach (OG), and option premium (OP) with specific parameters (the expected standard deviation in demand σ, a parameter of the (inverse) product differentiation τ, and the ratio of both unit variable costs β_{vc}). I use OP to represent the option value of the option-game approach in assessing an individual project at the outset of the development stages in the NPD process. The results of the sensitivity analyses imply that OP is influenced by the dimensions and characteristics in the buckets of asymmetric costs, uncertain market, and product-differentiated projects. In addition, the results demonstrate that the NPV approach could not only kill the potential project but also evaluate the project insufficiently when it involves interacting with a competitor's decisions.

- *Strategic decisions at the first sub-gate of the development stages*

Secondly, I validate the SNPVs of benchmark B and this approach at the first sub-gate of the development stages, which is after new information is updated by Bayesian analysis. I am interested in exploring the SNPVs by different settings of these two approaches. As most of the strategic values from these two approaches are the same as zero when the demand is low, I only compare them when demand is high. Hence, these two SNPVs of benchmark B and my approach at the status of "11" after collecting samples can be computed from equations (4.16) and (4.26), respectively.

As the values of SNPVs can be influenced by multiple parameters, further sensitivity analyses can provide the trends with specific parameters (the expected standard deviation in demand σ, a parameter of the (inverse) product differentiation τ, and the ratio of unit costs β_{vc}). All other parameters are set as the defaults from previous sections, and all the analyses are on the side of Firm i. The results show that the expected standard deviation in demand (σ) is the most significant parameter of both SNPVs.

While the SNPV of benchmark B grows dramatically with an increasing value of σ, the SNPV of the option-game approach is up and down as shown in Fig. 4.12. The main reason is that the SNPV of the option-game approach is influenced by both Firm *i*'s and Firm *j*'s decisions. When σ is low ($\sigma < 0.3$), Firm *i* takes the monopolistic profit due to Firm *i*'s cost advantage. At $\sigma = 0.4$, there is not a pure Nash equilibrium, but a Prisoner's Dilemma (the go/kill decision for both firms) results in a lower SNPV of Firm *i*. At σ = 0.5, both firms kill their projects at the intermediate status of "21" in the demand, a decision which makes the SNPV of the option-game approach at the status of "11" a pure Nash equilibrium again, and then Firm *i* gains the monopolistic profit. Until σ gets larger ($\sigma = 0.6$), both Firm *i* and *j* initiate the same action of "go" in a Cournot competition, resulting in a lower SNPV for Firm *i*.

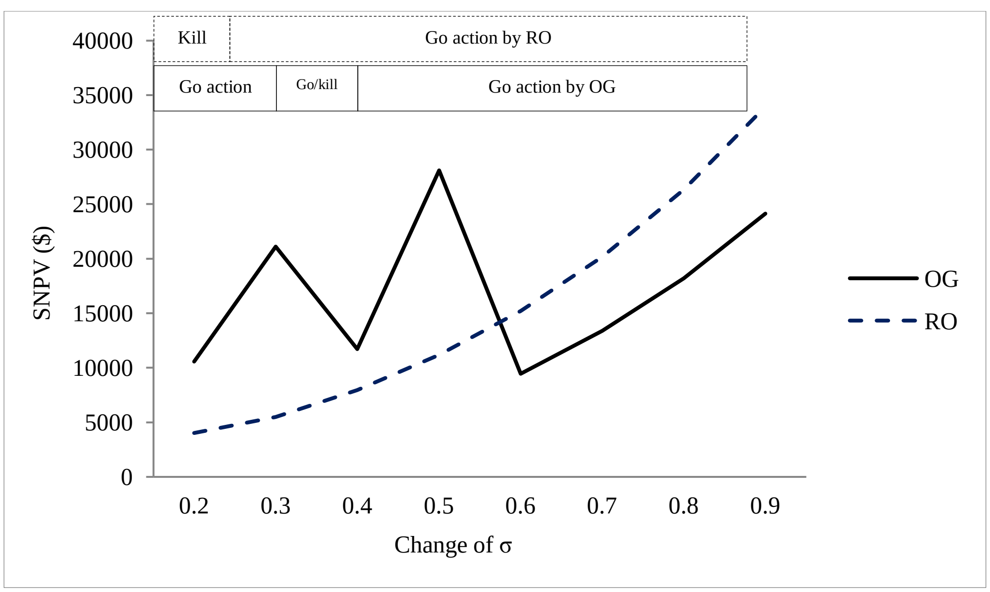

Fig. 4.12 Sensitivity analysis of SNPVs of Firm *i* by changing the expected standard deviation in demand σ

As the second parameter τ is considered in benchmark B as one of the components of the market share, Firm *i*'s SNPV of benchmark B decreases in a linear straight line when its rival's product is a high substitute or homogeneous product, as shown in Fig. 4.13. A lower value of the (inverse) product differentiation τ indicates that Firm *j*'s product is very different from Firm *i*'s, and Firm *j* is more willing to take the action of "go" in future periods. Hence, due to this decision of Firm *j*, the SNPV of Firm *i* before τ = 0.8 is zero.

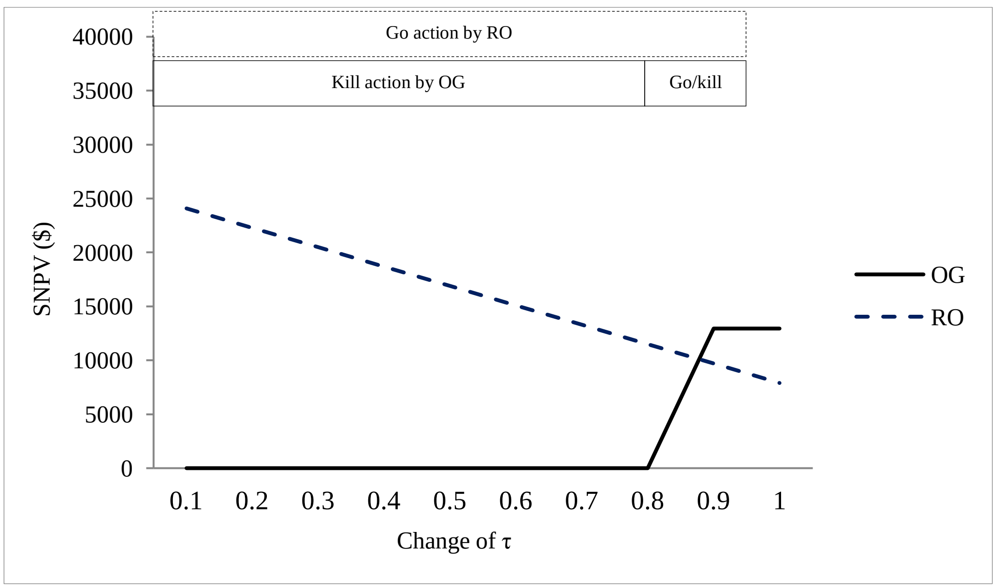

Fig. 4.13 Sensitivity analysis of SNPVs of Firm *i* by changing a parameter of the (inverse) product differentiation τ

When the parameter β_{vc} grows, the rival's unit variable cost increases. Hence, I expect the SNPV of Firm *i* by the option-game approach to go up with an increasing value of β_{vc}. In Fig. 4.14, when β_{vc} is low ($\beta_{vc} < 1$), Firm *j* gains the monopolistic profit due to its cost advantage, resulting in Firm *i* taking the action of "kill." At $\beta_{vc} = 1.2$, there is not a pure Nash equilibrium, but a Prisoner's Dilemma (the go/kill decision for both firms) results in a positive SNPV of Firm *i*. Until β_{vc} gets larger (β_{vc} = 1.4), Firm *j* kills its project, so that Firm *i* gains monopolistic profit. However, the SNPV shows a curve trend in the case of benchmark B, which may come from the same problem as explained previously in the settings of benchmark A. As the rival's marginal cost increases, the overall profits in the market decline with an increasing value of β_{vc} due to the setting of the average marginal cost, but the market share of Firm *i* increases. The above two components of the settings in benchmark B lead to a curve trend. Section 4.4.2 provides further discussion of this parameter.

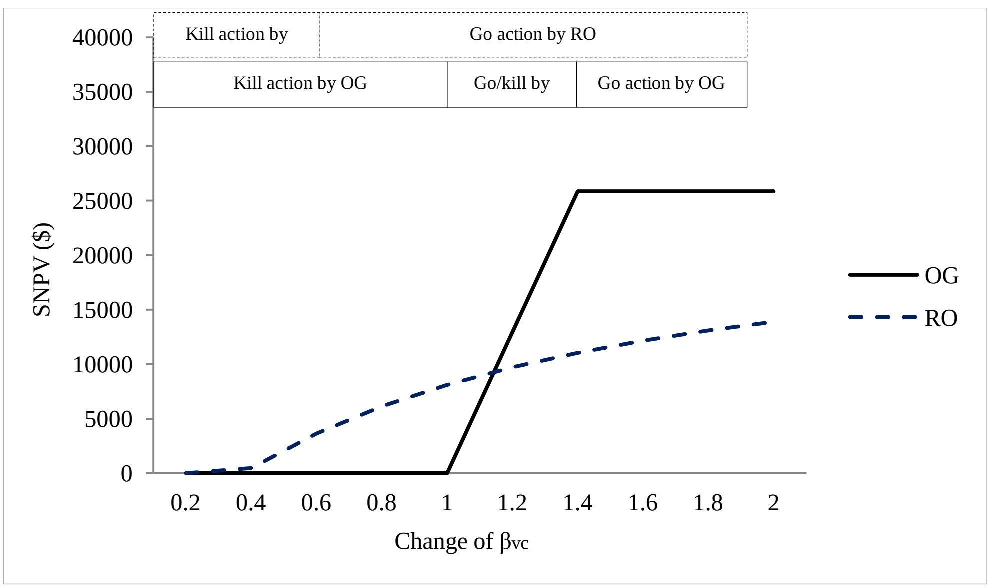

Fig. 4.14 Sensitivity analysis of SNPVs of Firm *i* by changing the ratio of unit costs β_{vc}

In summary, I compare the SNPVs of benchmark B and the option-game approach in a project with the characteristics and dimensions of asymmetric costs, an uncertain market, and one potential competitor. I consider the factor of market share in benchmark

B (not viewed as a monopolistic calculation), containing the components of (inverse) product differentiation and unit variable costs. However, from the results of sensitivity analyses, the SNPVs of benchmark B can be overestimated or underestimated compared to the option-game approach. The main reason is that the capacity of Firm *i* by benchmark B is a fraction of the overall quantities in the market place, where the maximum overall profit results from choosing to produce the output that equals the average marginal cost to marginal revenue. Secondly, the SNPVs of benchmark B are measured based on the market share with one competitor, but benchmark B does not take the competitor's decision into account. However, the option with the concept of game theory not only evaluates managerial flexibility but also depicts the influence of each firm on the other firm in the industry, given the likely outcomes of strategic interactions.

4.4.2 Discussion

The discrete option-game framework with Bayesian analysis is developed to evaluate a project at the gate of go-to-development and the sub-gates of the development stages in the NPD process (Fig. 4.2). In the following, I further discuss the model properties: the strategic decisions, the value of information about demand, the asymmetric unit costs of Firm *i* and *j*, and the (inverse) product differentiation τ.

- *The strategic decisions*

The results of sensitivity analyses when one parameter is changed have been demonstrated in previous sections. To further analyze the strategic decisions of Firm *i*, I here consider the changes of these three parameters simultaneously: (1) the expected standard deviation in demand σ (low = 0.25, medium = 0.45, and high = 0.75), (2) a parameter of the (inverse) product differentiation τ (low = 0.25, medium = 0.5, and high

= 1), and (3) the ratio of unit costs β_{vc} (low = 0.5, medium = 1, and high = 1.5). Hence, there are 27 combinations. All other parameters are set as the defaults from previous sections, and all of the analyses are on the side of Firm *i*. As a result, the strategic decisions of Firm *i* at the status of "11," according to these settings, are shown in Figs. 4.15 to 4.17.

Even though the fixed investment costs could also influence the strategic decisions, the results still provide the possible trends and allow decision makers to understand the impacts of these parameters. Generally, Firm *i* will initiate the action of "go" at the status of "11" when Firm *i* has the cost advantage in competing with Firm *j*'s highly comparable product or simply when Firm *i*'s target market has a high uncertainty.

Ratio of unit costs β_{vc} \ The (inverse) product differentiation τ	Low	Medium	High
High	**Kill**	**Kill**	**Go**
Medium	**Kill**	**Kill**	**Go**
Low	**Kill**	**Kill**	**Kill**

Fig. 4.15 Strategic decisions of Firm *i* with low expected standard deviation in demand σ

Ratio of unit costs β_{vc} / The (inverse) product differentiation τ	Low	Medium	High
High	**Kill**	**Go**	**Go**
Medium	**Kill**	**Kill**	**Go**
Low	**Kill**	**Kill**	**Kill**

Fig. 4.16 Strategic decisions of Firm *i* with medium expected standard deviation in demand σ

Ratio of unit costs β_{vc} / The (inverse) product differentiation τ	Low	Medium	High
High	**Go**	**Go**	**Go**
Medium	**Go**	**Go**	**Go**
Low	**Go**	**Go**	**Go**

Fig. 4.17 Strategic decisions of Firm *i* with high expected standard deviation in demand σ

- *Value of information about demand*

When a project is accepted at the gate of go-to-development, firms may allocate extra budget to marketing to collect new information. The maximum value to spend on the marketing information is the value of the option premium. In Artmann's (2009) real-option framework with Bayesian analysis, he proved that the value of an information update is always positive, indicating that the maximum project value, given the optimal managerial response to the posterior information, is always greater than that of the prior managerial policy. Accordingly, as the volatility of demand can be reduced with the posterior information about the market risk, the option-game framework with Bayesian analysis can provide a rigorous gate-criterion for decision-making.

Consequently, the value of information in the option-game approach can also be obtained by the project value of the optimal managerial response to the posterior information, deducing project value by the prior managerial policy, where the posterior expected standard deviation in demand is less than the prior expected standard deviation in demand. As the strategic decisions resulting from low demand (the status of "10") are the same action of "kill" in either the prior or posterior distribution, I will only discuss the strategic decisions resulting from high demand (the status of "11"). Suppose, based on the prior information, that the SNPV_{i11} suggests an action of "go." Hence, the maximum value of information ($\text{VI}^{\max}$) at the status of "11," with the collection of samples, can be computed as shown in equation (4.28).

$$\text{VI}_{i11}^{\max} = \begin{cases} \text{SNPV}_{i11}^{\text{OG}} - \text{SNPV}_{i11}^{\text{OG}'} & \text{if } \text{SNPV}_{i11}^{\text{OG}} \text{ takes an action of "go"} \\ 0 & \text{Otherwise} \end{cases} \tag{4.28}$$

Further sensitivity analysis provides the trend to the value of information (VI) by changing the updated expected standard deviation in demand σ'. All other parameters are set as the defaults from previous sections, the (inverse) product differentiation is unchanged (τ = τ' = 0.75), and the analysis is on the side of Firm *i*. Given the prior expected standard deviation in demand σ = 0.5, the x-axial in Fig. 4.18 is the range of the posterior expected standard deviation in demand σ'. Fig. 4.18 illustrates the maximum value of information from equation (4.28), showing that VI^{max} mainly depends on the quality of the collected samples and accordingly impacts Firm *i*'s and its rival's decisions. When the collected samples have smaller variance, the posterior expected standard deviation in demand is lower. Due to the low expected standard deviation in demand and the (inverse) product differentiation τ' = 0.75, Firm *i* will kill the project. Until increasing to σ' = 0.25, Firm *i* has a positive payoff at the status of "22," resulting in a Prisoner's Dilemma at the status of "11." This result explains why $\mathrm{SNPV}_{i11}^{\mathrm{OG'}}$ has positive values from σ' = 0.25 to 0.4, providing for a decrease in the value of information. Up to σ' = 0.45, Firm *j* has a positive payoff at the status of "21," causing Firm *i* to take the action of "kill" with $\mathrm{SNPV}_{i11}^{\mathrm{OG'}} = 0$.

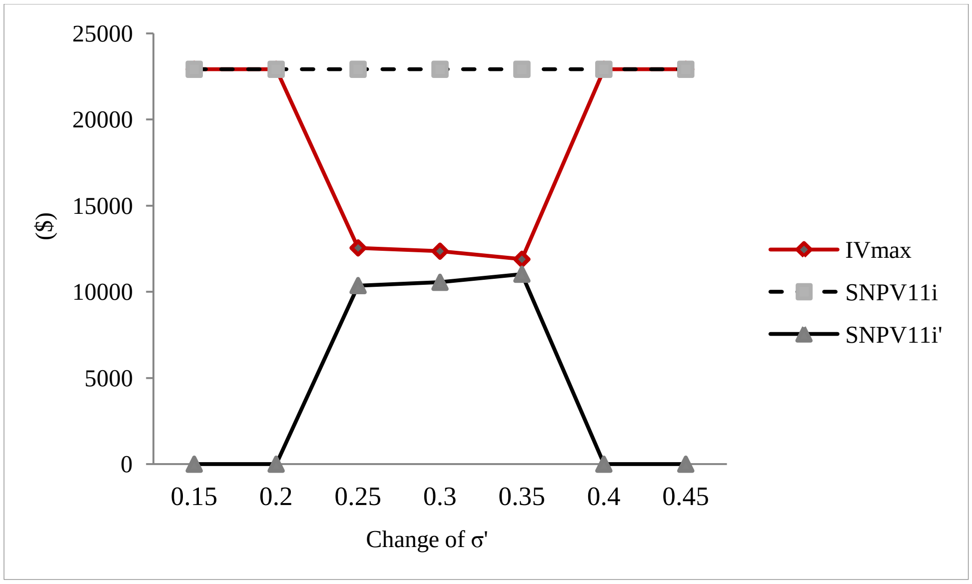

Fig. 4.18 Maximum value of information (VI^{max}) at status of "11" of Firm *i* by changing the updated expected standard deviation in demand *σ'*

- *Asymmetric unit costs of Firm i and its rival j*

As most products have counterparts that are competitive to certain degrees (Smith, 1995), I consider the fraction of market share in the benchmarks rather than assuming a monopoly. Hence, the components of (inverse) product differentiation and unit variable costs of Firm *i* and *j* are reflected in the market share, accordingly expressed in the settings of benchmark B. Nevertheless, when a project of Firm *i* is not a monopolistic product, benchmark B may overestimate or underestimate the profit functions resulting from the relationships between the market-clearing price and unit variable costs. The market-clearing price of benchmark B is defined by the (inverse) demand function, where the resulting equilibrium quantity of Firm *i* is computed by its market share, multiplying the overall product capacity in the marketplace based on the average unit variable cost. On the other hand, due to the strategic interactions of the option-game approach, Firm *i*'s quantity choice q_i ultimately depends on its own cost c_i, as well as on its rival's cost c_j and quantity choice q_j (Chevalier-Roignant & Trigeorgis, 2011).

Fig. 4.19 shows the sensitivity analysis of the profits in the market (Firms *i*, *j*, and total) by benchmark B and a Cournot competition in the option-game approach when changing the ratio of their unit costs in a substitute project (τ = 0.9) at the status of "22" in the demand binomial lattice. All other parameters are set as the defaults from previous sections, and the fixed costs are ignored. Even though the overall profits of both approaches are reduced when the value of β_{vc} grows, Fig. 4.19 illustrates that benchmark B overestimates the overall profits in the market. As the rival's unit variable cost directly influences Firm *i*'s market share, benchmark B still overestimates Firm *i*'s profit with an increasing value of β_{vc} and market share. This result explains the reason for an increasing curve trend by benchmark B in Fig. 4.14 and explains why benchmark B is inadequate in the profit functions when a competitor's actions are involved.

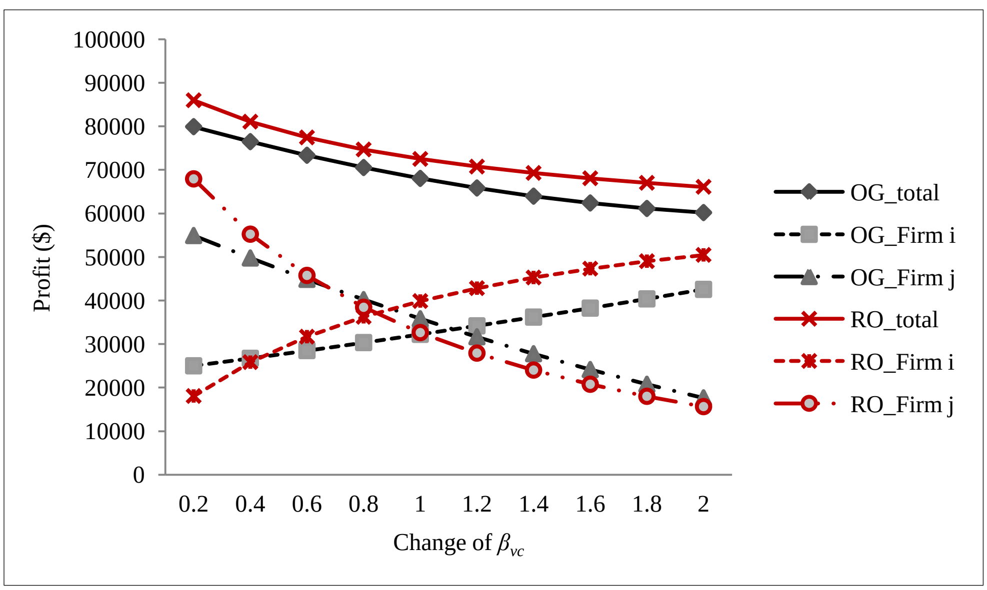

Fig. 4.19 Sensitivity analysis of the profits in the market by changing the ratio of unit costs β_{vc} (τ = 0.9)

- *The (inverse) product differentiation τ*

A parameter of the (inverse) product differentiation *τ* indicates whether goods *i* and *j* are substituted or independent, and to what degree (Motta, 2004). Based on Chevalier-Roignant and Trigeorgis (2011), the reaction functions of duopolists in quantity competition are downward sloping, i.e., they decrease the rival's capacity-setting action. As shown in equation (4.19) in Appendix A, the reaction functions of Firm *i* and *j* can be written as shown in equation (4.29). Hence, Fig. 4.20 illustrates the reaction functions in an asymmetric Cournot quantity competition at the status of "22" in the binomial demand lattice, in which all the parameters are set as the defaults from previous sections. As the reaction slope of Firm *i* is steeper than that of Firm *j* with the x-axial of Firm *i*'s quantity (Motta, 2004), the figure demonstrates the stability of the equilibrium.

$$\begin{cases} q_i = \dfrac{-\tau}{2} q_j + \dfrac{\bar{a}_2 - c_i}{2b} \\ q_j = \dfrac{-1}{2\tau} q_i + \dfrac{\bar{a}_2 - c_j}{2b\tau} \end{cases} \tag{29}$$

In addition, I can further study the quantity competition from the reaction functions with the parameter of the (inverse) product differentiation *τ*, as shown in Fig. 4.21. When the (inverse) product differentiation is changed, the resulting equilibrium quantity of Firm *i* is the same. The main reason is that the setting of Firm *i* is endogenous in the target market, where the (inverse) product differentiation is a parameter to define its rival's product. However, the (inverse) product differentiation of Firm *j* is an exogenous setting. When the (inverse) product differentiation is higher (close to 1), the products of Firm *i* and *j* are high substitutes, resulting in a lower equilibrium quantity of Firm *j*. In other words, Firms *i* and *j* are competing for exactly the same target market when the (inverse) product differentiation τ is 1. As long as the (inverse) product differentiation τ is less than 1 but greater than 0, then Firm *j*'s target market becomes the intersection area of Firm *i*'s target market.

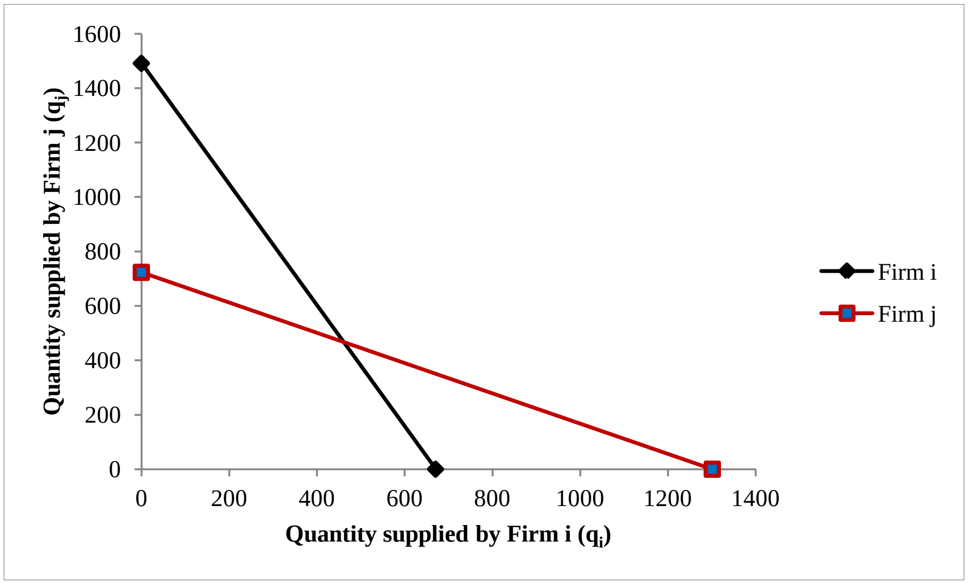

Fig. 4.20 Downward-sloping reaction functions in an asymmetric Cournot quantity competition

- *Limitations and possible extensions*

In this chapter, I analyze a compound option specifically during the development stages under the twice repeated game (Fig. 4.3) with one strategic variable (i.e., quantity), considering the degree of (inverse) product differentiation between the products of Firm *i* and its rival. So far, this model only takes into account the market risk from the demand side. I have not yet considered multiple qualitative and quantitative factors such as technical risks, multiple strategic variables, multi-stage game competitions, etc., so these may become possible extensions of this research. As the gate-criteria for projects are multidimensional in an NPD process (Cooper, 2008), different scorecards and criteria may be evaluated in different stages of the NPD process (Ronkainen, 1985). Hence, firms may make a number of decisions that affect their costs and their products according to the purpose of each decision point, such as entry decision, price decision, investment decision, etc. As Anderson (2008) pointed out, product portfolio management is one of the common areas of weakness in NPD management; therefore, further research in this area is required. Most importantly, portfolio management can be used in conjunction with other supportive methods in industry management (Cooper et al., 2001). Principally, it must be an integral part of the organization's culture and management practices.

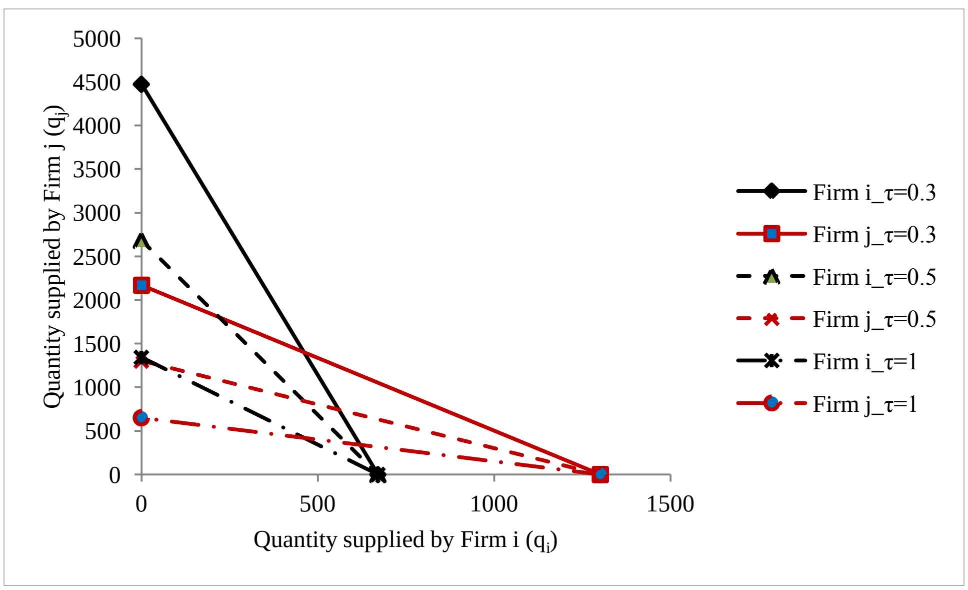

Fig. 4.21 Sensitivity analysis of reaction functions by changing the (inverse) product differentiation τ

4.5 Summary and Conclusion

In this chapter, I propose an option-game valuation framework that explicitly incorporates statistical decision theory in the form of Bayesian analysis in an NPD project. Specifically, I introduce this approach as a gate-criterion to evaluate a new project at the gate of go-to-development and the sub-gates of the development stages in an NPD process.

At the outset of the development stages, the target market has uncertain demand and the customers do not necessarily know their product requirements and preferences. The common financial gate-criterion, the NPV method (benchmark A), is insufficient when a project's success is uncertain, so that this method may result in killing the potential projects in the early stages or in not changing decisions later in the process. When the project is accepted at the gate of go-to-development, additional market research may be needed. Since customer requirements and preferences are an important indicator to estimate target markets (with known mean and unknown variance), with actual collected samples, they can be updated by Bayesian analysis. Accordingly, the high volatility in the initially uncertain market can be diminished via updated information about customer requirements and preferences. On the other hand, a parameter of (inverse) product differentiation is included in the option-game mechanism to describe the degree that a product from a potential competitor is related to the product in development. Until the first sub-gate of the development stages is reached, new information about a potential rival's product with its parameter of the (inverse) product differentiation becomes clearer. However, the real-option valuation (benchmark B) is inadequate when resolving an asymmetric duopoly game in which strategic interactions involve a firm's own quantity choice as well as its rival's. The results of sensitivity analyses of the option premium imply that the dimensions and characteristics in the buckets of asymmetric costs and uncertain-market projects have positive influences on the option premium. In addition, the results also show that the real-option valuation may overestimate or underestimate the SNPV when the project is not under monopolistic product development. As a result, the option-game approach not only evaluates managerial flexibility in a project at the gate of go-to-development, but also provides a rigorous evaluation method at the first sub-gate of the development stages after updating the information about demand by Bayesian analysis.

I develop the formal mathematical option-game framework in the discrete-time analysis of an NPD project with a finite project life. In particular, I analyze a compound option specifically during the development stages under the twice repeated game with one strategic variable (i.e., quantity). The approach can be applied to different degrees of (inverse) product differentiation in a competition game. Through an information update with Bayesian analysis, the volatility of the uncertain market is reduced. With dynamic settings, this approach can provide a rigorous evaluation method at the gate and the sub-gates of the development stages.

The strategic buckets approach in the early stages of the NPD process links the business's strategy and its portfolios (Cooper et al., 1997). The dynamic option-game framework as a gate-criterion of the development stages implements further evaluations of the individual projects in the development process. As product portfolio management is one of the common areas of weakness in NPD management (Anderson, 2008), further research in this area is needed. However, its most important benefit is that it can be used in conjunction with other supportive methods in industry management (Cooper et al., 2001). Principally, it must be combined with current corporate culture and management practices.

Chapter 5 Assessing Managerial Flexibility in a New Product Development Project: An Option-Game Approach in an Oligopoly with Bayesian Analysis

Abstract

Gate-criteria have been identified as critical drivers of the success of the new product development (NPD) process. The proposed gate-criterion of the real-option valuation is inadequate when project success is affected by the actions of competitors. In this chapter, I will extend the option-game valuation framework with Bayesian analysis discussed in the previous chapter by explicitly involving technical risk and the 3-player-game in an NPD project. Volatilities from the initially uncertain market are diminished by updated information about customer requirements and preferences, while the technical risk is diminished by updated information about product performance. In addition, the distribution of product correction is used to describe the level of additional correction costs in a project. I introduce this approach as a gate-criterion to evaluate a new project at the gate and sub-gates of the development stages in the NPD process. The results have important implications: when demand is high, the project initiates "go" action if at least one competitor has a high unit variable cost in competing with a highly comparable product or simply if the target market is highly uncertain. When demand is low, the project may initiate "go" action only if the firm has the cost advantage. Using this

approach, industry players can make strategic decisions in assessing a project at the decision points of the development stages.

Keywords: option-game, oligopoly competition, product differentiation, gate-criteria, new product development, Bayesian analysis, technical risk

5.1 Background

New product development (NPD) is commonly regarded as a central source of competitive advantage (Bessant & Francis, 1997), and gate-criteria are critically important for the success of the NPD process (Carbonell-Foulquié et al., 2004; Agan, 2010). However, gate-criteria are rated as one of the weakest areas in product development (Cooper, 2008; Cooper & Edgett, 2012; Cooper, Edgett, & Kleinschmidt, 2002, 2005).

5.1.1 Problem statement

The stage-gate NPD process is very similar to that of buying a series of options on an investment (Cooper, 2008), allowing developers to build real-option into product development for decision-making under uncertainty (Mun, 2006). Huchzermeier and Loch (2001) demonstrated the managerial flexibility of real-option and introduced an improvement option to take corrective actions during the NPD process to improve product performance. Instead of taking the traditional view that reducing uncertainty in real-option theory is a passive process, Artmann (2009) extended Huchzermeier and Loch's (2001) work by deriving the Bayesian update formulation for market requirement distribution and integrating this mechanism into a real-option framework. However, since "similar product developments exist in greater or lesser degree in almost all product areas" (Smith, 1995), real-option valuation methods fall short of resolving the dilemma when the moves of competitors are involved (Ferreira et al., 2009). In the previous chapter, I developed an improved discrete option-game valuation framework that explicitly incorporates statistical decision theory in the form of Bayesian analysis, particularly involving new information about one competitor's actions and considering customer requirements and preferences.

Nevertheless, technical risks from the supply side could influence the project values and option values, so the operational sources of uncertainty should be incorporated with real-option values of managerial flexibility (Huchzermeier & Loch, 2001; Artmann, 2009). Moreover, instead of a duopoly competition game, several players could compete in similar projects at the same time.

5.1.2 The scope of this chapter

In this chapter, I extend the previous model by relaxing some assumptions from chapter 4. In contrast to the assumptions in chapter 4, I consider that the technical risk from the supply side influences expected product performance and that the differences between the expected product performance and customer requirements and preferences could lead to additional correction costs. I assume that a new project is competing with two latent competitors in certain degrees of (inverse) product differentiation (the 3-player-game) in a target market, where the information might be unknown or uncertain at the outset of the development stages.

Because strategic fit determines the success of an NPD process (Cooper, 2008; Anderson, 2008), I assume, explicitly, the strategic buckets method of initial project screenings with the following dimensions and characteristics: high variability in the initial market, a high-risk product development technique, and uncertainty about whether the two latent rivals will produce similar and competitive products in the future. As time progresses toward development stages, variations in predicted demand are diminished by effective means of updating information about customer requirements and preferences, and variations in product performance are reduced by updated information about product development techniques. In addition, I consider managerial flexibility when two latent competitors in certain degrees of (inverse) product differentiation may be present in future competing markets. Consequently, with the above two factors, I extend the discrete option-game valuation framework incorporated with Bayesian analysis in an NPD project by explicitly involving technical risk and the 3-player-game. Jenner (2007) points out that projects are rarely killed at gates after the idea screening stage. Therefore, I introduce this approach as a rigorous gate-criterion to evaluate a new project during the stages of development.

The remaining chapter is organized as follows. In section 5.2, I develop this work by defining the model description and using an extended version of chapter 4 for my valuation model. The theory of Bayesian analysis is integrated into a valuation model that allows updating the variability of the target market and expected product performance. In addition, two latent rivals' product developments in certain degrees of (inverse) product differentiation are considered in the option-game approach. In section 5.3, I provide a case study to demonstrate the model and compare the results with two benchmarks. Benchmark A is the NPV method, used to represent the actions of "go/kill" at the gate of go-to-development and of "go/continue" later in the NPD process to highlight many industrial problems. Benchmark B is based on the concept of Artmann's study (2009), in which a real-option framework is incorporated with Bayesian analysis and product performance. In section 5.4, I further discuss the strategic decisions of my valuation model against benchmark B. Section 5.5 summarizes the results and concludes the chapter.

5.2 Model Development

As indicated in the preceding section, this model builds upon an extended version of the work in chapter 4. I start with a brief description of the extended model. Section 5.2.1 illustrates the evolution of demand by a basic binomial lattice combined with the concept of a product life cycle (as shown in chapter 3). The linkage of market demand and the distribution of customer requirements and preferences have been defined in chapter 4. Moreover, I define the distribution of product performance. Hence, these settings are the basis of the NPV method, benchmark A, taking the actions of "go/kill" at the gate of go-to-development and of "go/continue" for the later process. In section 5.2.2, I demonstrate how new information on customer requirements and preferences and product performance can be updated over time until the first sub-gate of the development stages using statistical decision theory in the form of Bayesian analysis. Therefore, these settings define the real-option framework with Bayesian analysis, benchmark B, taking the actions of go/kill at the first sub-gate. Section 5.2.3 considers managerial flexibility with two latent rivals in certain degrees of (inverse) product differentiation, representing a discrete option-game valuation framework in the 3-player-game. Finally, I compare this approach to two basic benchmarks in section 5.3 and further discuss the results in section 5.4.

Suppose that projects are initially screened and selected through the strategic buckets approach in the early stages of the NPD process. As described in previous chapters, I focus on individual project assessment at the gate of go-to-development and sub-gates of the development stages, assuming projects with the following characteristics: managerial flexibility, a short product life cycle, and high variability in the target market segment. Additionally, I focus on evaluating the buckets of projects by relaxing the assumptions of chapter 4 and assuming instead that (1) Firm *i* has two potential competing products from rivals *j* and *k* in certain degrees of (inverse) product differentiation τ_j, τ_k and (2) the technical risk for the product performance of Firm *i* is considered.

Fig. 5.1 shows the basic concept and scope of the NPD process as explored in this chapter. The gate of go-to-development with an initial development cost (I_0) is the starting point ($t = 0$) in cash flow. Next is the development stage, consisting of multiple sub-gates for product prototype development. To simplify the prototype process, I set two sub-gates during the development stage (Fig. 5.1) with the first and second advanced development costs (I_1 and I_2).

In the remainder of this chapter, the term "development stages" will refer to this entire step of the development process, including the two sub-gates. Following the development stages, the next two stages of testing/validation and production/launch have a testing cost (I_3) and a launch investment cost (I_4), respectively. Thereafter, products are sold to market, and the annual profit occurs one period after launch with N periods of project service life. To simplify the symbols of the model, I demonstrate that the time intervals of the cash flows are equivalent in the time horizon (Fig. 5.1). Note that different time intervals of the cash flows will be demonstrated in the next section with a case study.

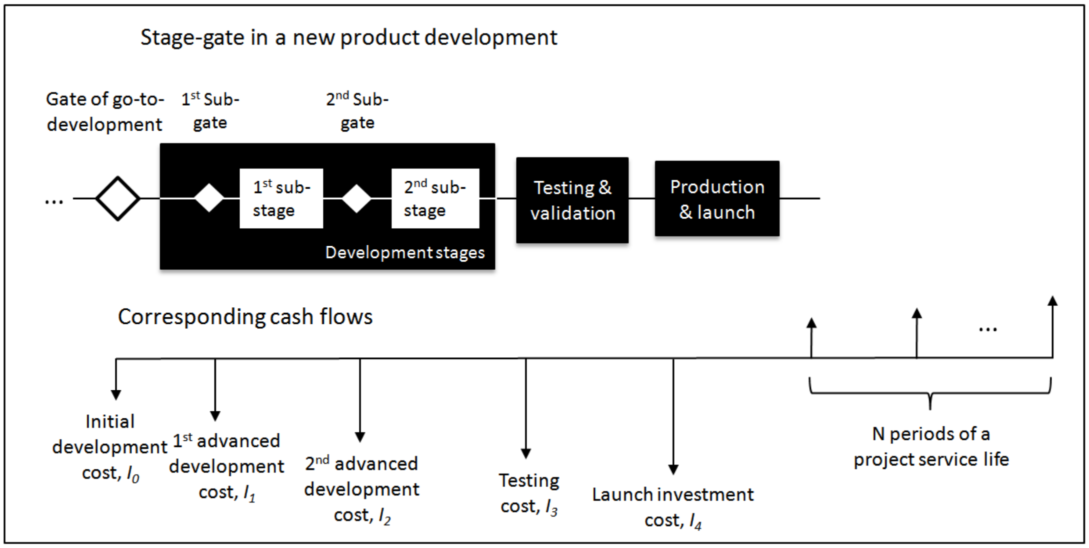

Fig. 5.1 Product development process and the corresponding cash flows (from Fig. 4.2)

5.2.1 Demand evolution and the probabilities of upward in demand

A binomial lattice framework is used to represent the market demand uncertainty (Q) within four periods as shown in Fig. 5.2. The binomial model is multiplicative in nature, and thus demand is always positive. Since the percentage changes in the demand (y) over short intervals of time are normally distributed (Luenberger, 1998; Park, 2011), I can define the normal random variable y with expected yearly growth rate g and volatility with yearly growth rate σ, i.e., $y \sim N(g, \sigma^2)$. The parameters of a binomial lattice from Luenberger (1998) are shown in equation (5.1).

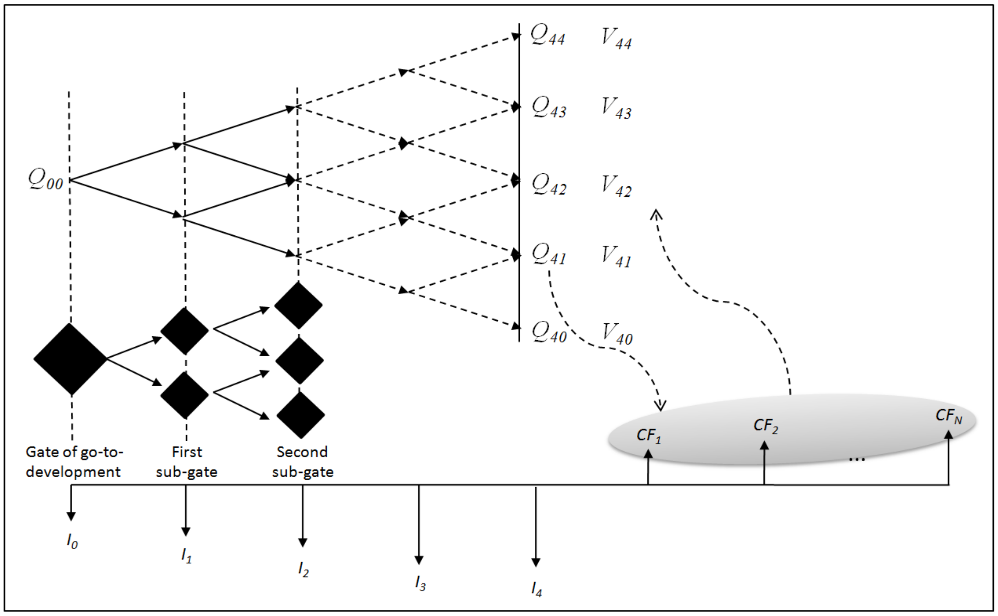

Fig. 5.2 Demand binomial lattice and decision gate and sub-gates (from Fig. 4.4)

· $u = e^{\sigma\sqrt{\Delta t}}, d = 1/u$

· Risk-neutral probability of an upward:

$$q_r = \frac{(1+r_f)-d}{u-d}, \text{where } r_f \text{:risk-free rate} \tag{5.1}$$

· The probability of an upward:

$$P = \frac{1}{2} + \frac{1}{2}\left(\frac{g}{\sigma}\right)\sqrt{\Delta t}$$

Suppose the market research contains information on market performance requirements and customer requirements and preferences. As shown in chapter 4, the random variable of customer requirements and preferences *x* is normally distributed with mean μ_x and variance ξ_x^2, i.e., $x \sim N(\mu_x, \xi_x^2)$. Since the factor of customer requirements and preferences *x* plays a key role on the demand side (Smith, 1995), I defined a positive correlation between customer requirements and preferences *x* and the percentage changes in the demand y in chapter 4, as expressed in equation (5.2), in which the correlation coefficient γ is estimated by the weighted ratios of the factors that affect demand.

$$y = \gamma x + \varepsilon \sim N(\gamma\mu_x + \varepsilon, \gamma^2 \xi_x^2) \tag{5.2}$$

where y: the percentage changes in the demand, $y \sim N(g, \sigma^2)$;
γ: the correlation coefficient, $0 < \gamma < 1$;
x: customer requirements and preferences, $x \sim N(\mu_x, \xi_x^2)$

To determine the market-clearing price and the firm profits, industry structure models commonly assume a linear (inverse) demand function (Chevalier-Roignant & Trigeorgis, 2011). Suppose that in the discrete-time model of Smit and Trigeorgis (2004) and Chevalier-Roignant and Trigeorgis (2011), the demand intercept in the linear market demand function follows a multiplicative binomial process as shown in equation (5.3).

$$\tilde{p}_t = \tilde{a}_t - bQ = \tilde{a}_t - b(q_i + q_j + q_k) \tag{5.3}$$

where $\tilde{a}_t, b$: constant parameters, $a_t, b > 0$, $t \le 4$;
Q: the total quantity will be supplied in the market;
q_i, q_j, q_k: product quantities of Firms i, j, and k;
$\tilde{a}_t$ follows a multiplicative binomial process

The intercept of demand function $\tilde{a}_t$ is followed by a stochastic binomial as shown in Fig. 5.3 for four periods: at each up move, $\tilde{a}_t$ is multiplied by u, while at each down move it is multiplied by d from equation (5.1). When $\tilde{a}_t$ goes to time 1, it is noted as $\tilde{a}_1$, which indicates it could be either $\tilde{a}_{11}$ or $\tilde{a}_{10}$. Similarly, when $\tilde{a}_t$ goes to time 2, it is noted as $\tilde{a}_2$, which indicates it could be $\tilde{a}_{22}$, $\tilde{a}_{21}$, or $\tilde{a}_{20}$. The same concepts are used for the notations at times 3 and 4.

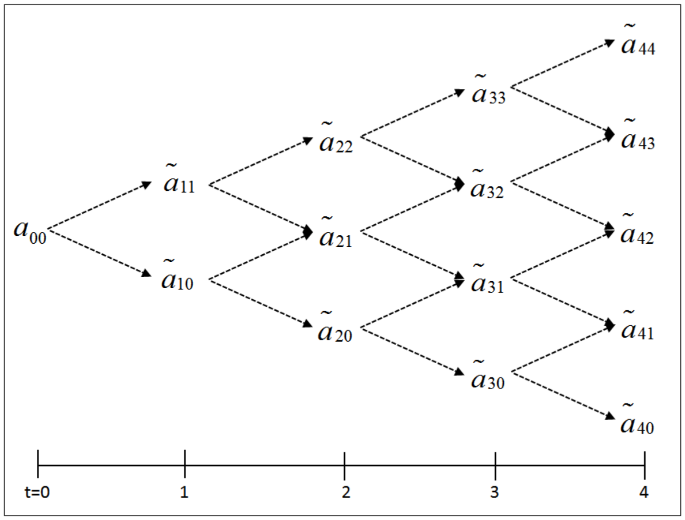

Fig. 5.3 Multiplicative binomial process followed by the intercept of demand $\tilde{a}_t$ at time t ($t \leq 4$) (from Fig. 4.5)

The expected intercept of demand at time 2, $\tilde{\bar{a}}_2$, can be computed by the intercepts of demand at time 4, multiplying by the corresponding cumulative probabilities from equation (5.1). Similarly, the expected intercept of demand at time 0, $\bar{a}_{00}$, can be obtained by the same procedures as shown in equation (5.4).

$$\tilde{\bar{a}}_2 : \begin{cases} \tilde{\bar{a}}_{22} = P^2 \tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2 \tilde{a}_{42} \\ \tilde{\bar{a}}_{21} = P^2 \tilde{a}_{43} + 2P(1-P)\tilde{a}_{42} + (1-P)^2 \tilde{a}_{41} \\ \tilde{\bar{a}}_{20} = P^2 \tilde{a}_{42} + 2P(1-P)\tilde{a}_{41} + (1-P)^2 \tilde{a}_{40} \end{cases} \tag{5.4}$$

$$a_0 : \bar{a}_{00} = P^2 \tilde{\bar{a}}_{22} + 2P(1-P)\tilde{\bar{a}}_{21} + (1-P)^2 \tilde{\bar{a}}_{20}$$

Suppose three firms are competing in the target marketplace and that the unit variable costs (c_i, c_j, and c_k) of Firm i and its rivals, Firms j and k, are constant ($c_i, c_j, c_k > 0$). Hence, the project values at time 4 (Fig. 5.2) can be computed from the future expected cash flows. The market-clearing price is calculated based on a linear (inverse) demand function with an average unit variable cost in the different statuses of the binomial lattice. As shown in Fig. 5.2, suppose the product is planned to be launched at time 5 with a project service life of N years. The demand after time 4 in the binomial lattice will correspond to the annual expected growth rates according to the product life cycle. The annual profit after time 4 in the binomial lattice grows at an annual expected growth rate g_{4+m} at time $4+m$ ($m = 1,2,\ldots,N$) with a risk-adjusted discount rate r ($r > g_{4+m}$). Hence, based on chapter 3, the total future growth of the project value at time 4, G_4, can be as expressed as shown in equation (5.5).

$$G_4 = \frac{1+g_5}{1+r} + \frac{(1+g_5)(1+g_6)}{(1+r)^2} + \ldots + \frac{(1+g_5)\ldots(1+g_{N+4})}{(1+r)^N} \tag{5.5}$$

- *The product performance of Firm i*

On the other hand, suppose that the technical risk of Firm i as the product performance s is normally distributed (Artmann, 2009) with mean μ_s and variance ξ_s^2, i.e., $s \sim N(\mu_s, \xi_s^2)$. Hence, there is an additional correction cost for Firm i from the parameter of product correction l, where product correction is defined by the difference (x-s) between customer requirements and preferences x and product performance s. Therefore, with the parameter of product correction, the unit of additional correction cost of Firm i can be defined by $c_{il} = c_i l$, where l is normally distributed with mean μ_l and variance ξ_l^2, i.e., $l \sim N(\mu_l, \xi_l^2) = N(\mu_x - \mu_s, \xi_x^2 + \xi_s^2)$.

- *The first benchmark: the NPV method (benchmark A)*

Therefore, with these settings, the profit function of Firm i by benchmark A at the second sub-gate (time 2) in Fig. 5.2 can be expressed as shown in equation (5.6) (also shown in Appendix A).

$$\begin{cases} \tilde{\pi}_{i2}^{A} = -I_{S2} + \dfrac{G_4 \omega}{(1+r)^2}[-bQ^2 - c_i Q - c_{il} Q + \tilde{\tilde{a}}_2 Q] & \text{if } l > 0 \\ \tilde{\pi}_{i2}^{A} = -I_{S2} + \dfrac{G_4 \omega}{(1+r)^2}[-bQ^2 - c_i Q + \tilde{\tilde{a}}_2 Q] & \text{if } l \le 0 \end{cases} \quad (5.6)$$

where ω: Firm i's market share; $I_{S2} = I_2 + \dfrac{I_3}{(1+r)^1} + \dfrac{I_4}{(1+r)^2}$, r: interest rate,
I_2: second advanced development cost, I_3: testing cost, I_4: launch investment cost;
c_{il}: unit correction variable cost $= c_i l; l \sim N(\mu_l, \xi_l^2)$

The profit function of Firm *i* by benchmark A in equation (5.6) is computed by an absolute fraction of all sales in the market, where the estimated market share ω represents the degree of dominance that Firm *i* has in the total product quantity within the particular market. Based on the possible factors that determine the estimated market share in Harper (2011), I define the estimated market share by the unit variable costs (c_i, c_j, and c_k) and the parameters of the (inverse) product differentiation (τ_j and τ_k) from two competitors, expressing the definition in equation (5.7) and Appendix A. As I assume that there are two competitors, the rivals' unit variable costs directly influence Firm *i*'s market share. The two parameters of the (inverse) product differentiation (τ_j and τ_k) consists of product functions and positions, Harper's (2011) comparative dominance of the developer's brand over competitors, comparative performance of the developer's product over competitors, and historical values for the developer's comparable products. If (τ_j or τ_k) = 0, then product *j* or *k* is independent of Firm *i*'s product. If (τ_j or τ_k) = 1, then product *j* or *k* can be viewed as a homogenous product to Firm *i*'s product, as shown in equation (5.7).

$$\omega = 1 - \frac{c_j^{'} \tau_j + c_k^{'} \tau_k}{c_{total}} \quad (5.7)$$

where $0 \le \tau_j, \tau_k \le 1; c_{total} = c_i + c_j + c_k$;

τ_j, τ_k : the degrees of (inverse) product differentiation of Firms *j*, *k*

Consequently, the profit function of Firm *i* by benchmark A at the gate of go-to-development in Fig. 5.2 can be calculated by moving equation (5.6) forward with two periods, as expressed in equation (5.8).

$$\begin{cases} \pi_{i00}^{\mathrm{A}} = -I + \dfrac{G_4\omega}{(1+r)^4}[-bQ^2 - c_iQ - c_{il}Q + \bar{a}_{00}Q] & \text{if } l > 0 \\ \pi_{i00}^{\mathrm{A}} = -I + \dfrac{G_4\omega}{(1+r)^4}[-bQ^2 - c_iQ + \bar{a}_{00}Q] & \text{if } l \le 0 \end{cases} \tag{5.8}$$

where $I = I_0 + \dfrac{I_1}{(1+r)^1} + \dfrac{I_{S2}}{(1+r)^2}$,

I_1 : first advanced development cost, I_0 : initial development cost

Under these settings in benchmark A, the profit of Firm *i* is based on its market share by overall product quantity in the target market. To earn the maximum overall profit, the industry chooses to produce the output that equals their average marginal cost to marginal revenue (Chevalier-Roignant & Trigeorgis, 2011). Therefore, the equilibrium quantity produced in the industry is shown in equation (5.9) and Appendix A.

$$Q = \frac{\bar{a}_{00} - \bar{c}}{2b} \tag{5.9}$$

where $\bar{c}$: average marginal cost $= \dfrac{c_i + c_j + c_k}{3}$

Finally, the resulting equilibrium profit of Firm *i* by benchmark A can be expressed as shown in equation (5.10) and Appendix A.

$$\begin{cases} \mathrm{NPV}_{i0} = -I + \dfrac{G_4\omega}{(1+r)^4}\dfrac{(\bar{a}_{00} - \bar{c})(\bar{a}_{00} + \bar{c} - 2c_i - 2c_{il})}{4b} & \text{if } l > 0 \\ \mathrm{NPV}_{i0} = -I + \dfrac{G_4\omega}{(1+r)^4}\dfrac{(\bar{a}_{00} - \bar{c})(\bar{a}_{00} + \bar{c} - 2c_i)}{4b} & \text{if } l \le 0 \end{cases} \tag{5.10}$$

5.2.2 Demand mean and variance update: Bayesian analysis

Both the new information about customer requirements and preferences and the new information about product performance are updated with statistical decision theory in the form of Bayesian analysis.

- *The update of customer requirements and preferences*

New information about customer requirements and preferences is updated in order to update the mean and variation of market demand at the first sub-gate of the development stages. Hence, suppose that the firms are uncertain about the true mean and true variance of customer requirements and preferences. As defined in section 5.2.1, customer requirements and preferences x follows a normal distribution with unknown mean μ_x ($\mu_x \in$ R) and unknown variance ξ_x^2 ($\xi_x > 0$). Since μ_x and ξ_x^2 are unknown, suppose further that the joint prior distribution of the mean and the variance is $f(\mu_x, \xi_x^2) = f_1(\mu_x | \xi_x^2) f_2(\xi_x^2)$, where $f_1(\mu_x | \xi_x^2)$ is a $N(\theta, \rho\xi_x^2)$ density ($\theta \in$ R, $\rho > 0$) and $f_2(\xi_x^2)$ is inverse gamma distributed $IG(\alpha,\beta)$ density ($\alpha > 0$, $\beta > 0$). According to Artmann's (2009) proof, therefore, customer requirements and preferences x at time 0, based on the prior information, is t distribution, as expressed in equation (5.11).

$$m(x) = St(x|\theta, \frac{\rho+1}{\alpha\beta}, 2\alpha) \quad (5.11)$$

with $E(x) = \theta$ and

$$Var(x) = Var(\mu_x) + E(\xi_x^2) = \frac{2\alpha\rho}{(2\alpha-2)\alpha\beta} + \frac{1}{\beta(\alpha-1)} = \frac{\rho+1}{(\alpha-1)\beta}$$

In order to determine the posterior predictive distribution of the customer requirements and preferences (x'), I need to first determine the joint posterior distribution of the unknown mean μ_x and variance ξ_x^2 based on sample observations.

As shown in Raiffa and Schlaifer (1961) and Artmann (2009), after the update with actual data z = $x_1,\ldots,x_{nx}$, which denotes a random sample from n_x independent observations of customer requirements and preferences, the joint posterior distribution of μ_x and ξ_x^2 given sample data $z = x_1,\ldots, x_{nx}$ is then expressed in equation (5.12).

$$f(\mu_x,\xi_x^2|z) = f_1(\mu_x|\xi_x^2,z)\,f_2(\xi_x^2|z) \tag{5.12}$$

$$\text{where } f_1(\mu_x|\xi_x^2,z) = N(\mu_x|\theta',\frac{\xi_x^2}{\rho^{-1}+n_x}) \text{ with } \theta' = \frac{\theta+n_x\rho\bar{x}}{n_x\rho+1}$$

$$f_2(\xi_x^2|z) = IG(\xi_x^2|\alpha+\frac{n_x}{2},\beta') \text{ with } \beta' = [\frac{1}{\beta}+\frac{1}{2}\sum_{i=1}^{n_x}(x_i-\bar{x})^2+\frac{n(\bar{x}-\theta)^2}{2(1+n_x\rho)}]^{-1}$$

According to Artmann (2009), while the determination of this conditional distribution is generally very difficult, it is much easier to estimate the key moments of the corresponding marginal distribution and then derive the key parameters of the conditional distribution, where the marginal probability density function of μ_x has the form of equation (5.13).

$$f(\mu_x) = St(\theta,\frac{\rho}{\alpha\beta},2\alpha) \tag{5.13}$$

$$\text{where } E(\mu_x) = \theta \text{ and } Var(\mu_x) = \frac{\rho}{(\alpha-1)\beta}$$

Hence, replacing the posterior parameter values of θ', ρ', α', and β' from equation (5.12), the posterior marginal distribution of μ_x and ξ_x^2 are t distribution and inverse gamma distribution in the form of equations (5.14) and (5.15), respectively.

$$f_1(\mu_x|z) = St(\mu_x|\theta',[(n_x+\frac{1}{\rho})(\alpha+\frac{n}{2})\beta']^{-1},2\alpha+n_x) \tag{5.14}$$

$$\text{with } E(\mu_x|z) = \theta' \text{ and } Var(\mu_x|z) = \frac{2\alpha+n_x}{(2\alpha+n_x-2)(\rho^{-1}+n_x)(\alpha+\frac{n_x}{2})\beta'}$$

$$f_2(\xi_x^2 | z) = IG(\xi_x^2 \left| \alpha + \frac{n_x}{2}, \beta^{'}) \right. \tag{5.15}$$

$$\text{with } E(\xi_x^2 | z) = \frac{1}{\beta^{'}(\alpha^{'} - 1)} \text{ and } Var(\xi_x^2 | z) = \frac{1}{\beta^{'2}(\alpha^{'} - 1)^2(\alpha^{'} - 2)}$$

With the update to the posterior marginal distribution of μ_x and ξ_x^2, given the actual sample data $z = x_1, x_2, \ldots, x_{nx}$, based on Artmann's (2009) proof, customer requirements and preferences x' is then t distributed with degree of freedom $2\alpha + n_x$ as expressed in equation (5.16).

$$m(x|z) = St(x \left| \theta^{'}, [\frac{(\rho^{-1} + n_x)(\alpha + \frac{n_x}{2})\beta^{'}}{\rho^{-1} + n_x + 1}]^{-1}, 2\alpha + n_x) \right. \tag{5.16}$$

with $E(x|z) = \theta^{'}$ and

$$Var(x|z) = Var(\mu_x | z) + E(\xi_x^2 | z)$$

$$= \frac{2\alpha + n_x}{(2\alpha + n_x - 2)(\rho^{-1} + n_x)(\alpha + \frac{n_x}{2})\beta^{'}} + \frac{1}{(\alpha + \frac{n_x}{2} - 1)\beta^{'}} = \frac{\rho^{-1} + n_x + 1}{(\alpha + \frac{n_x}{2} - 1)(\rho^{-1} + n_x)\beta^{'}}$$

As the number of degrees of freedom grows, the t-distribution approaches normal distribution. Hence, with the constant correlation coefficient γ, the percentage changes in the demand y from equation (5.2) can be updated as expressed in equation (5.17) and shown in Appendix A.

$$y^{'} = \gamma x^{'} + \varepsilon \approx N(\gamma \mu_x^{'} + \varepsilon, \gamma^2 \xi_x^{2'}) \tag{5.17}$$

where $y^{'}$: the updated percentage changes in the demand, $y^{'} \sim N(g^{'}, \sigma^{2'})$;
$x^{'}$: the updated customer requirements and preferences $\approx N(\mu_x^{'}, \xi_x^{2'})$ w/ $2\alpha + n_x > 30$

Therefore, as the expected yearly growth rate and the volatility of yearly growth rate are updated to g' and σ^{2}', the demand binomial lattice is re-structured after first period by recalculating the new parameters of the binomial lattice as shown in equation (5.18).

$$\cdot\ u^{'} = e^{\sigma^{'}\sqrt{\Delta t}}, d^{'} = 1/u^{'}$$

· The updated risk-neutral probability of an upward:

$$q_r^{'} = \frac{(1+r_f)-d^{'}}{u^{'}-d^{'}} \tag{5.18}$$

· The updated probability of an upward:

$$P^{'} = \frac{1}{2}+\frac{1}{2}\left(\frac{g^{'}}{\sigma^{'}}\right)\sqrt{\Delta t}$$

$$\text{where } g^{'} = \gamma\theta^{'}+\varepsilon \text{ and } \sigma^{2'} = \frac{\gamma^2(\rho^{-1}+n_x+1)}{(\alpha+\frac{n_x}{2}-1)(\rho^{-1}+n_x)\beta^{'}}$$

- *The update of product performance*

On the other hand, estimated product performance *s* is updated in order to diminish the variation in the technical risks of Firm *i* at the first sub-gate of the development stages. Hence, suppose the initial product technique has a specified value of mean, while Firm *i* is uncertain about the true variance of its product performance.

Given that product performance *s* (defined in section 5.2.1) follows a normal distribution with known mean μ_s ($\mu_s \in R$) and unknown variance ξ_s^2 ($\xi_s^2 > 0$), i.e., $f(s|\mu_s) = N(\mu_s, \xi_s^2)$, and since ξ_s^2 is unknown, suppose that the prior distribution of ξ_s^2, i.e., $g(\xi_s^2)$, is inverse gamma distributed, $IG(\alpha_s,\beta_s)$ ($\alpha_s,\beta_s > 0$). According to Artmann's (2009) proof, therefore, product performance at time 0, based on the prior information, is *t* distribution noted as $m(s) = St\ (s|\mu_s,(\alpha_s\beta_s)^{-1},2\alpha_s)$.

In order to determine the posterior predictive distribution of the product performance (*s*'), I need to first determine the posterior distribution of the unknown variance ξ_s^2 based on sample observations. As shown in Raiffa and Schlaifer (1961) and

Artmann (2009), after the update with actual data $z_s = s_1, \ldots, s_{ns}$, which denotes a random sample from n_s independent observations of product performance, the posterior distribution of ξ_s^2 is given by $g(\xi_s^2|z_s) = IG(\xi_s^2|\alpha_s', \beta_s')$. The values of α_s', β_s' are shown in equation (5.19).

$$\alpha_s' = \alpha_s + \frac{n_s}{2} \text{ and } \beta_s' = [\frac{1}{\beta_s} + \frac{1}{2}\sum_{i=1}^{n_s}(s_i - \mu_s)^2]^{-1} \tag{5.19}$$

n_s : number of the random samples of product performance

With the update to the posterior distribution of ξ_s^2, given the actual sample data $z_s = s_1, s_2, \ldots, s_{ns}$, based on Artmann (2009), the product performance s' is then t distributed, i.e., $m(s|z_s) = St(s|\mu_s, (\alpha_s'\beta_s')^{-1}, 2\alpha_s + n_s)$ with degree of freedom $2\alpha_s + n_s$. As the number of degrees of freedom grows, the t-distribution approaches normal distribution. As a result, with the update of customer requirements and preferences x and product performance s, the unit additional correction cost of Firm i can be updated as $c_{il}' = c_i l'$ where $l' \sim N(\mu_x' - \mu_s, \xi_x^{2'} + \xi_s^{2'})$.

- *The second benchmark: the real-option valuation (benchmark B)*

The second benchmark (benchmark B), the real-option framework with Bayesian analysis, is used to consider the actions of go/kill at the first sub-gate. Under these settings, the payoff functions of benchmark B at the second sub-gate can be written from equation (5.6) with the above new parameters as expressed in equation (5.20). Accordingly, the resulting equilibrium profit at the second sub-gate can be written as shown in equation (5.21).

$$\begin{cases} \tilde{\pi}_{i2}^{B'} = -I_{S2} + \frac{G_4^{'}\omega^{'}}{(1+r)^2}[-bQ^{2'} - c_i Q^{'} - c_{il}^{'} Q^{'} + \tilde{\bar{a}}_2^{'} Q^{'}] & \text{if } l^{'} > 0 \\ \tilde{\pi}_{i2}^{B'} = -I_{S2} + \frac{G_4^{'}\omega^{'}}{(1+r)^2}[-bQ^{2'} - c_i Q^{'} + \tilde{\bar{a}}_2^{'} Q^{'}] & \text{if } l^{'} \le 0 \end{cases} \tag{5.20}$$

$$\text{where B: benchmark B;} G_4^{'} = \frac{1+g_5^{'}}{1+r} + \frac{(1+g_5^{'})(1+g_6^{'})}{(1+r)^2} + ... + \frac{(1+g_5^{'})...(1+g_{N+4}^{'})}{(1+r)^N}$$

$$\begin{cases} \tilde{\pi}_{i2}^{B'} = -I_{S2} + \frac{G_4^{'}\omega^{'}}{(1+r)^2} \frac{(\tilde{\bar{a}}_2^{'} - \bar{c})(\tilde{\bar{a}}_2^{'} + \bar{c} - 2c_i - 2c_{il}^{'})}{4b} & \text{if } l^{'} > 0 \\ \tilde{\pi}_{i2}^{B'} = -I_{S2} + \frac{G_4^{'}\omega^{'}}{(1+r)^2} \frac{(\tilde{\bar{a}}_2^{'} - \bar{c})(\tilde{\bar{a}}_2^{'} + \bar{c} - 2c_i)}{4b} & \text{if } l^{'} \le 0 \end{cases} \tag{5.21}$$

Finally, with the new information updated by Bayesian analysis, the strategic net present value (SNPV) of benchmark B at the first sub-gates of up and down statuses can be written as shown in equation (5.22).

$$\begin{cases} \text{SNPV}_{i11}^{B'} = \tilde{\pi}_{i11}^{B'} = \frac{q_r^{'} \max[0, \tilde{\pi}_{i22}^{B'}] + (1-q_r^{'}) \max[0, \tilde{\pi}_{i21}^{B'}]}{1+r_f} \\ \text{SNPV}_{i10}^{B'} = \tilde{\pi}_{i10}^{B'} = \frac{q_r^{'} \max[0, \tilde{\pi}_{i21}^{B'}] + (1-q_r^{'}) \max[0, \tilde{\pi}_{i20}^{B'}]}{1+r_f} \end{cases} \tag{5.22}$$

5.2.3 Discrete option-game valuation

At the starting point (the gate of go-to-development), I consider managerial flexibility with two latent rivals with certain degrees of (inverse) product differentiation in the following periods of the two sub-gates, representing two potential competitors' involvements in the target market. The parameters τ_j, τ_k have been defined as the degrees of (inverse) product differentiation between Firm *i* and the two latent competitors, Firms *j* and *k*. From the first-order conditions of the consumer problem in the linear demand model (Motta, 2004), a linear (inverse) demand function with parameters τ_j, τ_k can be written as shown in in equation (5.23). If τ_j or τ_k = 0, then q_i and (q_j or q_k) are independent; the products have maximum differentiation. If $0 < \tau_j, \tau_k < 1$, then q_i and (q_j or q_k) are substitutes. If τ_j or τ_k = 1, then q_i and (q_j or q_k) are perfect substitutes (homogenous products).

$$\tilde{p}_4 = \tilde{\alpha}_4 - bq_i - b(\tau_j q_j + \tau_k q_k) \tag{5.23}$$

$$\text{where } \tilde{\alpha}_4 > c_i, c_j, c_k; c_i, c_j, c_k : \text{unit variable costs of Firms } i,\ j, \text{ and } k$$

Suppose that these three firms face the same interest rate r and risk free rate r_f. Consider that the three firms compete in quantities after product launch (i.e., Cournot competition), choosing q_i, q_j, and q_k so as to maximize their profits. The profit function of Firm i at the second sub-gate can be expressed as shown in equation (5.24) and Appendix A.

$$\begin{cases} \tilde{\pi}_{i2}^{\mathrm{C}} = -I_{S2} + \dfrac{G_4}{(1+r)^2}[-bq_i^2 + (\tilde{\tilde{\alpha}}_2 - c_i(1+l)]q_i - b\tau_j q_j - b\tau_k q_k\} & \text{if } l > 0 \\ \tilde{\pi}_{i2}^{\mathrm{C}} = -I_{S2} + \dfrac{G_4}{(1+r)^2}[-bq_i^2 + (\tilde{\tilde{\alpha}}_2 - c_i)q_i - b\tau_j q_j - b\tau_k q_k] & \text{if } l \le 0 \end{cases} \tag{5.24}$$

$$\text{where C} : \text{Cournot competition}$$

By substituting the three reaction functions, Firm i's equilibrium quantity with the two competitors can be written as shown in equation (5.25) (provided in Appendix A). Hence, Firm i's resulting profit with two competitors at the second sub-gate is derived as shown in Appendix A and equation (5.26).

$$\begin{cases} q_i^{\mathrm{C}} = \dfrac{\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k}{4b} & \text{if } l > 0 \\ q_i^{\mathrm{C}} = \dfrac{\tilde{\tilde{a}}_2 - 3c_i + c_j + c_k}{4b} & \text{if } l \le 0 \end{cases} \tag{5.25}$$

$$\begin{cases} \tilde{\pi}_{i2}^{\mathrm{C}} = -I_{S2} + \dfrac{G_4}{(1+r)^2} \dfrac{[\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k]^2}{16b} & \text{if } l > 0 \\ \tilde{\pi}_{i2}^{\mathrm{C}} = -I_{S2} + \dfrac{G_4}{(1+r)^2} \dfrac{[\tilde{\tilde{a}}_2 - 3c_i + c_j + c_k]^2}{16b} & \text{if } l \leq 0 \end{cases} \tag{5.26}$$

On the other hand, if Firm *i* has a monopoly, the linear (inverse) demand function from equation (5.23) is rewritten as $\tilde{p}_4 = \tilde{a}_4 - bq_i$. Hence, based on Chevalier-Roignant and Trigeorgis (2011), Firm *i*'s equilibrium quantity and profit in monopoly at the second sub-gate can be expressed as shown in equations (5.27) and (5.28), respectively, where M is the symbol of monopoly.

$$q_i^{\mathrm{M}} = \frac{\tilde{\tilde{a}}_2 - c_i}{2b} \tag{5.27}$$

$$\tilde{\pi}_{i2}^{\mathrm{M}} = -I_{S2} + \frac{G_4}{(1+r)^2} \left[\frac{(\tilde{\tilde{a}}_2 - c_i)^2}{4b}\right] \tag{5.28}$$

Alternatively, if Firm *i* competes with either Firm *j* or *k* (one player does not invest), then Firm *i*'s equilibrium quantity and profit at the second sub-gate will be defined by the duopoly game (as shown in chapter 4). As demonstrated in chapter 4, the 2-player payoff matrix at the second sub-gate and their resulting equilibrium outcome can be written as shown in equation (5.29).

$$(\tilde{X}_{h2}^{*}, \tilde{X}_{h'2}^{*}) = \begin{bmatrix} (\tilde{\pi}_{h2}^{\mathrm{C}}, \tilde{\pi}_{h'2}^{\mathrm{C}}) & (\tilde{\pi}_{h2}^{\mathrm{M}}, 0) \\ (0, \tilde{\pi}_{h'2}^{\mathrm{M}}) & (0, 0) \end{bmatrix} \tag{5.29}$$

where $h, h' = i, j, k,\ h \neq h'$;

$$\tilde{\pi}_{h2}^{\mathrm{C}} = -I_{S2} + \frac{G_4}{(1+r)^2} \frac{[\tilde{\tilde{a}}_2 - 2c_h(1+l) + c_{h'}]^2}{9b}$$

Therefore, the resulting equilibrium outcome in each status at the second sub-gate can be obtained from the 3-player payoff matrix by applying the Nash equilibrium concept, in which the 3-player competitive outcomes in each status are noted as $(\tilde{X}^*_{i2}, \tilde{X}^*_{j2}, \tilde{X}^*_{k2})$. The 3-player payoff matrices and their resulting equilibrium outcomes at the second sub-gate can be written as shown in equation (5.30). Accordingly, the strategic value of the option-game at the first sub-gate of Firm *i* can be obtained by the Nash equilibrium with the best response analysis, as expressed in equation (5.31), where OG is the symbol of option-game.

$$(\tilde{X}^*_{i2}, \tilde{X}^*_{j2}, \tilde{X}^*_{k2}) = \begin{bmatrix} (\tilde{\pi}^{\mathrm{C}}_{i2}, \tilde{\pi}^{\mathrm{C}}_{j2}, \tilde{\pi}^{\mathrm{C}}_{k2}) & (\tilde{\pi}^{\mathrm{C}}_{i2}, 0, \tilde{\pi}^{\mathrm{C}}_{k2}) & (\tilde{\pi}^{\mathrm{C}}_{i2}, \tilde{\pi}^{\mathrm{C}}_{j2}, 0) & (\tilde{\pi}^{\mathrm{M}}_{i2}, 0, 0) \\ (0, \tilde{\pi}^{\mathrm{C}}_{j2}, \tilde{\pi}^{\mathrm{C}}_{k2}) & (0, 0, \tilde{\pi}^{\mathrm{M}}_{k2}) & (0, \tilde{\pi}^{\mathrm{M}}_{j2}, 0) & (0,0,0) \end{bmatrix} \quad (5.30)$$

$$\begin{cases} \mathrm{SNPV}^{\mathrm{OG}}_{i11} = \tilde{X}^*_{i11} + I_1 \\ \mathrm{SNPV}^{\mathrm{OG}}_{i10} = \tilde{X}^*_{i10} + I_1 \end{cases} \quad (5.31)$$

$$\text{where } (\tilde{X}^*_{i1}, \tilde{X}^*_{j1}, \tilde{X}^*_{k1}) = \begin{bmatrix} (\tilde{\pi}^{\mathrm{C}}_{i1}, \tilde{\pi}^{\mathrm{C}}_{j1}, \tilde{\pi}^{\mathrm{C}}_{k1}) & (\tilde{\pi}^{\mathrm{C}}_{i1}, 0, \tilde{\pi}^{\mathrm{C}}_{k1}) & (\tilde{\pi}^{\mathrm{C}}_{i1}, \tilde{\pi}^{\mathrm{C}}_{j1}, 0) & (\tilde{\pi}^{\mathrm{M}}_{i1}, 0, 0) \\ (0, \tilde{\pi}^{\mathrm{C}}_{j1}, \tilde{\pi}^{\mathrm{C}}_{k1}) & (0, 0, \tilde{\pi}^{\mathrm{M}}_{k1}) & (0, \tilde{\pi}^{\mathrm{M}}_{j1}, 0) & (0,0,0) \end{bmatrix}$$

$$\tilde{\pi}^{\mathrm{C}}_{i11} = \frac{q_r(\tilde{X}^*_{i22}) + (1-q_r)(\tilde{X}^*_{i21})}{1+r_f} - I_1; \tilde{\pi}^{\mathrm{C}}_{i10} = \frac{q_r(\tilde{X}^*_{i21}) + (1-q_r)(\tilde{X}^*_{i20})}{1+r_f} - I_1$$

Finally, the strategic value of the option-game approach at the gate of go-to-development of Firm *i* can be obtained from the 3-player payoff matrix by the Nash equilibrium with the best response analysis, as expressed in equation (5.32).

$$\mathrm{SNPV}^{\mathrm{OG}}_{i00} = X^*_{i00} + I_0 \quad (5.32)$$

where $(X^*_{i00}, X^*_{j00}, X^*_{k00}) = \begin{bmatrix} (\pi^{C}_{i00}, \pi^{C}_{j00}, \pi^{C}_{k00}) & (\pi^{C}_{i00}, 0, \pi^{C}_{k00}) & (\pi^{C}_{i00}, \pi^{C}_{j00}, 0) & (\pi^{M}_{i00}, 0, 0) \\ (0, \pi^{C}_{j00}, \pi^{C}_{k00}) & (0, 0, \pi^{M}_{k00}) & (0, \pi^{M}_{j00}, 0) & (0,0,0) \end{bmatrix}$

$$\pi^{C}_{i00} = \frac{q_r(\tilde{X}^*_{i11}) + (1-q_r)(\tilde{X}^*_{i10})}{1+r_f} - I_0$$

As time goes to the first sub-gate, suppose that the customer requirements and preferences have been updated with collected data (section 5.2.2). The new strategic value of the option-game approach at the first sub-gate of Firm *i* can then be obtained from the updated 3-player payoff matrices by the Nash equilibrium with the best response analysis as shown in equation (5.33).

$$\begin{cases} \text{SNPV}^{\text{OG}'}_{i11} = \tilde{\pi}^{\text{OG}'}_{i11} = \tilde{X}^{*'}_{i11} + I_1 \\ \text{SNPV}^{\text{OG}'}_{i10} = \tilde{\pi}^{\text{OG}'}_{i10} = \tilde{X}^{*'}_{i10} + I_1 \end{cases} \tag{5.33}$$

where $\tilde{X}^{*'}_{i2}, \tilde{X}^{*'}_{i1}$: the updated competitive outcomes of Firm *i* at time 2 and 1;

$$(\tilde{X}^{*'}_{i1}, \tilde{X}^{*'}_{j1}, \tilde{X}^{*'}_{k1}) = \begin{bmatrix} (\tilde{\pi}^{C'}_{i1}, \tilde{\pi}^{C'}_{j1}, \tilde{\pi}^{C'}_{k1}) & (\tilde{\pi}^{C'}_{i1}, 0, \tilde{\pi}^{C'}_{k1}) & (\tilde{\pi}^{C'}_{i1}, \tilde{\pi}^{C'}_{j1}, 0) & (\tilde{\pi}^{M'}_{i1}, 0, 0) \\ (0, \tilde{\pi}^{C'}_{j1}, \tilde{\pi}^{C'}_{k1}) & (0, 0, \tilde{\pi}^{M'}_{k1}) & (0, \tilde{\pi}^{M'}_{j1}, 0) & (0,0,0) \end{bmatrix};$$

$$\tilde{\pi}^{C'}_{i11} = \frac{q^{'}_r(\tilde{X}^{*'}_{i22}) + (1-q^{'}_r)(\tilde{X}^{*'}_{i21})}{1+r_f} - I_1 \; ; \; \tilde{\pi}^{C'}_{i10} = \frac{q^{'}_r(\tilde{X}^{*'}_{i21}) + (1-q^{'}_r)(\tilde{X}^{*'}_{i20})}{1+r_f} - I_1$$

5.3 Case Study

In this section, I demonstrate a numerical example by analyzing and comparing a project. At the starting point (the gate of go-to-development), Firm *i* considers managerial flexibility with two latent rivals with certain degrees of (inverse) product differentiation τ_j, τ_k at the future sub-gates of the development stages. In section 5.3.1, I compare this approach to benchmark A, the NPV method, which is the most widely used conventional financial method in gate-criterion, and observe the strategic decisions and present payoff values resulting from both approaches at the starting point. Section 5.3.2 illustrates the update of customer requirements and preferences with collected sample data, accordingly updating the demand when the market demand follows a binomial lattice with a product life cycle. In addition, I compute the update of product performance with collected sample data to diminish the variance of technical risk of Firm *i*. I compare my approach to benchmark B, the real-option approach with Bayesian analysis, and observe the strategic decisions and payoffs at the first sub-gate of the development stages resulting from both approaches. Finally, I summarize the case study in section 5.3.3.

Suppose that Firm *i* is assessing an individual project in the NPD process and that all the individual projects have been screened and preliminarily investigated through the strategic buckets approach in the early stages. Some portions of the buckets are the projects with the specific dimensions of uncertain market, high technical risks, short life cycles, two potential competitors, and rapidly changing environments. Firm *i* will need to evaluate these categories of projects at the gate of go-to-development and the sub-gates during the development stages as shown in Fig. 5.4. The questions for Firm *i* are how to evaluate this project at these gate-decisions when there might be two latent competitive products at the next decision point, and, should this project proceed to the next stage, how different approaches change the decisions at the sub-gates when additional sample information is collected and when the technical risk of Firm *i* is considered.

Fig. 5.4 shows this project's current and remaining gates and stages in the NPD process in the following sequence: the gate of go-to-development, the first and second sub-gates of development, the stage of testing and validation, and the stage of production and launch, with the corresponding costs of an initial development cost (I_0 = \$4,500), the first advanced development cost (I_{S1} = \$6,000), the second advanced development cost (I_a), the testing cost (I_b), and the launch investment cost (I_c). Assume that the sum of the value for the last three fixed costs is given at the second sub-gate as I_{S2} = \$25,000 (assuming the rivals have the same fixed costs). Firm *i* and two rivals (Firms *j* and *k*) may share an option to invest and manage the similar NPD projects with initial parameters of the (inverse) product differentiation $\tau_j = 0.95$, $\tau_k = 0.9$. The option will expire in six months ($T = 2/4$), which is at the second sub-gate of the development stages. The project will operate for a finite service life of $N = 4$ years after product launch with the same interest rate $r = 12\%$ and risk free rate $r_f = 5\%$.

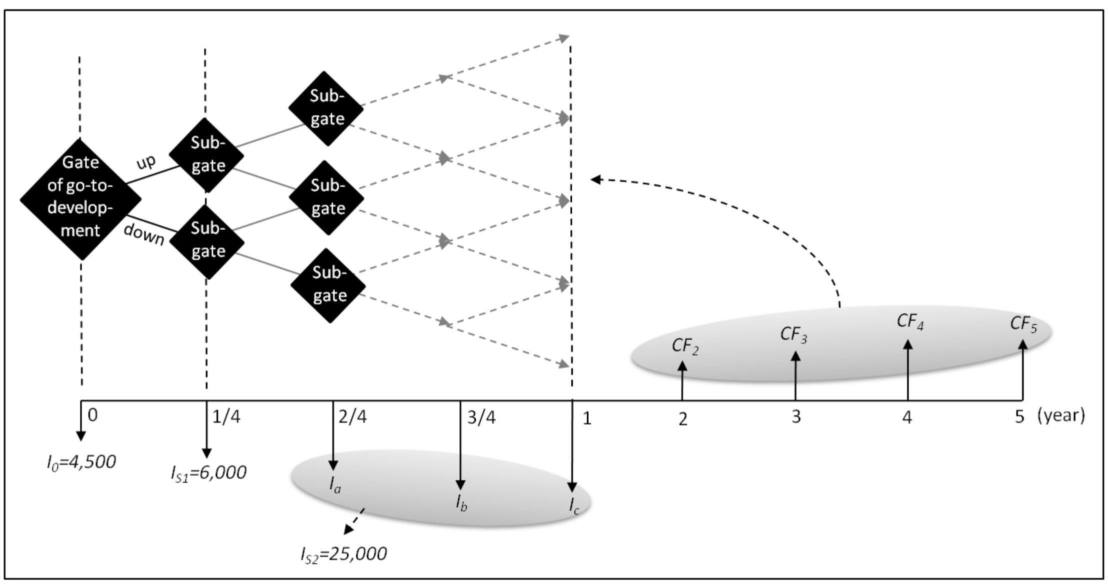

Fig. 5.4 Cash flows in this numerical example (from Fig. 4.6)

Based on the initial market research and past experience, assume that customer requirements and preferences *x* is normally distributed with mean μ_x = 2% and standard deviation ξ_x = 62.5%. The current demand is given as Q_{00} = 750. With the estimated correlation coefficient γ = 0.8 and ε = 6.4%, an expected yearly growth rate of g = 8% in demand and the expected standard deviation of σ = 50% are obtained. Firm i's unit variable cost is c_i = \$10 and Firm j's and k's unit variable costs are c_j = \$12 and c_k = \$13, respectively. The product performance s of Firm i is normally distributed with mean μ_s = 0 and standard deviation ξ_s = 45%. Hence, the product correction distribution l is normally distributed with computed mean μ_l = 2% and standard deviation ξ_l = 77.01%. The current (inverse) demand function is given as $p_0 = 68 - 0.05Q$.

5.3.1 Strategic decisions at the starting point (the gate of go-to-development)

With the above information (g = 8%, σ = 50%, r_f = 5%, T = 2/4, Δt = 1/4), I can calculate the parameters of the binomial lattice from equation (5.1) and obtain the following: u = 1.2840, d = 0.7788, q_r = 0.5368, 1-q_r = 0.4632, P = 0.54, and 1-P = 0.46.

Appendix B shows the details of the calculations and Table 5.1 summarizes the current payoffs at the starting point (the gate of go-to-development). Based on the expected value of product correction distribution, while the NPV method suggests the action of "kill" with a negative payoff value of \$135.05, the option-game approach instead obtains a positive payoff value of \$8,918.17. Since the initial development cost is \$4,500, the option-game approach will suggest an opposite action of "go."

As the product correction distribution l is normally distributed with the computed mean μ_l = 2% and standard deviation ξ_l = 77.01%, the strategic decisions of Firm i can be obtained with the x-axial of $\mu_l \pm 3\xi_l$ as shown in Fig. 5.5. If the product correction is more than one standard deviation, the correction cost for the project of Firm i is too high, and the option-game approach will suggest that Firm *i* kill the project. Otherwise, the project will initiate an action of "go" via the option-game approach.

Table 5.1 Current payoffs (gate of go-to-development) of Firm *i* by benchmark A and my model

	benchmark A: NPV method	**OG: Option-game**
Current payoff π	$\text{NPV}_{i00} = -\$135.05$	$\text{SNPV}_{i00}^{\text{OG}} = \$8,918.17$
Action taken	kill	go

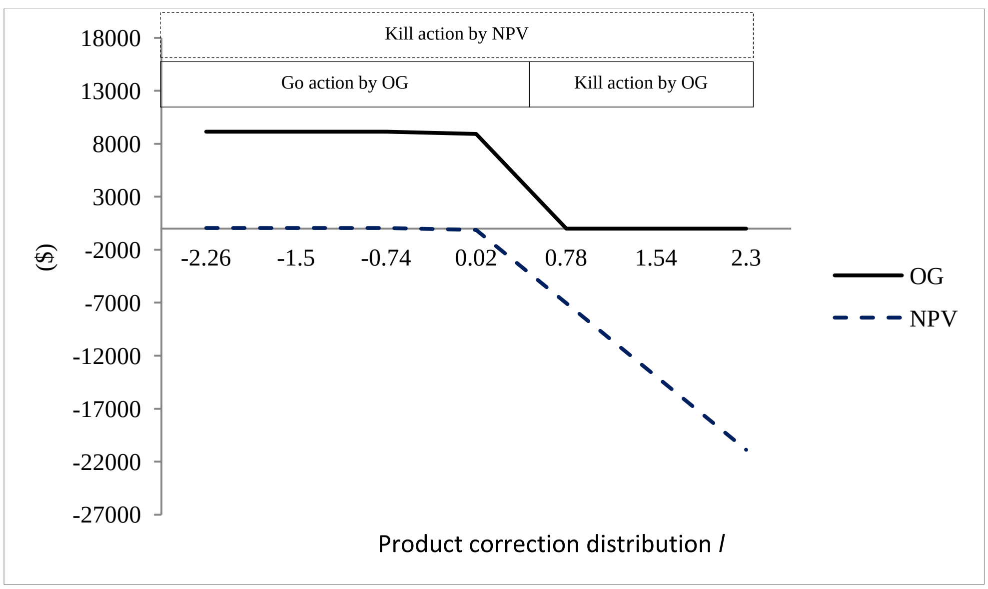

Fig. 5.5 The strategic decisions of Firm *i* in the distribution of product correction at time 0

5.3.2 Strategic decisions at the sub-gates with Bayesian analysis

Suppose that if the project has taken the action of "go" at the gate of go-to-development, the developer will collect actual samples for the customer requirements and preferences. Suppose the firms have some uncertainty about both the true mean and the true variance of customer requirements and preferences *x* prior to starting a development project in this market. The customer requirements and preferences are normally distributed with the prior mean following a normal and prior variance following an inverse gamma distribution. The estimated mean and variance of the two conjugate prior distributions of customer requirements and preferences *x* are summarized in Table 5.2.

Table 5.2 Estimated moments of prior distribution of customer requirements and preferences

Unknown parameter	**Moment**	**Value**
Mean μ_x	$E(\mu_x)$	0.0200
	$Var(\mu_x)$	0.1953
Variance ξ_x^2	$E(\xi_x^2)$	0.1953
	$Var(\xi_x^2)$	0.0214

Assume now that the firms conduct an additional market study to update the initial estimates. Thus, the marketing department interviewed $n_x = 6$ potential key customers and experts on the product. The results of the study reveal that on average, the samples show $\bar{x} = 0.05$ with $\sum_{i=1}^{6}(x_i - \bar{x})^2 = 0.125$. Hence, the values of the corresponding prior and posterior parameters are calculated in Appendix B. The prior and posterior distributions of customer requirements and preferences *x* are shown in Fig. 5.6.

Suppose further that the product technique of Firm *i* has the known mean $\mu_s = 0$, but the variance of product performance ξ_s is unknown. The parameters of prior distribution are given in Table 5.3.

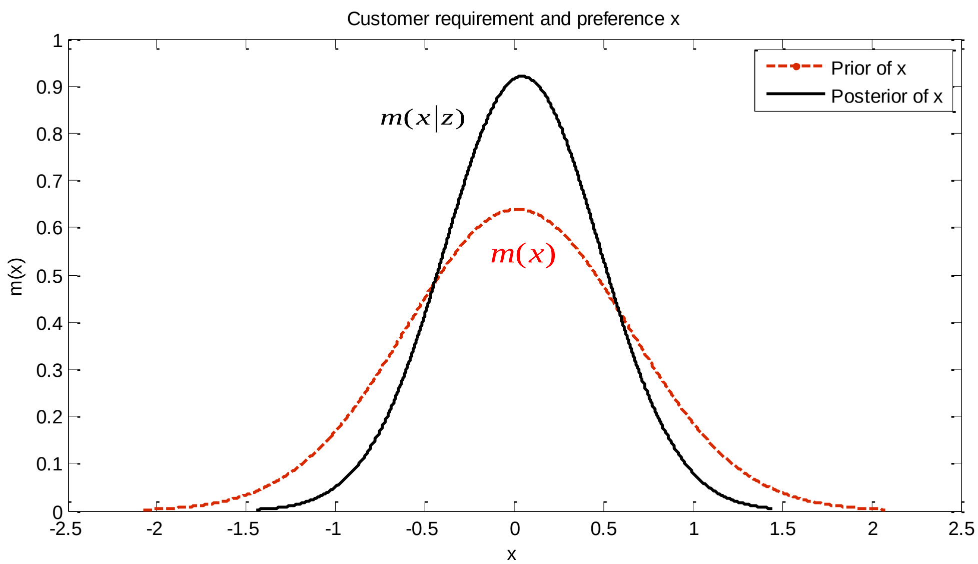

Fig. 5.6 Prior and posterior distributions of customer requirements and preferences *x*

Table 5.3 Parameters of prior distribution of product performance *s*

Parameter	Value
α_s	15.0025
β_s	0.3527
μ_s	0.0000

Suppose that Firm *i* makes sample inspections with n_s = 8 random samples in the products. The results show the samples with a spread of $\sum_{i=1}^{8}(s_i - 0)^2 = 0.125$. Appendix B shows the details of calculations for Bayesian analysis, and Table 5.4 summaries the parameters of posterior distribution. The posterior product performance is then *t* distribution, i.e., $m(s|z_s) = St(s|0,0.1525,38.005)$ with an expected value of $E(s|z_s) = 0$ and the variance of $Var(s|z_s) = 0.161$. Fig. 5.7 shows prior and posterior density distribution and Appendix B provides density distributions for mean and variance of product performance.

Table 5.4 Parameters of posterior distribution of product performance

Parameter	Value
α_s'	19.0025
β_s'	0.3450
ξ_s'	0.4012

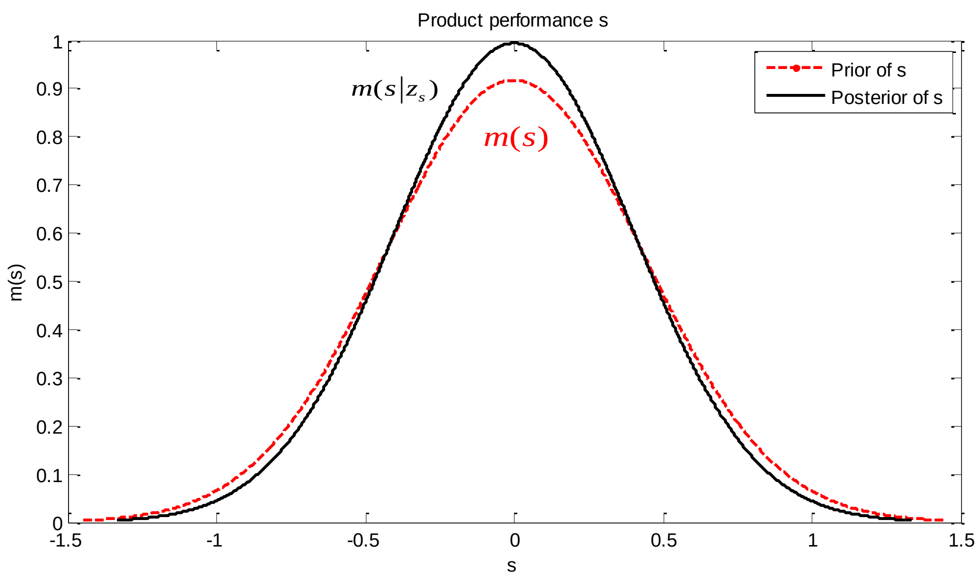

Fig. 5.7 Prior and posterior distributions of product performance *s*

In addition, parameters of the (inverse) product differentiation are updated and given as τ_j' = 1, τ_k' = 0.9. Therefore, with the updated information (σ' = 34.72%), I can also update the parameters of the binomial lattice from equation (5.18) and obtain the following: *u*' = 1.1896, *d*' = 0.8406, q_r' = 0.6, 1-q_r' = 0.4, *P*' = 0.5724, and 1-*P*' = 0.4276. The binomial tree in demand at launch stage (at time 1 in Fig. 5.4) can be described as a lognormal distribution. Based on Park (2011), I can determine the mean and variance of the demand distribution at t = 1. Hence, the posterior demand is lognormal distribution with an expected value of $E(Q_1|z)$ = 829.38 and the variance of

$Var(Q_1|z)$ = 88,125.5. Fig. 5.8 shows prior and posterior density distribution and Appendix B shows density distributions for mean and variance for this example.

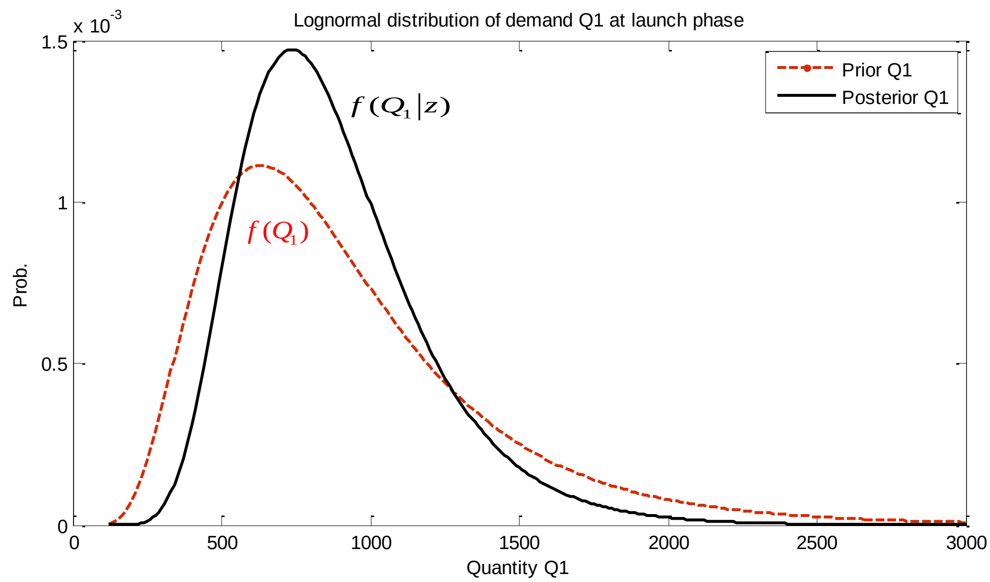

Fig. 5.8 Prior and posterior of demand at product launch phase Q_1 (at time 1)

Appendix B shows the details of calculations after information is updated and Table 5.5 summarizes the SNPVs at the first sub-gates of development. Based on the expected value of product correction distribution for the sub-gate at the status of "11," the SNPVs by benchmark B and my approach are \$32,798.69 and \$12,547.47, respectively. Since the first advanced development cost I_{S1} is \$6,000, benchmark B will suggest the action of "go." However, the option-game approach will take the action of "go/kill," since these three firms face a Prisoner's Dilemma, meaning that the maximum payoff for each firm is obtained only when two of them invest and one of them does not. Hence, at this point, Firm *i* takes this project under further investigation and may re-evaluate it later by carefully observing its rivals' actions, meanwhile looking for possibilities to lower costs.

For the sub-gate at the status of "10," benchmark B suggests an action of "kill." On the contrary, the option-game approach suggests the opposite action of "go." Since Firm *i* has the cost advantage compared to Firms *j* and *k*, Firm *i* may take the monopolistic profit when the demand is low.

Table 5.5 The SNPVs (first sub-gate of development) of Firm *i* by benchmark B and my approach after Bayesian analysis

	benchmark B: Real-option	**OG: Option-game**
Up status payoff π	$SNPV_{i11}^{B'} = \$32,798.69$	$SNPV_{i11}^{OG'} = \$12,547.47$
Action taken	go	go/kill
Down status payoff π	$SNPV_{i10}^{B'} = \$4,887.45$	$SNPV_{i10}^{OG'} = \$6,574.79$
Action taken	kill	go

As the updated product correction distribution *l'* is normally distributed with the computed mean μ_l' = 4.57% and standard deviation ξ_l' = 59.1%, the strategic decisions of up and down statuses at the first sub-gate of development of Firm *i* can be obtained with the x-axial of $\mu_l' \pm 3\xi_l'$, as shown in Figs. 5.9 and 5.10. At the status of "11," benchmark B suggests the action of "go," regardless of the distribution of product correction. In contrast, the strategic decisions of the option-game approach will differ depending on the distribution of product correction. If the product correction is close to or more than one standard deviation, the correction cost for the project is too high, and the option-game approach will suggest that Firm *i* kill the project. Otherwise, the project will initiate the action of "go."

At the status of "10," benchmark B suggests the action of "kill," regardless of the distribution of product correction. In contrast, the strategic decisions of the option-game approach will differ based on the distribution of product correction. If the product correction is more than its expected value, the option-game approach will suggest that Firm *i* kill the project. Otherwise, the project will initiate the action of "go," meaning that Firm *i* may take the monopolistic profit when the demand is low, since Firm *i* has the cost advantage compared to Firms *j* and *k*.

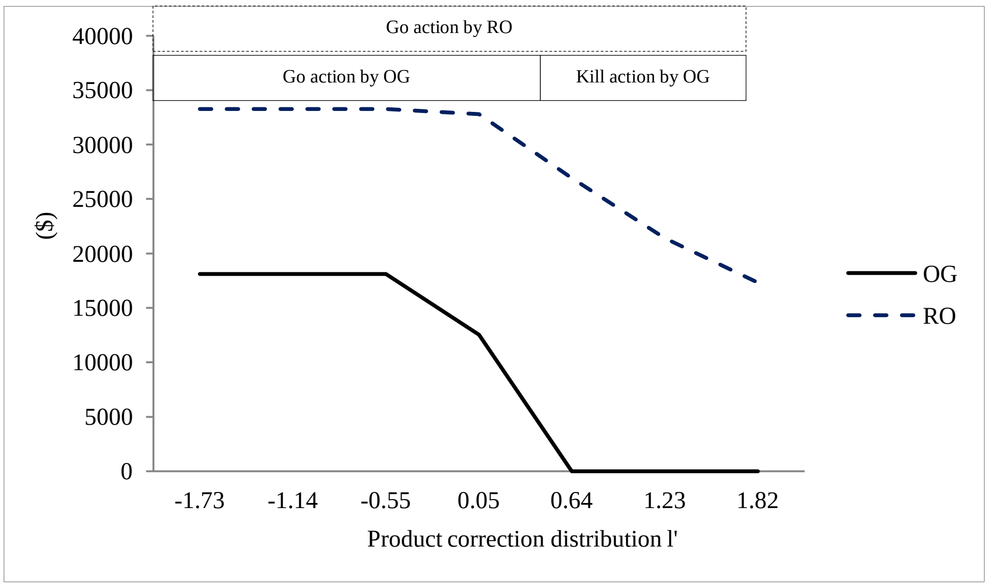

Fig. 5.9 The strategic decisions of Firm *i* in the distribution of product correction at the status of "11"

As a result, with the updated information with Bayesian analysis, the variability in customer requirements and preferences, market demands, and product performance is reduced. Thus, the payoff values at the sub-gates of development by both approaches become smaller compared to those without an information update. With additional information about the latent competing products with the parameters of the (inverse) product differentiation τ_j' = 1 and τ_k' = 0.9, I can observe that the rivals' actions influence Firm *i*'s strategic decisions.

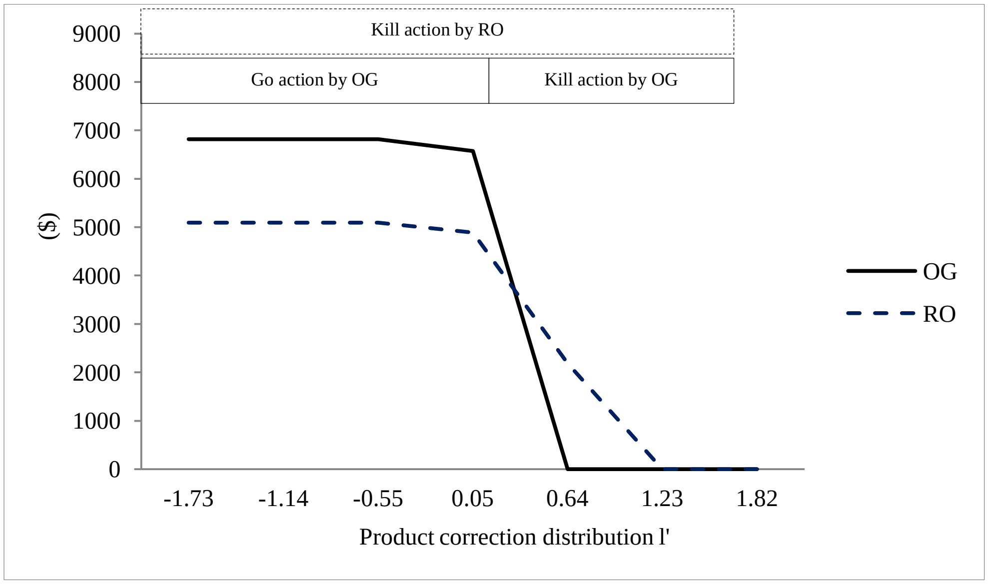

Fig. 5.10 The strategic decisions of Firm *i* in the distribution of product correction at the status of "10"

5.3.3 Interpretation of the results

The option-game framework with Bayesian analysis is demonstrated as a criterion at the gate of go-to-development and sub-gates of the development stages in the NPD process. First of all, I evaluate a project at the starting point (the gate of go-to-development). Benchmark A, the NPV method, assesses a project based on the assumption that decisions will not change in the future if the project is undertaken. In contrast, the option-game approach not only evaluates managerial flexibility but also considers two potential competitors' actions in the future.

When a project at the gate of go-to-development is allowed to proceed, additional market research may be needed to update information about customer requirements and preferences. As customer requirements and preferences are an important indicator for estimating the target market, suppose that the mean and variance are unknown. Using actual collected samples, customer requirements and preferences are updated by Bayesian analysis (Fig. 5.6). Accordingly, the mean and volatility of the yearly growth rate in the demand and the parameters of the demand binomial lattice are successively updated. Hence, the structure of demand binomial lattice is re-calculated, reducing variability compared to the initial estimator (Fig. 5.8). On the other hand, suppose that the product technique of Firm *i* has a known mean and unknown variance. Using actual collected samples, product performance is also updated by Bayesian analysis (Fig. 5.7).

The updated demand lattice is done by the first sub-gate of development. As time goes to the first sub-gate decision point, the demand either goes up or down. Hence, the payoff value at the up sub-gate of development is reduced compared to the value without an information update. Until the first sub-gate, new information about the two potential rivals' products and their parameters of (inverse) product differentiations can be updated. By considering these updated factors, the SNPVs of benchmark B and the option-game approach can be recalculated (Table 5.5). In addition, by considering product correction distribution, the strategic decisions of Firm *i* may be influenced by the changes of the corresponding correction costs (Figs. 5.5, 5.9, and 5.10). This case study shows that the option-game approach not only evaluates managerial flexibility in a project at the gate of go-to-development, but also provides a rigorous evaluation method at the first sub-gate of development after updating the information about demand and the product performance of Firm *i* by Bayesian analysis. As a case study cannot generalize the results, I further discuss the results in the next section.

5.4 Model Properties

Some model properties have been analyzed and discussed in chapter 4 and section 5.3. I verify the value of managerial flexibility in a project by using the strategic present value of the option-game approach to incorporate potential flexibility, a factor which benchmark A (the NPV method) does not consider. In chapter 4, I use the option premium to represent the option value of the option-game approach in assessing an individual project at the decision points during the development stages in the NPD process. In addition, in chapter 4, I validate the SNPVs given by benchmark B and my approach at the first sub-gate of the development stages after the new information is updated by Bayesian analysis. The analysis illustrates that when a project of Firm *i* is not a monopolistic product, benchmark B may overestimate or underestimate the profit functions, which are based on the relationships between the market-clearing price and unit variable costs. It also demonstrates that benchmark B is not capable of depicting the outcomes of strategic interactions between each firm and the other firms in the industry.

Moreover, the value of information in the option-game approach is demonstrated in chapter 4 by the project value of the optimal managerial response to the posterior information, deducing the project value as prior managerial policy. Furthermore, the distribution of product correction *l* directly influences the unit additional correction cost of Firm *i*. In section 5.3, I observe how the product correction distribution *l* affects NPV and SNPVs, as shown in Figs. 5.5, 5.9, and 5.10. When the product correction is less than or equal to zero, the product technique of Firm *i* meets customer requirements; hence, Firm *i* does not spend any additional correction costs for its product development. Otherwise, Firm *i* may have a higher additional correction cost, leading to lower values of

NPV or SNPVs. In the following section, I mainly focus on the strategic decisions at the first sub-gate of development of Firm *i* by benchmark B and the option-game approach in the 3-player competition.

5.4.1 Strategic decisions at the first sub-gate of development

To further analyze the strategic decisions of Firm *i*, I consider the changes of these five parameters simultaneously: (1) the expected standard deviation of demand σ at three levels (low = 0.25, medium = 0.45, and high = 0.75), (2) the two parameters of the (inverse) product differentiation τ_j and τ_k at two levels of each (low = 0.25 and high = 1), and (3) the two ratios of unit costs β_{vc1} and β_{vc2} at two levels of each (low = 0.5 and high = 1.5), where $\beta_{vc1} = c_j / c_i, \beta_{vc2} = c_k / c_i$. Hence, there are 48 combinations at each status of the first sub-gate.

However, except for the above parameters, the other settings for both competitors are identical. Hence, the 48 combinations can be reduced because of the duplicated settings. For example, the setting of $\tau_j = 1, \beta_{vc1} = 0.5, \tau_k = 0.25, \beta_{vc2} = 1.5,$ will get the same result as the setting of $\tau_j = 0.25, \beta_{vc1} = 1.5, \tau_k = 1, \beta_{vc2} = 0.5.$ From Firm *i*'s point of view, these two settings represent the same situation: one competitor has a high (inverse) product differentiation but a low unit cost, while the other has a low (inverse) product differentiation but a high unit cost. Therefore, the combinations can be reduced to 30 at each status. All other parameters are set as the defaults from previous sections, and all the analyses are on the side of Firm *i*. As a result, based on the expected value of the product correction, the strategic decisions of Firm *i* according to these settings are shown in Tables 5.6 and 5.7.

Table 5.6 Strategic decisions at the status of “11” of Firm *i* when σ = 0.25, 0.45, and 0.75

At the status of “11”					σ = 0.25		σ = 0.45		σ = 0.75	
	τ_j	β_{vc1}	τ_k	β_{vc2}	OG_{11}	RO_{11}	OG_{11}	RO_{11}	OG_{11}	RO_{11}
s1	L	L	L	L	Kill	Go	Kill	Go	Go	Go
s2	L	L	L	H	Kill	Go	Kill	Go	Go	Go
s3	L	L	H	L	Kill	Go	Kill	Go	Go	Go
s4	L	H	H	L	Kill	Go	Kill	Go	Go	Go
s5	H	L	H	L	Kill	Go	Kill	Go	Go	Go
s6	L	H	L	H	Kill	Go	Go	Go	Go	Go
s7	L	L	H	H	Go	Go	Go	Go	Go	Go
s8	L	H	H	H	Go	Go	Go	Go	Go	Go
s9	H	L	H	H	Go	Go	Go	Go	Go	Go
s10	H	H	H	H	Go	Go	Go	Go	Go	Go

Based on the results shown in Table 5.6, benchmark B suggests the action of “go” when the demand goes up to the status of “11” at the first sub-gate of development. However, the strategic decisions of the option-game approach will be influenced by the settings in the parameters of the two rivals’ unit variable costs, the (inverse) product differentiation, and the expected standard deviation in demand. If we take the bold set when σ = 0.25 in Table 5.6 as an example, Firm *i* will kill the project from series 1 to 6. When one of the competitors has the setting of a high unit variable cost and a high (inverse) product differentiation (from series 7 to 9), Firm *i* will take the action of “go” in the duopoly competition. When both competitors have the setting of high unit variable costs and high (inverse) product differentiations (series 10), Firm *i* will take the action of “go” and gain the monopolistic profit (Fig. 5.11). Increasing the expected standard deviation in demand creates more series of the settings to take the action of “go.” Until σ = 0.75, all ten of these series will take the action of “go” by the option-game approach (Table 5.6).

On the other hand, based on the results shown in Table 5.7, benchmark B suggests the action of "go" to more than half of the combinations when the demand goes down to the status of "10" at the first sub-gate of development. As the strategic decisions of the option-game approach are sensitive to the conditions of the considered parameters, most cases are killed by the option-game approach when the demand is low at the first sub-gate of development. However, when both competitors have the setting of high unit variable costs and high (inverse) product differentiations (series 10), Firm *i* will instead take the action of "go" and gain the monopolistic profit.

Table 5.7 Strategic decisions at the status of "10" of Firm *i* when σ = 0.25, 0.45, and 0.75

At the status of "10"					$\sigma = 0.25$		$\sigma = 0.45$		$\sigma = 0.75$	
	τ_j	β_{vc1}	τ_k	β_{vc2}	OG_{10}	RO_{10}	OG_{10}	RO_{10}	OG_{10}	RO_{10}
s1	L	L	L	L	Kill	Go	Kill	Go	Kill	Go
s2	L	L	L	H	Kill	Go	Kill	Go	Kill	Go
s3	L	L	H	L	Kill	Go	Kill	Go	Kill	Kill
s4	L	H	H	L	Kill	Go	Kill	Kill	Kill	Kill
s5	H	L	H	L	Kill	Kill	Kill	Kill	Kill	Kill
s6	L	H	L	H	Kill	Go	Kill	Go	Kill	Go
s7	L	L	H	H	Kill	Go	Kill	Go	Kill	Go
s8	L	H	H	H	Kill	Go	Kill	Go	Kill	Kill
s9	H	L	H	H	Kill	Kill	Kill	Kill	Kill	Kill
s10	H	H	H	H	Go	Go	Go	Kill	Go	Kill

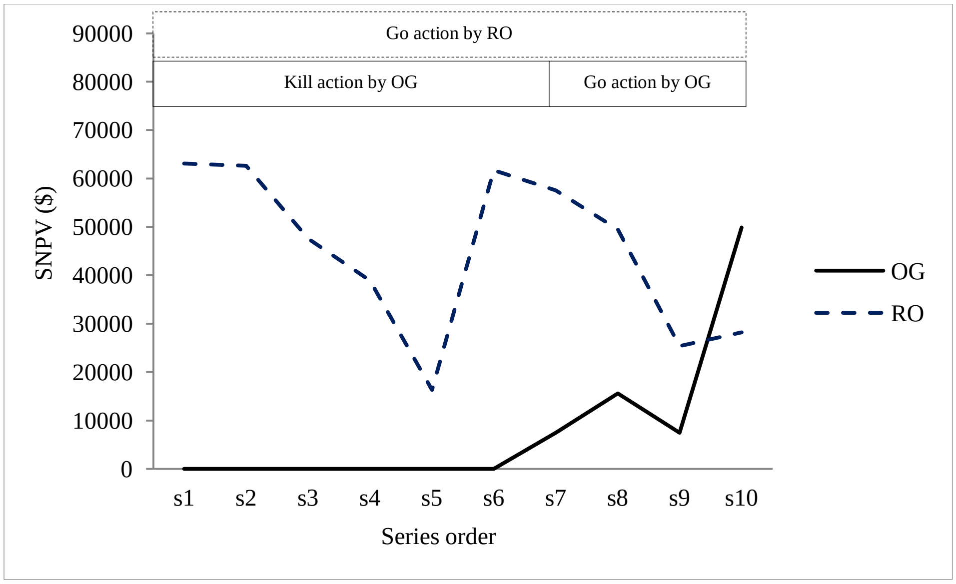

Fig. 5.11 The SNPVs from Table 5.6 when σ is low (σ = 0.25)

The complete sets of combinations are summarized in Figs. 5.12 to 5.14. Figs. 5.12 to 5.14 illustrate the strategic decisions of Firm *i* at the status of "11," based on the two parameters of the (inverse) product differentiation τ_j and τ_k, at two levels of each (low = 0.25, and high = 1) and the two ratios of unit costs β_{vc1} and β_{vc2}, at two levels of each (low = 0.5, and high = 1.5), when the expected standard deviation of demand σ changes at three levels (low = 0.25, medium = 0.45, and high = 0.75). Since the strategic decisions of Firm *i* with different settings of the expected standard deviation of demand at the status of "10" are the same, I only show them in Fig. 5.15.

		The (inverse) product differentiation τ_j: Low		High	
Ratio of unit costs β_{vc1}	β_{vc2}	τ_k: L	τ_k: H	τ_k: L	τ_k: H
High	H	Kill	Go	Go	Go
High	L	Kill	Kill	Go	Go
Low	H	Kill	Go	Kill	Go
Low	L	Kill	Kill	Kill	Kill

Fig. 5.12 Strategic decisions at the status of "11" of Firm i when σ is low (σ = 0.25)

		The (inverse) product differentiation τ_j: Low		High	
Ratio of unit costs β_{vc1}	β_{vc2}	τ_k: L	τ_k: H	τ_k: L	τ_k: H
High	H	Go	Go	Go	Go
High	L	Kill	Kill	Go	Go
Low	H	Kill	Go	Kill	Go
Low	L	Kill	Kill	Kill	Kill

Fig. 5.13 Strategic decisions at the status of "11" of Firm i when σ is medium (σ = 0.45)

		The (inverse) product differentiation τ_j: Low		High	
Ratio of unit costs β_{vc1}	β_{vc2}	τ_k: L	τ_k: H	τ_k: L	τ_k: H
High	H	Go	Go	Go	Go
High	L	Go	Go	Go	Go
Low	H	Go	Go	Go	Go
Low	L	Go	Go	Go	Go

Fig. 5.14 Strategic decisions at the status of "11" of Firm i when σ is high (σ = 0.75)

Ratio of unit costs β_{vc1}	β_{vc2}	The (inverse) product differentiation τ_j: Low, τ_k: L	Low, τ_k: H	High, τ_k: L	High, τ_k: H
High	H	Kill	Kill	Kill	Go
High	L	Kill	Kill	Kill	Kill
Low	H	Kill	Kill	Kill	Kill
Low	L	Kill	Kill	Kill	Kill

Fig. 5.15 Strategic decisions at the status of "10" of Firm *i* when σ = 0.25, 0.45, or 0.75

Even though the strategic decision could also be influenced by fixed investment costs, the results still provide the possible trends and allow decision makers to understand the impacts of the parameters. Generally, based on the expected value of the product correction, if the demand goes up to the status of "11," Firm *i* will initiate the action of "go" when at least one competitor has a high unit variable cost and competes with a highly comparable product, or simply when Firm *i*'s target market has high uncertainty.

5.4.2 Limitations and possible extensions

In this chapter, I analyze a compound option specifically during the development stages under the twice repeated game (Fig. 5.2) with one strategic variable (i.e., quantity), where the degrees of (inverse) product differentiation are considered for Firm *i*'s products compared to its rivals'. So far, my model assumes that the unit variable costs of Firm *i* and its competitors are constant. Clearly, in reality, firms can adjust their unit costs in different periods. When the information about customer requirements and preferences and Firm *i*'s product performance is updated, unit variable costs can also be updated by simply extending this model. In addition, this model only takes into account the market risk from the demand side and the technical risk of Firm *i*. Multiple qualitative and quantitative factors, such as technical risks from the rivals, several strategic variables, multi-stage game competitions, etc., are not yet contained, so these factors may become extensions of this research. Since the gate-criteria for projects are multidimensional in the NPD process (Cooper, 2008), different scorecards and criteria may be evaluated at different stages of the NPD process (Ronkainen, 1985). Hence, firms make a number of decisions that affect their costs and their products according to the purpose of each decision point, such as entry decision, price decision, investment decision, etc. As Anderson (2008) points out, product portfolio management is one of the common areas of weakness in NPD management. Therefore, further research on these factors of portfolio management is needed. Most importantly, this approach can be used in conjunction with other supportive methods in industry management (Cooper et al., 2001). Principally, this approach must be an integral part of the organization's culture and management practices.

5.5 Summary and Conclusion

In this chapter, I extend the option-game valuation framework with Bayesian analysis from chapter 4 by explicitly involving technical risk and the 3-player-game in an NPD project. Specifically, I introduce this approach as a gate-criterion to evaluate a new project at the gate of go-to-development and sub-gates of the development stages in NPD process.

At the outset of the development stages, the initial market demand is uncertain, and customers do not necessarily know their product requirements and preferences. The common financial gate-criterion, the NPV method (benchmark A), is inadequate when a project involves uncertainty, resulting in firms' killing potential projects unnecessarily in the early stages or not changing decisions in the later stages of the process. When a project at the gate of go-to-development is allowed to proceed, additional market research may be needed. As customer requirements and preferences are an important indicator to estimate the target market (with an unknown mean and unknown variance), information about customer requirements and preferences can be updated by Bayesian analysis based on actual collected samples, thus diminishing the high volatility in an initial uncertain market. Furthermore, product performance is included in the option-game mechanism to describe the distribution of Firm *i*'s technical risk in a project. New information on product performance can be updated over time until the first sub-gate, directly influencing the firm's additional correction costs. The results show that the real-option valuation (benchmark B) is insufficient when interacting with competitors in an asymmetric competition game, in which strategic interactions should involve a firm's own quantity choice as well as its rivals'.

From the results of strategic decisions at the first sub-gate of development, based on the expected value of product correction, if the demand goes up to the status of "11," Firm *i* will take the action of "go" when at least one competitor has a high unit variable cost in competing with a highly comparable product, or simply when Firm *i*'s target market has high uncertainty. If the demand goes down to the status of "10," the option-game approach will kill the project unless both competitors have high unit variable costs and high (inverse) product differentiations. In that case, Firm *i* will instead take the action of "go" and gain the monopolistic profit. The results of the strategic decisions can also be further analyzed with the distribution of product correction. The option-game approach not only evaluates managerial flexibility in a project but also provides a rigorous evaluation method which considers competitors' interactions after updating the information about the demand and product performance by Bayesian analysis.

I analyze a compound option specifically during the development stages under the twice repeated game with one strategic variable (i.e., quantity). In particular, I develop the formal mathematical option-game framework in the discrete-time analysis of an NPD project by the extending the results discussed in chapter 4 by adding technical risk and the 3-player-game. Through the information update with Bayesian analysis, both the volatilities of an uncertain market and technical risk are reduced. With dynamic settings, this approach can provide a rigorous evaluation method at the gate of go-to-development and sub-gates of the development stages.

The strategic buckets approach in the early stages of the NPD process links business strategy and portfolios (Cooper et al., 1997). When used as a gate-criterion of the development stages, the dynamic option-game framework implements further evaluations of the individual projects of development process. Since product portfolio management is one of the common areas of weakness in NPD management (Anderson, 2008), further research on this approach is needed. Most importantly, this approach can be used in conjunction with other supportive methods in industry management (Cooper et al., 2001). Principally, however, it must be combined with the corporate culture at management level.

Chapter 6 Summary and Conclusions

This study proposes a decision model for the gate criteria in an NPD project by deriving the option-game approach. The approach also allows for updating information about uncertain market demand via Bayesian analysis and incorporating this information into option-game valuation models.

In chapter 3, I develop an option-game framework as a gate-criterion for a project in the NPD process for which the market demand is uncertain and the product life cycle is short. I integrate product adoption rates (Rogers, 1995; Bollen, 1999) into the option-game framework for evaluating an NPD project, considering both simultaneous and sequential investment decisions in each scenario of the duopolistic game. The common conventional financial method in a gate-criterion, the NPV method, is inadequate when projects face uncertainty. But while the NPV criterion offers a go/kill decision, the option-game approach instead provides a go/wait decision. The decision to wait adds flexibility, allowing firms to use a passive wait-and-see strategy or an active market research strategy while delaying. Predominantly, high risk and uncertain projects have a higher value of flexibility.

In chapter 4, I propose an option-game valuation framework that explicitly incorporates statistical decision theory in the form of Bayesian analysis into an NPD project. In chapter 5, I extend the option-game valuation framework with Bayesian analysis from chapter 4 by explicitly involving technical risk and the 3-player-game in an NPD project. Specifically, I introduce this approach as a gate-criterion to evaluate a new project at the gate of go-to-development and sub-gates of the development stages in the NPD process.

At the outset of development stages, the level of demand in the target market is uncertain and the customers do not necessarily know their product requirements and preferences. The common financial gate-criterion, the NPV method (benchmark A), is inadequate when a project involves uncertainty, so that potential projects may be killed in the early stages or decisions may remain unchanged at later stages. When a project at the gate of go-to-development is allowed to proceed, additional market research may be needed. Since customer requirements and preferences are an important indicator to estimate target markets (with an unknown mean and unknown variance), they can be updated by Bayesian analysis based on actual collected samples. Accordingly, the high volatility in the initially uncertain market can be diminished via updated information about customer requirements and preferences. In addition, product performance is included in the option-game mechanism to describe the distribution of Firm *i*'s technical risk in a project. Until the first sub-gate of development, Firm *i* can also update information about product performance, information which directly influences its additional correction costs. Moreover, the option-game mechanism also includes the parameters of (inverse) product differentiation to describe the degree of similarity of potential competitors' related products. Based on the results of this research, the real-option valuation (benchmark B) is insufficient for interacting with competitors in an asymmetric competition game, in which strategic interactions should involve a company's own quantity choice as well as its rivals'.

Chapter 5 shows the results of the strategic decisions at the first sub-gate of development based on the expected value of product correction: when the demand goes up to the status of "11," Firm *i* should initiate the action of "go" if at least one competitor has a high unit variable cost in competing in a highly comparable product, or simply if Firm *i*'s target market has a high uncertainty. When the demand goes down to the status of "10," the option-game approach will kill the project, except when both competitors have high unit variable costs and high (inverse) product differentiations. In that case, Firm *i*, instead, may take the action of "go" and gain the monopolistic profit. The results of the strategic decisions can be further analyzed with the distribution of product correction. The option-game approach not only evaluates the managerial flexibility in a project but also provides a rigorous evaluation method which considers competitors' interactions after updating the information in the demand and product performance by Bayesian analysis.

The strategic buckets approach in the early stages of the NPD process links a business's strategy with its portfolios (Cooper et al., 1997). By using the dynamic option-game framework as a gate-criterion of the development stages, managers can implement further evaluations of the individual projects in the development process. Overall, this research provides a practical and quantitative tool to help a product development team make development decisions.

In this research, I analyze a compound option specifically during the development stages in twice repeated games with one strategic variable (i.e., quantity), considering the degrees of (inverse) product differentiation between Firm *i*'s products and its rivals'. Various extensions of the model are possible. So far, the model assumes that the unit variable costs of Firm *i* and its competitors are constant. Clearly, in reality, firms can adjust their unit costs in different periods. When information about customer requirements and preferences and Firm *i*'s product performance is updated, unit variable costs can be updated with a simple extension of the model. In addition, the model only takes into account the market risk from the demand side and the technical risk of Firm *i*. Multiple qualitative and quantitative factors that are not yet contained, such as technical risks from the rivals, multiple strategic variables, multi-stage game competitions, etc., may become extensions of my model. Since the gate-criteria for projects are multidimensional in the NPD process (Cooper, 2008), different scorecards and criteria may be evaluated in the different stages of the NPD process (Ronkainen, 1985). Hence, firms make a number of decisions that affect their costs and their products according to the purpose of each decision point, such as entry decision, price decision, investment decision, etc. Because product portfolio management is one of the common areas of weakness in NPD management (Anderson, 2008), further research on this approach is needed. Most importantly, this approach can be used in conjunction with other supportive methods in industry management (Cooper et al., 2001). Principally, it must be an integral part of the organization's culture and management practices.

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Appendix A: Strategic Outcomes and Derivation of Equations

A.1 Strategic Outcomes of Nash Equilibrium

A.1.1 Profit maximization of scenario 1

From equation (3.10), the first-order condition for Firm *h*'s profit maximization yields (Firm *h* and the rival Firm *h'*), where *h*=Firm *i* or *j*

$$\frac{\partial \pi_h^{\mathrm{C}}(q_i, q_j)}{\partial q_h} =$$
$$(1+r)^{-1}[P_1(\tilde{a}_u - \tilde{a}_d) + \tilde{a}_d - c_h] - 2b(1+r)^{-1} q_h - b(1+r)^{-1} q_{h'}$$
$$+(1+r)^{-2}(1+G_0)\{P_1P_2\tilde{a}_{uu} + [P_1(1-P_2) + P_2(1-P_1)]\tilde{a}_{ud} - (1-P_1)(1-P_2)\tilde{a}_{dd} - c_h\}$$
$$-2(1+r)^{-2}(1+G_0)bq_h - b(1+r)^{-2}(1+G_0)q_{h'} = 0$$

Let $R^{-1} = (1+r)^{-1}, R^{-2} = (1+r)^{-2}$

$$\Rightarrow$$
$$R[P_1(\tilde{a}_u - \tilde{a}_d)\tilde{a}_d - c_h] + (1+G_0)\{P_1P_2\tilde{a}_{uu} + [P_1(1-P_2) + P_2(1-P_1)]\tilde{a}_{ud} + (1-P_1)(1-P_2)\tilde{a}_{dd} - c_h\}$$
$$-b(R+1+G_0)q_{h'} - 2b(R+1+G_0)q_h = 0$$
$$\therefore q_h = [2b(R+1+G_0)]^{-1}\{R[P_1(\tilde{a}_u - \tilde{a}_d)\tilde{a}_d - c_h] + (1+G_0)[P_1P_2\tilde{a}_{uu} + [P_1(1-P_2) + P_2(1-P_1)]\tilde{a}_{ud}$$
$$+(1-P_1)(1-P_2)\tilde{a}_{dd} - c_h]\} - 0.5q_{h'}$$

$$\Rightarrow (q_i^*, q_j^*) = [q_i^{\mathrm{C}}(q_j^{\mathrm{C}}(q_i^{\mathrm{C}})), q_j^{\mathrm{C}}(q_i^{\mathrm{C}}(q_j^{\mathrm{C}}))] \quad \therefore (\pi_i^{\mathrm{C}*}, \pi_j^{\mathrm{C}*}) = [\pi_i^{\mathrm{C}}(q_i^*, q_j^*), \pi_j^{\mathrm{C}}(q_i^*, q_j^*)]$$

A.1.2 Profit maximization of scenario 2

Case 1: From equation (3.11) and (3.12), the first-order condition for both firms' profit maximizations yields

$$\therefore \frac{\partial \pi_i^{\mathrm{L}}(q_i, q_j)}{\partial q_i} = (1+r)^{-1} P_1(\tilde{a}_u - \tilde{a}_d) + (1+r)^{-1}(\tilde{a}_d - c_i)$$

$$+(1+r)^{-2}(1+G_0)\{P_1P_2\tilde{\alpha}_{uu}+[P_1(1-P_2)+P_2(1-P_1)]\tilde{\alpha}_{ud}-(1-P_1)(1-P_2)\tilde{\alpha}_{dd}-c_i\}$$

$$-2b(1+r)^{-1}q_i-2b(1+r)^{-2}(1+G_0)q_i-b(1+r)^{-2}G_0q_j=0$$

$$\frac{\partial\pi_{j(2)}^{\mathrm{F}}(q_i,q_j)}{\partial q_j}=(1+r)^{-2}G_0\{P_1P_2\tilde{\alpha}_{uu}+[P_1(1-P_2)+P_2(1-P_1)]\tilde{\alpha}_{ud}-(1-P_1)(1-P_2)\tilde{\alpha}_{dd}-c_j\}$$

$$-2b(1+r)^{-2}G_0q_j-b(1+r)^{-2}G_0q_i=0$$

$$\Rightarrow(q_i^*,q_j^*)=[q_i^{\mathrm{L}}(q_j^{\mathrm{F}}(q_i^{\mathrm{L}})),q_j^{\mathrm{F}}(q_i^{\mathrm{L}}(q_j^{\mathrm{F}}))]\quad\therefore(\pi_i^{\mathrm{L}*},\pi_{j(2)}^{\mathrm{F}*})=[\pi_i^{\mathrm{L}}(q_i^*,q_j^*),\pi_{j(2)}^{\mathrm{F}}(q_i^*,q_j^*)]$$

Case 2: From equation (3.13), the first-order condition for Firm i's profit maximization yields

$$\frac{\partial\pi_i^{\mathrm{M}}(q_i,q_j)}{\partial q_i}=(1+r)^{-1}P_1(\tilde{\alpha}_u-\tilde{\alpha}_d)+(1+r)^{-1}(\tilde{\alpha}_d-c_i)-2b(1+r)^{-1}q_i$$

$$+(1+r)^{-2}(1+G_0)\{P_1P_2\tilde{\alpha}_{uu}+[P_1(1-P_2)+P_2(1-P_1)]\tilde{\alpha}_{ud}-(1-P_1)(1-P_2)\tilde{\alpha}_{dd}-c_i\}$$

$$-2b(1+r)^{-2}(1+G_0)q_i=0$$

$$\Rightarrow(q_i^*,0)=(q_i^{\mathrm{M}},0)\quad\therefore(\pi_i^{\mathrm{M}*},\pi_j^*)=[\pi_i^{\mathrm{M}}(q_i^*,0),0]$$

Case 3: From equation (3.14) and (3.15), the first-order condition for both firms' profit maximizations yields

$$\frac{\partial\pi_i^{\mathrm{L}}(q_i,q_j)}{\partial q_i}=(1+r)^{-1}P_1(\tilde{\alpha}_u-\tilde{\alpha}_d)+(1+r)^{-1}(\tilde{\alpha}_d-c_i)-2b(1+r)^{-1}q_i$$

$$+(1+r)^{-2}(1+G_0)\{P_1P_2\tilde{\alpha}_{uu}+[P_1(1-P_2)+P_2(1-P_1)]\tilde{\alpha}_{ud}-(1-P_1)(1-P_2)\tilde{\alpha}_{dd}-c_i\}$$

$$-2b(1+r)^{-2}(1+G_0)q_i-b(1+r)^{-2}(1+G_0)q_j=0$$

$$\frac{\partial\pi_{j(1)}^{\mathrm{F}}(q_i,q_j)}{\partial q_j}=(1+r)^{-2}(1+G_0)\{P_1P_2\tilde{\alpha}_{uu}+[P_1(1-P_2)+P_2(1-P_1)]\tilde{\alpha}_{ud}-(1-P_1)(1-P_2)\tilde{\alpha}_{dd}-c_j\}$$

$$-2b(1+r)^{-2}(1+G_0)q_j-b(1+r)^{-2}(1+G_0)q_i=0$$

$$\Rightarrow(q_i^*,q_j^*)=[q_i^{\mathrm{L}}(q_j^{\mathrm{F}}(q_i^{\mathrm{L}})),q_j^{\mathrm{F}}(q_i^{\mathrm{L}}(q_j^{\mathrm{F}}))]\quad\therefore(\pi_i^{\mathrm{L}*},\pi_{j(1)}^{\mathrm{F}*})=[\pi_i^{\mathrm{L}}(q_i^*,q_j^*),\pi_{j(1)}^{\mathrm{F}}(q_i^*,q_j^*)]$$

Finally, the profit maximization of scenario 2 can be obtained by

$$\Rightarrow\begin{cases}\text{Firm } i:\pi_i^{\mathrm{L}}(\pi_j^{\mathrm{F}}(q_i,q_j^{**}))\\ \text{Firm } j:\pi_j^{\mathrm{F}}(q_i,q_j^{**})=\max[\pi_{j(2)}^{\mathrm{F}}(q_i,q_j^*),\pi_{j(1)}^{\mathrm{F}}(q_i,q_j^*),0]\end{cases}$$

A.1.3 Profit maximization of scenario 3

Similarly, scenario 3 is the same concept as scenario 2 but with the firms playing opposite roles. Hence, Firm *j* has only one move, so the payoff functions of scenario 3 will thus mainly depend on Firm *i*'s decision.

$$\Rightarrow \begin{cases} \text{Firm i}: \pi_i^F(q_i^{**}, q_j) = \max[\pi_{i(2)}^F(q_i^*, q_j), \pi_{i(1)}^F(q_i^*, q_j), 0] \\ \text{Firm } j: \pi_j^L(\pi_i^F(q_i^{**}, q_j)) \end{cases}$$

A.1.4 Profit maximization of scenario 4

(1) The payoff matrix at time 2 (terminal statuses)

- Both invest at time 2 (Cournot competition) from equation (3.18); the first-order condition for both firms' profit maximizations yields

$$\frac{\partial \tilde{c}_{h2}(q_i, q_j)}{\partial q_h} = -2bG_2 q_h + (\tilde{\alpha}_2 - c_h)G_2 - bG_2 q_{h'} = 0$$

where $\tilde{C}_{h2}(q_i, q_j) = -I_2 - bG_2 q_h^2 + (\tilde{\alpha}_2 - c_h)G_2 q_h - bG_2 q_h q_{h'}$

$$\Rightarrow (q_i^*, q_j^*) = [q_i^{\mathrm{C}}(q_j^{\mathrm{C}}(q_i^{\mathrm{C}})), q_j^{\mathrm{C}}(q_i^{\mathrm{C}}(q_j^{\mathrm{C}}))] \quad \therefore (\tilde{C}_{i2}^*, \tilde{C}_{j2}^*) = [\tilde{C}_{i2}(q_i^*, q_j^*), \tilde{C}_{j2}(q_i^*, q_j^*)]$$

- Firm *i* invests and Firm *j* abandons the project at time 2 (monopoly of Firm *i*) from equation (3.19); the first-order condition for Firm *i*'s profit maximization yields

$$\frac{\partial \widetilde{M}_{i2}(q_i, q_j)}{\partial q_i} = -2bG_2 q_i + (\tilde{\alpha}_2 - c_i)G_2 = 0 \quad \text{where } \widetilde{M}_{i2}(q_i, q_j) = -I_2 - bG_2 q_i^2 + (\tilde{\alpha}_2 - c_i)G_2 q_i$$

$$\Rightarrow (q_i^*, 0) = (q_i^{\mathrm{M}*}, 0) \quad \therefore (\widetilde{M}_{i2}^*, 0) = [\widetilde{M}_{i2}(q_i^*, 0), 0]$$

- Firm *j* invests and Firm *i* abandons the project at time 2 (monopoly of Firm *j*) from equation (3.19); the first-order condition for Firm *j*'s profit maximization yields

$$\frac{\partial \tilde{M}_{j2}(q_i, q_j)}{\partial q_j}$$

$$= -2bG_2q_j + (\tilde{\alpha}_2 - c_j)G_2 = 0 \quad \text{where } \tilde{M}_{j2}(q_i, q_j) = -I_2 - bG_2q_j^2 + (\tilde{\alpha}_2 - c_j)G_2q_j$$

$$\Rightarrow (0, q_j^*) = [0, q_j^{M*}] \quad \therefore (0, \tilde{M}^*_{j2}) = [0, \tilde{M}_{j2}(0, q_j^*)]$$

- If both abandon the project at time 2, then the payoff is zero.

Hence, applying the Nash equilibrium with the best response analysis, the competitive outcomes $[\tilde{X}_{i2}(q_i^*, q_j^*), \tilde{X}_{j2}(q_i^*, q_j^*)]$ at terminal statuses can be obtained from the payoff matrices of time 2.

(2) The payoff matrix at time 1 (intermediate statuses)

- Both invest at time 1 (Cournot competition) from equation (3.20); the first-order condition for both firms' profit maximizations yields

$$\frac{\partial \tilde{C}_{h1}(q_i, q_j)}{\partial q_h} =$$

$$-2b(1+r)^{-1}(1+G_1)q_h + (1+r)^{-1}(1+G_1)[P_2(\tilde{\alpha}_2 - \tilde{\alpha}_{2'}) + \tilde{\alpha}_{2'} - c_h] - b(1+r)^{-1}(1+G_1)q_{h'} = 0$$

where $\tilde{C}_{h1}(q_i, q_j) =$

$$-I_1 - b(1+r)^{-1}(1+G_1)q_h^2 + (1+r)^{-1}(1+G_1)[P_2(\tilde{\alpha}_2 - \tilde{\alpha}_{2'}) + \tilde{\alpha}_{2'} - c_h]q_h - b(1+r)^{-1}(1+G_1)q_hq_{h'}$$

$$\Rightarrow (q_i^*, q_j^*) = [q_i^C(q_j^C(q_i^C)), q_j^C(q_i^C(q_j^C))] \quad \therefore (\tilde{C}^*_{i1}, \tilde{C}^*_{j1}) = [\tilde{C}_{i1}(q_i^*, q_j^*), \tilde{C}_{j1}(q_i^*, q_j^*)]$$

- Firm *i* invests and Firm *j* waits at time 1 from equation (3.21)
  - Firm *i* invests at time 1 and Firm *j* invests at time 2 (sequential investment). The first-order condition for Firm *i*'s profit maximization yields

$$\therefore \frac{\partial \pi_i^L(q_i, q_j)}{\partial q_i} =$$

$$-2b(1+r)^{-1}[1+1+G_1]q_i+[P_2(\tilde{\alpha}_2-\tilde{\alpha}_{2'})+\tilde{\alpha}_{2'}-c_i][1+1+G_1](1+r)^{-1}-b(1+r)^{-1}[1+G_1]q_j=0$$

where $\pi_i^{\mathrm{L}}(q_i,q_j)=-I_1-b(1+r)^{-1}[1+1+G_1]q_i^2+[P_2(\tilde{\alpha}_2-\tilde{\alpha}_{2'})+$
$\tilde{\alpha}_{2'}-c_i][1+1+G_1](1+r)^{-1}q_i-b(1+r)^{-1}[1+G_1]q_iq_j$

$$\frac{\partial\pi_{j(2)}^{\mathrm{F}}(q_i,q_j)}{\partial q_j}=-2b(1+r)^{-1}G_1q_j+[P_2(\tilde{\alpha}_2-\tilde{\alpha}_{2'})+\tilde{\alpha}_{2'}-c_j]G_1(1+r)^{-1}-b(1+r)^{-1}G_1q_i=0$$

where $\pi_{j(2)}^{\mathrm{F}}(q_i,q_j)=-I_2-b(1+r)^{-1}G_1q_j^2+[P_2(\tilde{\alpha}_2-\tilde{\alpha}_{2'})+$
$\tilde{\alpha}_{2'}-c_j]G_1(1+r)^{-1}q_j-b(1+r)^{-1}G_1q_iq_j$

$$\Rightarrow(q_i^*,q_j^*)=[q_i^{\mathrm{L}}(q_j^{\mathrm{F}}(q_i^{\mathrm{L}})),q_j^{\mathrm{F}}(q_i^{\mathrm{L}}(q_j^{\mathrm{F}}))]\quad\therefore(\pi_{i(1)}^{\mathrm{L}*},\pi_{j(2)}^{\mathrm{F}*})=[\pi_{i(1)}^{\mathrm{L}}(q_i^*,q_j^*),\pi_{j(2)}^{\mathrm{F}}(q_i^*,q_j^*)]$$

- Firm *i* invests at time 1 and Firm *j* abandons at time 2 (monopoly of Firm *i*). The first-order condition for Firm *i*'s profit maximization yields

$$\frac{\partial\pi_i^{\mathrm{M}}(q_i,q_j)}{\partial q_i}=-2b(1+G_1)(1+r)^{-1}q_i+[P_2(\tilde{\alpha}_2-\tilde{\alpha}_{2'})+\tilde{\alpha}_{2'}-c_i](1+G_1)(1+r)^{-1}=0$$

where $\pi_i^{\mathrm{M}}(q_i,q_j)=-I_1-b(1+G_1)(1+r)^{-1}q_i^2+[P_2(\tilde{\alpha}_2-\tilde{\alpha}_{2'})+\tilde{\alpha}_{2'}-c_i](1+G_1)(1+r)^{-1}q_i$

$$\Rightarrow(q_i^*,0)=(q_i^{\mathrm{M}*},0)\quad\therefore(\pi_i^{\mathrm{M}*},0)=[\pi_i^{\mathrm{M}}(q_i^*,0),0]$$

- Firm *j* invests and Firm *i* waits at time 1 from equation (3.21)

The same procedures are used as in the previous case (Firm *i* invests and Firm *j* waits at time 1).

- Firm *j* invests at time 1 and Firm *i* invests at time 2 (sequential investment)

$$\Rightarrow(q_i^*,q_j^*)=[q_i^{\mathrm{F}}(q_j^{\mathrm{L}}(q_i^{\mathrm{F}})),q_j^{\mathrm{L}}(q_i^{\mathrm{F}}(q_j^{\mathrm{L}}))]\quad\therefore(\pi_{i(2)}^{\mathrm{F}*},\pi_{j(1)}^{\mathrm{L}*})=[\pi_{i(2)}^{\mathrm{F}}(q_i^*,q_j^*),\pi_{j(1)}^{\mathrm{L}}(q_i^*,q_j^*)]$$

- Firm *j* invests at time 1, and Firm *i* abandons at time 2 (monopoly of Firm *j*)

$$\Rightarrow(0,q_j^*)=(0,q_j^{\mathrm{M}*})\quad\therefore(0,\pi_j^{\mathrm{M}*})=[0,\pi_j^{\mathrm{M}}(0,q_j^*)]$$

- Both wait at time 1 from equation (3.22)

If both firms wait at time 1 at the same time, the result will be the option value from the optimal matrix outcome of time 2.

$\left[\widetilde{W}_{i1}(q_i, q_j), \widetilde{W}_{j1}(q_i, q_j)\right] = [\frac{q_r \tilde{x}^*_{i2} + (1-q_r)\tilde{x}^*_{i2'}}{1+r_f}, \frac{q_r \tilde{x}^*_{j2} + (1-q_r)\tilde{x}^*_{j2'}}{1+r_f}]$ as shown in equation (3.22)

Hence, the payoff functions of scenario 4 are the competitive outcomes at intermediate statuses obtained from the payoff matrices of time 1 ($\tilde{X}^*_{i1}, \tilde{X}^*_{j1}$) by applying the Nash equilibrium concept.

$$\therefore [\pi_i^W(q_i, q_j), \pi_j^W(q_i, q_j)] = [\frac{q_r \tilde{X}^*_{iu} + (1-q_r)\tilde{X}^*_{id}}{1+r_f}, \frac{q_r \tilde{X}^*_{ju} + (1-q_r)\tilde{X}^*_{jd}}{1+r_f}]$$

as shown in equation (3.23)

Finally, the resulting equilibrium for the gate decision of the development stage can be obtained from the payoff matrix at time $t = 0$ (Fig. 3.7) by applying the Nash equilibrium with the best response analysis, where the competitive outcomes are noted as $[X_i(q_i^*, q_j^*), X_j(q_i^*, q_j^*)]$.

A.1.5 The equilibrium quantity in the overall industry by the NPV approach:

Given total profits in the industry

$$\text{NPV} = -I_0 + G[(p_0 - \bar{c})Q] = -I_0 + G[(a_0 - bQ - \bar{c})Q]$$
$$= -I_0 + G(-bQ^2 - \bar{c}Q + a_0 Q)$$
$$\Rightarrow \frac{\partial \text{NPV}}{\partial Q} = G[-2bQ + (a_0 - \bar{c})] = 0, \ \therefore$$

$Q = \frac{a_0 - \bar{c}}{2b}$ as shown in equation (3.24)

A.1.6 The equilibrium result of Firm *i* by the NPV approach in equation (3.26):

NPV of Firm i: $\text{NPV}_i = -I_0 + (p_0 - c_i)q_i G = -I_0 + (a_0 - bQ - c_i)q_i G$

Given $q_i = \omega Q, \Rightarrow \text{NPV}_i = -I_0 + (a_0 - bQ - c_i)(\omega Q)G$

Given $Q = \dfrac{a_0 - \bar{c}}{2b}$ from equation (3.24)

$$\Rightarrow \text{NPV}_i = -I_0 + [a_0 - b(\frac{a_0 - \bar{c}}{2b}) - c_i][\omega(\frac{a_0 - \bar{c}}{2b})]G$$

$= -I_0 + \dfrac{(a_0 - \bar{c})(a_0 + \bar{c} - 2c_i)}{4b}$ as shown in equation (3.26)

A.2 Derivation of Equations

A.2.1 Equation (4.6)

Payoffs at the three statuses of the second sub-gate:

$$\begin{cases} \tilde{\pi}_{i22}^{A} = -I_2 - (1+r)^{-1} I_3 - (1+r)^{-2} I_4 + (1+r)^{-2}[P^2 \tilde{V}_{44} + 2P(1-P)\tilde{V}_{43} + (1-P)^2 \tilde{V}_{42}] \\ \tilde{\pi}_{i21}^{A} = -I_2 - (1+r)^{-1} I_3 - (1+r)^{-2} I_4 + (1+r)^{-2}[P^2 \tilde{V}_{43} + 2P(1-P)\tilde{V}_{42} + (1-P)^2 \tilde{V}_{41}] \\ \tilde{\pi}_{i20}^{A} = -I_2 - (1+r)^{-1} I_3 - (1+r)^{-2} I_4 + (1+r)^{-2}[P^2 \tilde{V}_{42} + 2P(1-P)\tilde{V}_{41} + (1-P)^2 \tilde{V}_{40}] \end{cases} \quad (4.6a)$$

Let $I_{S2} = I_2 + \dfrac{I_3}{(1+r)^1} + \dfrac{I_4}{(1+r)^2}$, $\tilde{V}_4 = (\tilde{p}_4 - c_i)q_i G_4 = (\tilde{a}_4 - bQ - c_i)q_i G_4$, and

$q_i = \omega Q$ (ω: market share of Firm i), rewrite (4.6a) as

$$\tilde{\pi}_{i22}^{A} = -I_{S2} + \frac{G_4 \omega}{(1+r)^2}\{-bQ^2 - c_i Q + [P^2 \tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2 \tilde{a}_{42}]Q\} \quad (4.6b)$$

From equation (4.4), $\tilde{\tilde{a}}_{22} = P^2 \tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2 \tilde{a}_{42}$ rewrite (4.6b) as

$\tilde{\pi}_{i22}^{A} = -I_{S2} + \dfrac{G_4 \omega}{(1+r)^2}[-bQ^2 - c_i Q + \tilde{\tilde{a}}_{22} Q]$, the same procedures for $\tilde{\pi}_{i21}^{A}, \tilde{\pi}_{i20}^{A}$,

$\therefore \tilde{\pi}_{i2}^{A} = -I_{S2} + \dfrac{G_4 \omega}{(1+r)^2}[-bQ^2 - c_i Q + \tilde{\tilde{a}}_{2} Q]$ as shown in equation (4.6)

A.2.2 Equation (4.7)

Given $0 \le \tau \le 1$, total quantity is Q

$\therefore$ The quantity in demand of Firm j: $(\dfrac{c_i}{c_i + c_j} Q)\tau$

$\Rightarrow$ The quantity in demand of Firm *i*: $Q-(\frac{c_i}{c_i+c_j}Q)\tau=(1-\frac{c_i\tau}{c_i+c_j})Q=[\frac{c_i(1-\tau)+c_j}{c_i+c_j}]Q$

$\therefore$ The market share of Firm $i: \omega=\frac{c_i(1-\tau)+c_j}{c_i+c_j}$ as shown in equation (4.7)

A.2.3 Equation (4.9) and (5.9)

Given total profits in the industry $\pi_{00}^{\mathrm{A}}=-I+\frac{G_4}{(1+r)^4}[-bQ^2-\bar{c}Q+\bar{a}_{00}Q]$

$\Rightarrow \frac{\partial\pi_{00}^{\mathrm{A}}}{\partial Q}=\frac{G_4}{(1+r)^4}[-2bQ+(\bar{a}_{00}-\bar{c})]=0,\ \therefore Q=\frac{\bar{a}_{00}-\bar{c}}{2b}$ as shown in equation (4.9)

A.2.4 Equation (4.10)

Given equation (4.9) $Q=\frac{\bar{a}_{00}-\bar{c}}{2b}$ into equation (4.8)

$\Rightarrow \pi_{i00}^{\mathrm{A}}$

$=-I+\frac{G_4\omega}{(1+r)^4}[-bQ^2-c_iQ+\bar{a}_{00}Q]=-I+\frac{G_4\omega}{(1+r)^4}[-b(\frac{\bar{a}_{00}-\bar{c}}{2b})^2-c_i(\frac{\bar{a}_{00}-\bar{c}}{2b})+\bar{a}_{00}(\frac{\bar{a}_{00}-\bar{c}}{2b})]$

$=-I+\frac{G_4\omega}{(1+r)^4}(\frac{\bar{a}_{00}-\bar{c}}{2b})[-(\frac{\bar{a}_{00}-\bar{c}}{2})+(\bar{a}_{00}-c_i)]=-I+\frac{G_4\omega}{(1+r)^4}(\frac{\bar{a}_{00}-\bar{c}}{2b})[\frac{-(\bar{a}_{00}-\bar{c})+2(\bar{a}_{00}-c_i)}{2}]$

$=-I+\frac{G_4\omega}{(1+r)^4}(\frac{\bar{a}_{00}-\bar{c}}{2b})[\frac{(\bar{a}_{00}+\bar{c}-2c_i)}{2}]=-I+\frac{G_4\omega}{(1+r)^4}\frac{(\bar{a}_{00}-\bar{c})(\bar{a}_{00}+\bar{c}-2c_i)}{4b}$

$\therefore \mathrm{NPV}_{i00}=-I+\frac{G_4\omega}{(1+r)^4}\frac{(\bar{a}_{00}-\bar{c})(\bar{a}_{00}+\bar{c}-2c_i)}{4b}$ as shown in equation (4.10)

A.2.5 Equation (4.12)

Customer requirements and preferences x is updated as

$x'\sim St[\mu_x,(\alpha'\beta')^{-1},2\alpha+n_x]$ with mean μ_x and variance $\frac{(2\alpha+n_x)(\alpha'\beta')^{-1}}{2\alpha+n_x-2}$

Let $2\alpha+n_x>30$,

$x'\approx N[\mu_x,\frac{(2\alpha+n_x)(\alpha'\beta')^{-1}}{2\alpha+n_x-2}]\Rightarrow y'\sim N(g,\sigma^{2}{}')=\gamma x'\approx N[\gamma\mu_x,\frac{\gamma^2(2\alpha+n_x)(\alpha'\beta')^{-1}}{2\alpha+n_x-2}]$

Hence, the percentage changes in the demand y is updated as

$$\begin{cases} g' = \gamma\mu_x = g \\ \sigma^2{}' = \dfrac{\gamma^2(2\alpha + n_x)}{(\alpha'\beta')(2\alpha + n_x - 2)} \end{cases} \text{ where } \alpha' = \alpha + \frac{n_x}{2} \text{ and } \beta' = [\frac{1}{\beta} + \frac{1}{2}\sum_{i=1}^{n_x}(x_i - \mu_x)^2]^{-1}$$

[Note] Before update with Bayesian analysis

Customer requirements and preferences x is shown as

$x \sim St[\mu_x, (\alpha\beta)^{-1}, 2\alpha]$ with mean μ_x and variance $\dfrac{1}{\beta(\alpha - 1)}$

Let $\alpha > 15$,

$$x \approx N[\mu_x, \frac{1}{\beta(\alpha-1)}] \Rightarrow y = \gamma x \approx N[\gamma\mu_x, \frac{\gamma^2}{\beta(\alpha-1)}]$$

Hence, the percentage changes in the demand y is shown as

$$\begin{cases} g = \gamma\mu_x \\ \sigma^2 = \dfrac{\gamma^2}{\beta(\alpha-1)} \end{cases}$$

A.2.6 Equation (4.18)

The payoff function of Firm i at the up sub-gate under Cournot competition is

Let $I_{S2} = I_2 + \dfrac{I_3}{(1+r)^1} + \dfrac{I_4}{(1+r)^2}$,

$$\tilde{\pi}_{i22}^{\mathrm{C}} = -I_{S2} + (1+r)^{-2}[P^2\tilde{V}_{44} + 2P(1-P)\tilde{V}_{43} + (1-P)^2\tilde{V}_{42}]$$

$$= -I_{S2} + (1+r)^{-2}G_4[P^2(\tilde{p}_{44}^{C} - c_i)q_i + 2P(1-P)(\tilde{p}_{43}^{C} - c_i)q_i + (1-P)^2(\tilde{p}_{42}^{C} - c_i)q_i]$$

$$= -I_{S2} + (1+r)^{-2}G_4\{P^2[-bq_i^2 + (\tilde{a}_{44} - b\tau q_j - c_i)q_i] +$$

$$2P(1-P)[-bq_i^2 + (\tilde{a}_{43} - b\tau q_j - c_i)q_i] + (1-P)^2[-bq_i^2 + (\tilde{a}_{42} - b\tau q_j - c_i)q_i]\}$$

$$= -I_{S2} + (1+r)^{-2}G_4\{-bq_i^2[P^2 + 2P(1-P) + (1-P)^2] +$$

$$(-b\tau q_j - c_i)q_i[P^2 + 2P(1-P) + (1-P)^2] + [P^2\tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2\tilde{a}_{42}]q_i\}$$

$$\because P^2 + 2P(1-P) + (1-P)^2 = 1$$

$$\Rightarrow \tilde{\pi}_{i22}^{\mathrm{C}} = -I_{S2} + (1+r)^{-2}G_4\{-bq_i^2 + (-b\tau q_j - c_i)q_i + [P^2\tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2\tilde{a}_{42}]q_i\}$$

From equation (4.4), $\tilde{\tilde{a}}_{22} = P^2 \tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2 \tilde{a}_{42}$

$\Rightarrow \tilde{\pi}^{C}_{i22} = -I_{S2} + (1+r)^{-2} G_4[-bq_i^2 + (\tilde{\tilde{a}}_{22} - c_i)q_i - \tau b q_j q_i]$ same procedures for $\tilde{\pi}^{C}_{i21}, \tilde{\pi}^{C}_{i20}$

$\therefore \tilde{\pi}^{C}_{i2} = -I_{S2} + \dfrac{G_4}{(1+r)^2}[-bq_i^2 + (\tilde{\tilde{a}}_2 - c_i)q_i - \tau b q_j q_i]$ as shown in equation (4.18)

A.2.7 Equation (4.19)

From the first-order profit-maximizing condition, Firm *i*'s and *j*'s reaction functions are

$$\frac{\partial \tilde{\pi}^{C}_{i2}}{\partial q_i} = -2bq_i - b\tau q_j + (\tilde{\tilde{a}}_2 - c_i) = 0 \quad (4.19a); \quad \frac{\partial \tilde{\pi}^{C}_{j2}}{\partial q_j} = -2\tau b q_j - bq_i + (\tilde{\tilde{a}}_2 - c_j) = 0 \quad (4.19b)$$

From (4.19b), we can get $q_j = -\dfrac{1}{2\tau} q_i + \dfrac{\tilde{\tilde{a}}_2 - c_j}{2b\tau}$, bringing into (4.19a)

$$-2bq_i - b\tau\left(-\frac{1}{2\tau} q_i + \frac{\tilde{\tilde{a}}_2 - c_j}{2b\tau}\right) + (\tilde{\tilde{a}}_2 - c_j) = 0 \Rightarrow -4bq_i + bq_i - \tilde{\tilde{a}}_2 + c_j + 2\tilde{\tilde{a}}_2 - 2c_i = 0$$

$$\Rightarrow 3bq_i = \tilde{\tilde{a}}_2 - 2c_i + c_j \Rightarrow q_i^{C} = \frac{\tilde{\tilde{a}}_2 - 2c_i + c_j}{3b}$$ as shown in equation (4.19)

Hence, it represents the same structure of equilibrium quantity in the case of cost asymmetric Cournot competition in homogeneous goods, where $q_i^{C} = \dfrac{a - 2c_i + c_j}{3b}$ (in Chevalier-Roignant, & Trigeorgis, 2011).

A.2.8 Equation (4.20): Firm *i*'s resulting profit

From (4.18), I can write payoff functions as

$$\tilde{\pi}^{C}_{i2} = -I_{S2} + \frac{G_4}{(1+r)^2}[-bq_i^2 + (\tilde{\tilde{a}}_2 - c_i)q_i - \tau b q_j q_i]$$

Let $V = -bq_i^2 + (\tilde{\tilde{a}}_2 - c_i)q_i - \tau b q_j q_i$

Given equation (4.19) $q_i = \dfrac{\tilde{\tilde{a}}_2 - 2c_i + c_j}{3b}$, and $q_j = \dfrac{\tilde{\tilde{a}}_2 - 2c_j + c_i}{3\tau b}$ putting into V

$$\Rightarrow V = -b\left(\frac{\tilde{\tilde{a}}_2 - 2c_i + c_j}{3b}\right)^2 + (\tilde{\tilde{a}}_2 - c_i)\left(\frac{\tilde{\tilde{a}}_2 - 2c_i + c_j}{3b}\right) - b\tau\left(\frac{\tilde{\tilde{a}}_2 - 2c_j + c_i}{3\tau b}\right)\left(\frac{\tilde{\tilde{a}}_2 - 2c_i + c_j}{3b}\right)$$

$$= \left(\frac{\tilde{\tilde{a}}_2 - 2c_i + c_j}{3b}\right)\left[\frac{-(\tilde{\tilde{a}}_2 - 2c_i + c_j) + 3(\tilde{\tilde{a}}_2 - c_i) - (\tilde{\tilde{a}}_2 - 2c_j + c_i)}{3}\right]$$

$$\therefore V = \frac{(\tilde{\tilde{a}}_2 - 2c_i + c_j)^2}{9b}$$ bringing back into equation (4.18)

$$\Rightarrow \tilde{\pi}^{\mathrm{C}}_{i2} = -I_{S2} + \frac{G_4}{(1+r)^2}\left[\frac{(\tilde{\tilde{a}}_2 - 2c_i + c_j)^2}{9b}\right.$$ as shown in equation (4.20)

A.2.9 Equation (5.6)

Payoffs at the three statuses of the second sub-gate:

$$\begin{cases} \tilde{\pi}^{\mathrm{A}}_{i22} = -I_2 - (1+r)^{-1} I_3 - (1+r)^{-2} I_4 + (1+r)^{-2}[P^2 \tilde{V}_{44} + 2P(1-P)\tilde{V}_{43} + (1-P)^2 \tilde{V}_{42}] \\ \tilde{\pi}^{\mathrm{A}}_{i21} = -I_2 - (1+r)^{-1} I_3 - (1+r)^{-2} I_4 + (1+r)^{-2}[P^2 \tilde{V}_{43} + 2P(1-P)\tilde{V}_{42} + (1-P)^2 \tilde{V}_{41}] \\ \tilde{\pi}^{\mathrm{A}}_{i20} = -I_2 - (1+r)^{-1} I_3 - (1+r)^{-2} I_4 + (1+r)^{-2}[P^2 \tilde{V}_{42} + 2P(1-P)\tilde{V}_{41} + (1-P)^2 \tilde{V}_{40}] \end{cases} \quad (5.6a)$$

Let $I_{S2} = I_2 + \frac{I_3}{(1+r)^1} + \frac{I_4}{(1+r)^2}$, $\tilde{V}_4 = (\tilde{p}_4 - c_i - c_{il}) q_i G_4 = (\tilde{a}_4 - bQ - c_i - c_{il}) q_i G_4$, and $q_i = \omega Q$ (ω: market share of Firm i), rewrite (5.6a) as

$$\tilde{\pi}^{\mathrm{A}}_{i22} = -I_{S2} + \frac{G_4 \omega}{(1+r)^2}\{-bQ^2 - c_i Q - c_{il} Q + [P^2 \tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2 \tilde{a}_{42}]Q\} \quad (5.6b)$$

From equation (5.4), $\tilde{\tilde{a}}_{22} = P^2 \tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2 \tilde{a}_{42}$ rewrite (5.6b) as

$\tilde{\pi}^{\mathrm{A}}_{i22} = -I_{S2} + \frac{G_4 \omega}{(1+r)^2}[-bQ^2 - c_i Q - c_{il} Q + \tilde{\tilde{a}}_{22} Q]$, the same procedures for $\tilde{\pi}^{\mathrm{A}}_{i21}, \tilde{\pi}^{\mathrm{A}}_{i20}$,

$$\begin{cases} \tilde{\pi}^{\mathrm{A}}_{i2} = -I_{S2} + \frac{G_4 \omega}{(1+r)^2}[-bQ^2 - c_i Q - c_{il} Q + \tilde{\tilde{a}}_2 Q] & \text{if } l > 0 \\ \tilde{\pi}^{\mathrm{A}}_{i2} = -I_{S2} + \frac{G_4 \omega}{(1+r)^2}[-bQ^2 - c_i Q + \tilde{\tilde{a}}_2 Q] & \text{if } l \le 0 \end{cases}$$ as shown in equation (5.6)

A.2.10 Equation (5.7)

Given $0 \le \tau_j, \tau_k \le 1$, total quantity is Q,

Firm i has two competitors in the target market; totally there are three products.

The three firms are ordered in the ascending sequence according to their unit variable costs.

The fraction of all sales of Firm j or k is
the numerator as a given $c_j^{'}, c_k^{'}$ to the denominator as total variable costs $c_i + c_j + c_k$,
where the unit cost $c_j^{'}, c_k^{'}$ to Firm j or k is given
in the descending sequence to their unit variable costs.

$\therefore$ The quantity in demand of Firm j or k: $(\frac{c_j^{'}}{c_i + c_j + c_k} Q)\tau_j$ or $(\frac{c_k^{'}}{c_i + c_j + c_k} Q)\tau_k$

$\Rightarrow$ The quantity in demand of Firm i:

$$Q - (\frac{c_j^{'}}{c_i + c_j + c_k} Q)\tau_j - (\frac{c_k^{'}}{c_i + c_j + c_k} Q)\tau_k$$

$$= Q(1 - \frac{c_j^{'}\tau_j}{c_i + c_j + c_k} - \frac{c_k^{'}\tau_k}{c_i + c_j + c_k}) = (1 - \frac{c_j^{'}\tau_j + c_k^{'}\tau_k}{c_i + c_j + c_k})Q$$

$\therefore$ The market share of Firm $i: \omega = 1 - \frac{c_j^{'}\tau_j + c_k^{'}\tau_k}{c_{total}}$ as shown in equation (5.7)

A.2.11 Equation (5.10)

Given equation (5.9) $Q = \frac{\bar{a}_{00} - \bar{c}}{2b}$ into equation (5.8)

$$\Rightarrow \pi_{i00}^{\mathrm{A}} = -I + \frac{G_4\omega}{(1+r)^4}[-bQ^2 - c_i Q - c_{il}Q + \bar{a}_{00}Q]$$

$$= -I + \frac{G_4\omega}{(1+r)^4}[-b(\frac{\bar{a}_{00} - \bar{c}}{2b})^2 - c_i(\frac{\bar{a}_{00} - \bar{c}}{2b}) - c_{il}(\frac{\bar{a}_{00} - \bar{c}}{2b}) + \bar{a}_{00}(\frac{\bar{a}_{00} - \bar{c}}{2b})]$$

$$= -I + \frac{G_4\omega}{(1+r)^4}(\frac{\bar{a}_{00} - \bar{c}}{2b})[-(\frac{\bar{a}_{00} - \bar{c}}{2}) + (\bar{a}_{00} - c_i - c_{il})]$$

$$= -I + \frac{G_4\omega}{(1+r)^4}(\frac{\bar{a}_{00} - \bar{c}}{2b})[\frac{-(\bar{a}_{00} - \bar{c}) + 2(\bar{a}_{00} - c_i - c_{il})}{2}]$$

$$= -I + \frac{G_4\omega}{(1+r)^4}(\frac{\bar{a}_{00} - \bar{c}}{2b})[\frac{(\bar{a}_{00} + \bar{c} - 2c_i - 2c_{il})}{2}] = -I + \frac{G_4\omega}{(1+r)^4}\frac{(\bar{a}_{00} - \bar{c})(\bar{a}_{00} + \bar{c} - 2c_i - 2c_{il})}{4b}$$

$$\therefore \begin{cases} \pi_{i00}^{\mathrm{A}} = -I + \frac{G_4\omega}{(1+r)^4}\frac{(\bar{a}_{00} - \bar{c})(\bar{a}_{00} + \bar{c} - 2c_i - 2c_{il})}{4b} & \text{if } l > 0 \\ \pi_{i00}^{\mathrm{A}} = -I + \frac{G_4\omega}{(1+r)^4}\frac{(\bar{a}_{00} - \bar{c})(\bar{a}_{00} + \bar{c} - 2c_i)}{4b} & \text{if } l \le 0 \end{cases}$$ as shown in equation (5.10)

A.2.12 Equation (5.17)

Customer requirements and preferences x is updated as

$x' \sim St(x|\theta', [\frac{(\rho^{-1}+n_x)(\alpha+\frac{n_x}{2})\beta'}{\rho^{-1}+n_x+1}]^{-1}, 2\alpha+n_x)$ with mean θ' and variance $\frac{\rho^{-1}+n_x+1}{(\alpha+\frac{n_x}{2}-1)(\rho^{-1}+n_x)\beta'}$

Let $2\alpha+n_x>30$,

$$x' \approx N[\theta', \frac{\rho^{-1}+n_x+1}{(\alpha+\frac{n_x}{2}-1)(\rho^{-1}+n_x)\beta'}] \Rightarrow y' \sim N(g', \sigma^2{}')$$

$$= \gamma x' + \varepsilon \approx N[\gamma\theta' + \varepsilon, \frac{\gamma^2(\rho^{-1}+n_x+1)}{(\alpha+\frac{n_x}{2}-1)(\rho^{-1}+n_x)\beta'}]$$

Hence, the percentage changes in the demand y is updated as

$$\begin{cases} g' = \gamma\theta' + \varepsilon \\ \sigma^2{}' = \frac{\gamma^2(\rho^{-1}+n_x+1)}{(\alpha+\frac{n_x}{2}-1)(\rho^{-1}+n_x)\beta'} \end{cases}$$

A.2.13 Equation (5.24)

The payoff function of Firm i at the up sub-gate under Cournot competition is

Let $I_{S2} = I_2 + \frac{I_3}{(1+r)^1} + \frac{I_4}{(1+r)^2}$,

$$\tilde{\pi}^{C}_{i22} = -I_{S2} + (1+r)^{-2}[P^2\tilde{V}_{44} + 2P(1-P)\tilde{V}_{43} + (1-P)^2\tilde{V}_{42}]$$

$$= -I_{S2} + (1+r)^{-2}G_4[P^2(\tilde{p}^{C}_{44} - c_i - c_{il})q_i + 2P(1-P)(\tilde{p}^{C}_{43} - c_i - c_{il})q_i + (1-P)^2(\tilde{p}^{C}_{42} - c_i - c_{il})q_i]$$

$$= -I_{S2} + (1+r)^{-2}G_4\{P^2[-bq_i^2 + (\tilde{a}_{44} - b\tau_j q_j - b\tau_k q_k - c_i - c_{il})q_i] +$$

$$2P(1-P)[-bq_i^2 + (\tilde{a}_{43} - b\tau_j q_j - b\tau_k q_k - c_i - c_{il})q_i]$$

$$+(1-P)^2[-bq_i^2 + (\tilde{a}_{42} - b\tau_j q_j - b\tau_k q_k - c_i - c_{il})q_i]\}$$

$$= -I_{S2} + (1+r)^{-2}G_4\{-bq_i^2[P^2 + 2P(1-P) + (1-P)^2] +$$

$$(-b\tau_j q_j - b\tau_k q_k - c_i - c_{il})q_i[P^2 + 2P(1-P) + (1-P)^2]$$

$$+[P^2\tilde{a}_{44} + 2P(1-P)\tilde{a}_{43} + (1-P)^2\tilde{a}_{42}]q_i\}$$

$$\because P^2 + 2P(1-P) + (1-P)^2 = 1$$

$$\Rightarrow \tilde{\pi}_{i22}^{C} = -I_{S2} +$$

$$(1+r)^{-2} G_4\{-bq_i^2 + (-b\tau_j q_j - b\tau_k q_k - c_i - c_{il})q_i + [P^2 \tilde{\alpha}_{44} + 2P(1-P)\tilde{\alpha}_{43} + (1-P)^2 \tilde{\alpha}_{42}]q_i\}$$

From equation (5.4), $\tilde{\tilde{\alpha}}_{22} = P^2 \tilde{\alpha}_{44} + 2P(1-P)\tilde{\alpha}_{43} + (1-P)^2 \tilde{\alpha}_{42}$, $c_{il} = c_i l$

$$\Rightarrow \tilde{\pi}_{i22}^{C} = -I_{S2} + (1+r)^{-2} G_4[-bq_i^2 + (\tilde{\tilde{\alpha}}_{22} - c_i - c_i l)q_i - b\tau_j q_j - b\tau_k q_k]$$

same procedures for $\tilde{\pi}_{i21}^{C}, \tilde{\pi}_{i20}^{C}$

$$\therefore \begin{cases} \tilde{\pi}_{i2}^{C} = -I_{S2} + \dfrac{G_4}{(1+r)^2}[-bq_i^2 + (\tilde{\tilde{\alpha}}_2 - c_i(1+l)]q_i - b\tau_j q_j - b\tau_k q_k\} & \text{if } l > 0 \\ \tilde{\pi}_{i2}^{C} = -I_{S2} + \dfrac{G_4}{(1+r)^2}[-bq_i^2 + (\tilde{\tilde{\alpha}}_2 - c_i)q_i - b\tau_j q_j - b\tau_k q_k] & \text{if } l \le 0 \end{cases}$$

as shown in equation (5.24)

A.2.14 Equation (5.25)

From the first-order profit-maximizing condition, Firms *i*'s, *j*'s and *k*'s reaction functions are

$$\frac{\partial \tilde{\pi}_{i2}^{C}}{\partial q_i} = -2bq_i - b\tau_j q_j - b\tau_k q_k + \tilde{\tilde{\alpha}}_2 - c_i(1+l) = 0$$

$$\frac{\partial \tilde{\pi}_{j2}^{C}}{\partial q_j} = -2b\tau_j q_j - bq_i - b\tau_k q_k + (\tilde{\tilde{\alpha}}_2 - c_j) = 0$$

$$\frac{\partial \tilde{\pi}_{k2}^{C}}{\partial q_k} = -2b\tau_k q_k - bq_i - b\tau_j q_j + (\tilde{\tilde{\alpha}}_2 - c_k) = 0$$

Hence, I can get

$$q_i = -\frac{\tau_j q_j}{2} - \frac{\tau_k q_k}{2} + \frac{\tilde{\tilde{\alpha}}_2 - c_i(1+l)}{2b} \quad (5.25a)$$

$$q_j = -\frac{q_i}{2\tau_j} - \frac{\tau_k q_k}{2\tau_j} + \frac{\tilde{\tilde{\alpha}}_2 - c_j}{2b\tau_j} \quad (5.25b)$$

$$q_k = -\frac{q_i}{2\tau_k} - \frac{\tau_j q_j}{2\tau_k} + \frac{\tilde{\tilde{\alpha}}_2 - c_k}{2b\tau_k} \quad (5.25c)$$

Bringing (5.25c) into (5.25b),

$$q_j = \frac{q_i}{2\tau_j} - \frac{\tau_k}{2\tau_j}\left(-\frac{q_i}{2\tau_k} - \frac{\tau_j q_j}{2\tau_k} + \frac{\tilde{\tilde{a}}_2 - c_k}{2b\tau_k}\right) + \frac{\tilde{\tilde{a}}_2 - c_j}{2b\tau_j}$$

$$= -\frac{2}{4\tau_j} q_i + \frac{1}{4\tau_j} q_i + \frac{1}{4} q_j - \frac{\tilde{\tilde{a}}_2 - c_k}{4b\tau_j} + \frac{2\tilde{\tilde{a}}_2 - 2c_j}{4b\tau_j}$$

$$\Rightarrow q_j = -\frac{1}{3\tau_j} q_i + \frac{\tilde{\tilde{a}}_2 - 2c_j + c_k}{3b\tau_j} \qquad (5.25d)$$

Bringing (5.25*c*) into (5.25*a*),

$$q_i = -\frac{\tau_j q_j}{2} - \frac{\tau_k}{2}\left(-\frac{q_i}{2\tau_k} - \frac{\tau_j q_j}{2\tau_k} + \frac{\tilde{\tilde{a}}_2 - c_k}{2b\tau_k}\right) + \frac{\tilde{\tilde{a}}_2 - c_i(1+l)}{2b}$$

$$= -\frac{2\tau_j}{4} q_j + \frac{1}{4} q_i + \frac{\tau_j}{4} q_j - \frac{\tilde{\tilde{a}}_2 - c_k}{4b} + \frac{2\tilde{\tilde{a}}_2 - 2c_i(1+l)}{4b}$$

$$\Rightarrow q_i = -\frac{\tau_j}{3} q_j + \frac{\tilde{\tilde{a}}_2 - 2c_i(1+l) + c_k}{3b} \qquad (5.25e)$$

Bringing (5.25*d*) into (5.25*e*),

$$q_i = -\frac{\tau_j}{3}\left(-\frac{1}{3\tau_j} q_i + \frac{\tilde{\tilde{a}}_2 - 2c_j + c_k}{3b\tau_j}\right) + \frac{\tilde{\tilde{a}}_2 - 2c_i(1+l) + c_k}{3b}$$

$$= \frac{1}{9} q_i + \frac{2\tilde{\tilde{a}}_2 - 6c_i(1+l) + 2c_j + 2c_k}{9b} \Rightarrow q_i^{\mathrm{C}} = \frac{\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k}{4b}$$

$$\therefore \begin{cases} q_i^{\mathrm{C}} = \dfrac{\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k}{4b} & \text{if } l > 0 \\ q_i^{\mathrm{C}} = \dfrac{\tilde{\tilde{a}}_2 - 3c_i + c_j + c_k}{4b} & \text{if } l \le 0 \end{cases} \quad \text{as shown in equation (5.25)}$$

A.2.15 Equation (5.26): Firm *i*'s resulting profit

$$q_j = -\frac{1}{3\tau_j}\left[\frac{\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_j}{4b}\right] + \frac{\tilde{\tilde{a}}_2 - 2c_j + c_k}{3b\tau_j} = \frac{\tilde{\tilde{a}}_2 - 3c_j + c_i(1+l) + c_k}{4b\tau_j}$$

$$q_k = \frac{\tilde{\tilde{a}}_2 - 3c_k + c_i(1+l) + c_j}{4b\tau_k}$$

$$\Rightarrow \tilde{\pi}_{i2}^{C} = -I_{S2} + \frac{G_4}{(1+r)^2}\{-bq_i^2 + [\tilde{\tilde{a}}_2 - c_i(1+l)]q_i - bq_i\tau_j q_j - bq_i\tau_k q_k\}$$

Let $V = -bq_i^2 + [\tilde{\tilde{a}}_2 - c_i(1+l)]q_i - bq_i\tau_j q_j - bq_i\tau_k q_k$

Bring q_j, q_k, q_i into V,

$$V = -b\left(\frac{\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k}{4b}\right)^2 + [\tilde{\tilde{a}}_2 - c_i(1+l)]\left(\frac{\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k}{4b}\right)$$
$$-b\tau_j\left(\frac{\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k}{4b}\right)\left(\frac{\tilde{\tilde{a}}_2 - 3c_j + c_i(1+l) + c_k}{4b\tau_j}\right)$$
$$-b\tau_k\left(\frac{\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k}{4b}\right)\left(\frac{\tilde{\tilde{a}}_2 - 3c_k + c_i(1+l) + c_j}{4b\tau_k}\right) = \frac{[\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k]^2}{16b}$$

$$\therefore \tilde{\pi}_{i2}^{C} = -I_{S2} + \frac{G_4}{(1+r)^2}\frac{[\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k]^2}{16b}$$

$$\tilde{\pi}_{i2}^{C} = -I_{S2} + \frac{G_4}{(1+r)^2}\frac{[\tilde{\tilde{a}}_2 - 3c_i(1+l) + c_j + c_k]^2}{16b} \quad \text{if } l > 0$$

as shown in equation (5.26)

$$\tilde{\pi}_{i2}^{C} = -I_{S2} + \frac{G_4}{(1+r)^2}\frac{[\tilde{\tilde{a}}_2 - 3c_i + c_j + c_k]^2}{16b} \quad \text{if } l \le 0$$

Appendix B: Case Study

B.1 Section 3.3

B.1.1 Demand structure patterns with product diffusion

- Demand structure pattern 2: if the project is first invested at time 1

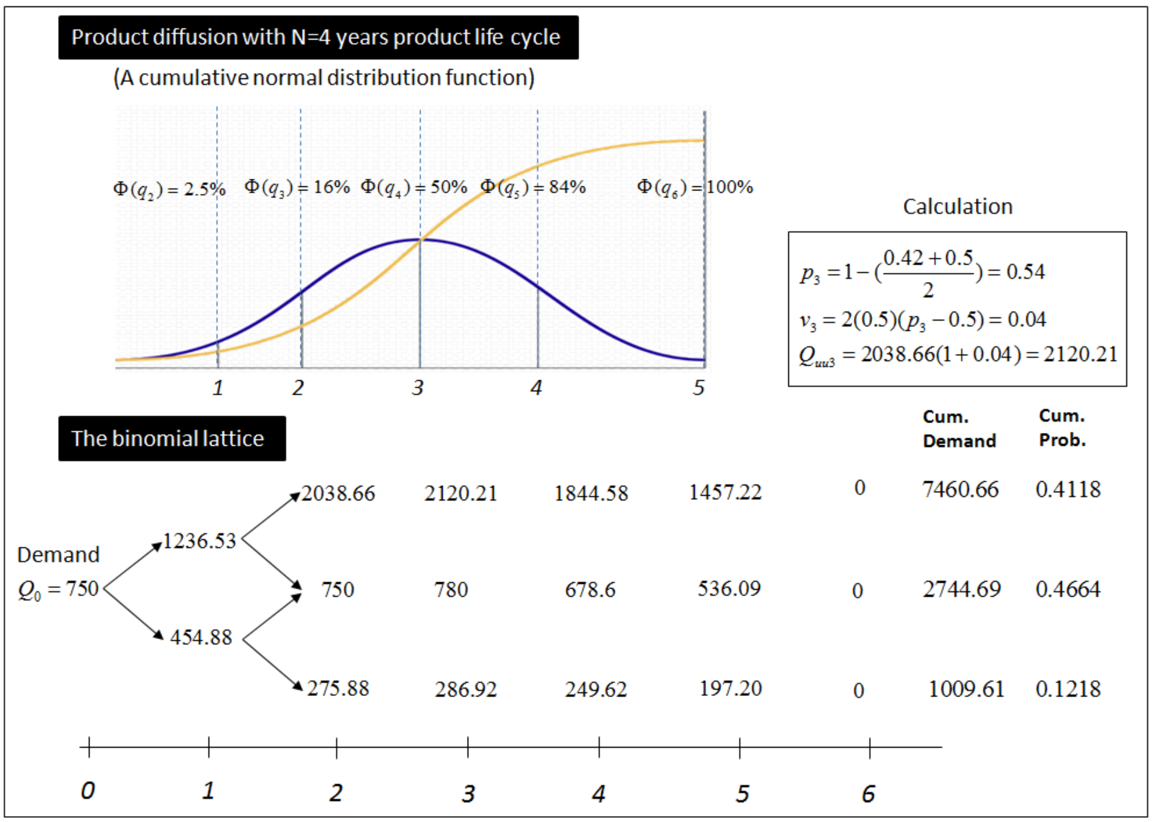

Fig. B1 The binomial lattice with product diffusion of N = 4 years product life cycle
(The second demand structure pattern: if the project is first invested at time 1)

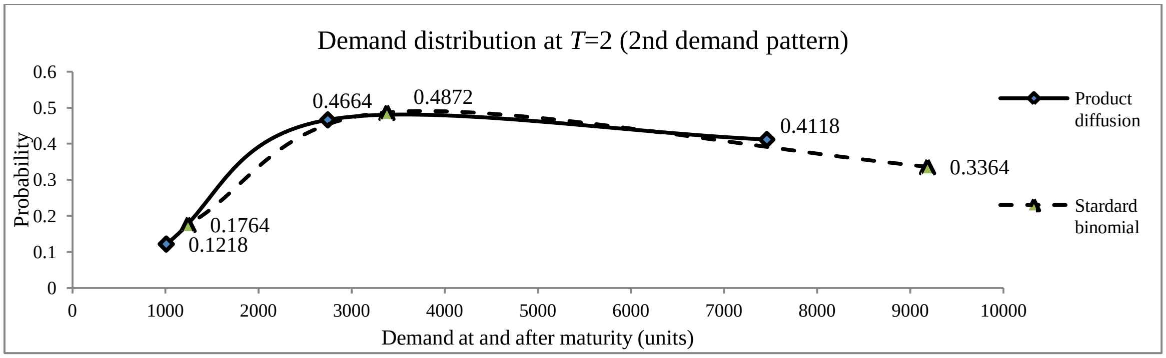

Fig. B2 Demand distribution at $T = 2$
(The second demand structure pattern: if the project is first invested at time 1)

- Demand structure pattern 3: if the project is first invested at time 2

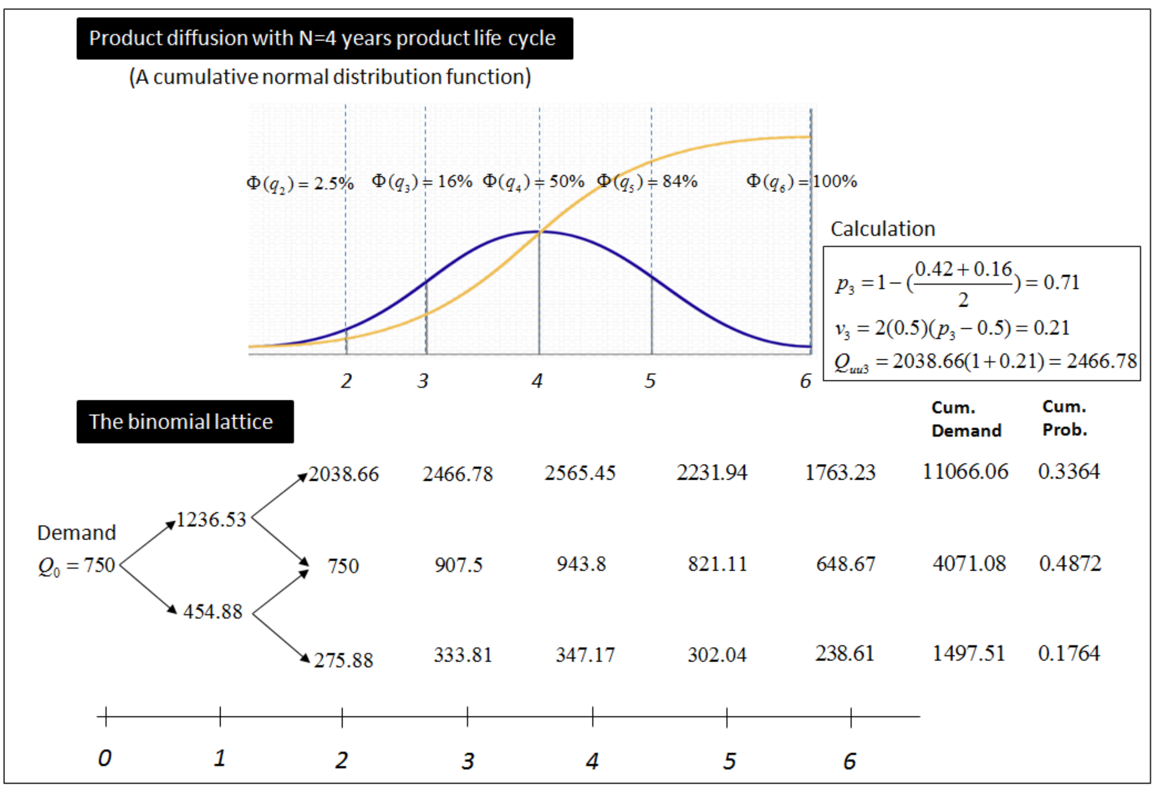

Fig. B3 The binomial lattice with product diffusion of $N = 4$ years product life cycle
(The third demand structure pattern: if the project is first invested at time 2)

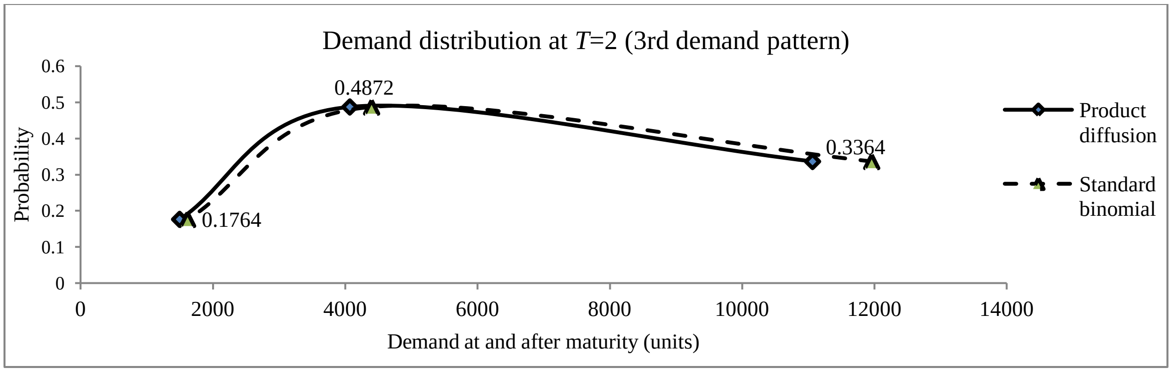

Fig. B4 Demand distribution at T = 2
(The third demand structure pattern: if the project is first invested at time 2)

B.1.2 Competitive outcome of the payoff matrix at time *t* = 0

- Scenario 1: Both invest

$$\pi_i^{\mathrm{C}}(q_i, q_j) = -34,500 + 178.5426 q_i - 0.1373 q_i^2 - 0.1373 q_i q_j$$
$$\frac{\partial \pi_i^{\mathrm{C}}(q_i, q_j)}{\partial q_i} = 178.5426 - 0.2746 q_i - 0.1373 q_j = 0, \quad \therefore q_i = 650.17 - 0.5 q_j$$
$$\pi_j^{\mathrm{C}}(q_i, q_j) = -34,500 + 164.8122 q_j - 0.1373 q_j^2 - 0.1373 q_i q_j$$
$$\frac{\partial \pi_j^{\mathrm{C}}(q_i, q_j)}{\partial q_j} = 164.8122 - 0.2746 q_j - 0.1373 q_i = 0, \quad \therefore q_j = 600.17 - 0.5 q_i$$
$$(q_i^*, q_j^*) = (466.78, 366.78) \Rightarrow (\pi_i^*, \pi_j^*) = (-4,583.59, -16,028.75)$$

- Scenario 2: Firm *i* invests now and Firm *j* waits
    - Case 1: Firm i invests now and Firm *j* invests at year 2

$$\pi_i^{\mathrm{L}}(q_i, q_j) = -34,500 + 168.5407 q_i - 0.1373 q_i^2 - 0.0528 q_i q_j$$
$$\frac{\partial \pi_i^{\mathrm{C}}(q_i, q_j)}{\partial q_i} = 168.5407 - 0.2746 q_i - 0.0528 q_j = 0, \quad \therefore q_i = 613.7476 - 0.1923 q_j$$
$$\pi_{j(2)}^{\mathrm{F}}(q_i, q_j) = -24926.3 + 67.2943 q_j - 0.0528 q_j^2 - 0.0528 q_i q_j$$
$$\frac{\partial \pi_{j(2)}^{\mathrm{F}}(q_i, q_j)}{\partial q_j} = 67.2943 - 0.1056 q_j - 0.0528 q_i = 0, \quad \therefore q_j = 637.2322 - 0.5 q_i$$
$$(q_i^*, q_j^*) = (543.47, 365.50) \Rightarrow (\pi_i^{\mathrm{L}*}, \pi_{j(2)}^{\mathrm{F}*}) = (6,054.15, -17,872.51)$$

- Case 2: Firm *i* invests now and Firm *j* abandons at time 2

$$\pi_i^{\mathrm{M}}(q_i, q_j) = -34,500 + 168.5407q_i - 0.1373q_i^2$$
$$\frac{\partial \pi_i^{\mathrm{C}}(q_i, q_j)}{\partial q_i} = 168.5407 - 0.2746q_i = 0, \quad \therefore q_i = 613.7476$$
$$(q_i^*, 0) = (613.75, 0) \Rightarrow (\pi_i^{\mathrm{M}*}, 0) = (17,220.72, 0)$$

- Case 3: Firm *i* invests now and Firm *j* invests at time 1

$$\pi_i^{\mathrm{L}}(q_i, q_j) = -34,500 + 168.5407q_i - 0.1373q_i^2 - 0.0927q_i q_j$$
$$\frac{\partial \pi_i^{\mathrm{L}}(q_i, q_j)}{\partial q_i} = 168.5407 - 0.2746q_i - 0.0927q_j = 0, \quad \therefore q_i = 613.7476 - 0.3374q_j$$
$$\pi_{j(1)}^{\mathrm{F}}(q_i, q_j) = -29325 + 118.0941q_j - 0.0926q_j^2 - 0.0926q_i q_j$$
$$\frac{\partial \pi_{j(1)}^{\mathrm{F}}(q_i, q_j)}{\partial q_j} = 118.0941 - 0.1853q_j - 0.0927q_i = 0, \quad \therefore q_j = 637.2322 - 0.5q_i$$
$$(q_i^*, q_j^*) = (479.65, 397.41) \Rightarrow (\pi_i^{\mathrm{L}*}, \pi_{j(1)}^{\mathrm{F}*}) = (-2,911.15, -14,690.70)$$

$$\Rightarrow \begin{cases} \text{Firm } j : \pi_j^{\mathrm{F}}(q_i, q_j^{**}) = \max[\pi_{j(2)}^{\mathrm{F}}(q_i, q_j^*), \pi_{j(1)}^{\mathrm{F}}(q_i, q_j^*), 0] = 0 \\ \text{Firm } i : \pi_i^{\mathrm{L}}(\pi_j^{\mathrm{F}}(q_i, q_j^{**})) = 17,220.72 \end{cases} \quad \text{(Case 2 is selected)}$$

- Scenario 3: Firm *j* invests now and Firm *i* waits

Scenario 3 is the same concept as shown in scenario 2, hence,

$$\begin{cases} \text{Firm i} : \pi_i^{\mathrm{F}}(q_i^{**}, q_j) = \max[\pi_{i(2)}^{\mathrm{F}}(q_i^*, q_j), \pi_{i(1)}^{\mathrm{F}}(q_i^*, q_j), 0] = 0 \\ \text{Firm } j : \pi_j^{\mathrm{L}}(\pi_i^{\mathrm{F}}(q_i^{**}, q_j)) = 9,136.95 \end{cases}$$
$$\therefore (q_i^*, q_j^*) = (0, 563.75)$$

(Case 2 is selected: Firm j invests now and Firm i abandons at $t = 2$)

- Scenario 4: Both wait

  - At time 2 (the UU status)

(1) Both invest at time 2

$$\pi_{i2}^{\mathrm{C}}(q_i, q_j) = -24{,}926.3 + 429.6777 q_i - 0.1706 q_i^2 - 0.1706 q_i q_j$$

$$\frac{\partial \pi_{i2}^{\mathrm{C}}(q_i, q_j)}{\partial q_i} = 429.6777 - 0.3412 q_i - 0.1706 q_j = 0, \quad \therefore q_i = 1{,}259.14 - 0.5 q_j$$

$$\pi_{j2}^{\mathrm{C}}(q_i, q_j) = -24926.3 + 412.6154 q_j - 0.1706 q_j^2 - 0.1706 q_i q_j$$

$$\frac{\partial \pi_{j2}^{\mathrm{C}}(q_i, q_j)}{\partial q_j} = 412.6154 - 0.3412 q_j - 0.1706 q_i = 0, \quad \therefore q_j = 1{,}209.141 - 0.5 q_i$$

$$(q_i^*, q_j^*) = (872.76, 772.76) \Rightarrow (\pi_{i2}^{\mathrm{C}*}, \pi_{j2}^{\mathrm{C}*}) = (105{,}039.45, 76{,}963.02)$$

(2) Firm *i* invests and Firm *j* abandons at time 2

$$\pi_{i2}^{\mathrm{M}}(q_i, q_j) = -24{,}926.3 + 429.6777 q_i - 0.1706 q_i^2$$

$$\frac{\partial \pi_{i2}^{\mathrm{M}}(q_i, q_j)}{\partial q_i} = 429.6777 - 0.3412 q_i = 0, \therefore q_i = 1{,}259.14$$

$$(q_i^*, q_j^*) = (1{,}259.14, 0) \Rightarrow (\pi_{i2}^{\mathrm{M}*}, 0) = (245{,}586.14, 0)$$

(3) Firm *j* invests and Firm *i* abandons at time 2

$$\pi_{j2}^{\mathrm{M}}(q_i, q_j) = -24{,}926.3 + 412.6154 q_j - 0.1706 q_j^2$$

$$\frac{\partial \pi_{j2}^{\mathrm{M}}(q_i, q_j)}{\partial q_j} = 412.6054 - 0.3412 q_j = 0, \therefore q_j = 1{,}209.14$$

$$(q_i^*, q_j^*) = (0, 1{,}209.14) \Rightarrow (0, \pi_{j2}^{\mathrm{M}*}) = (0, 224{,}528.81)$$

(4) Both abandon at time 2 with values $= (0, 0)$

Therefore, the payoff matrix of the status UU at time 2 is summarized as

π_i, π_j		Firm *j*			
		Invest		Wait	
Firm *i*	Invest	105,039.45	76,963.02	245,586.14	0.00
	Wait	0.00	224,528.81	0.00	0.00

- At time 2 (the UD status)

The procedure is the same as above. The payoff matrix of the status UD at time 2 is shown as

π_i, π_j		Firm j			
		Invest		Wait	
Firm i	Invest	-9,570.15	-18,101.32	2,373.49	0.00
	Wait	0.00	-4,024.89	0.00	0.00

- At time 2 (the DD status)

The payoff matrix of the status DD at time 2 is summarized as

π_i, π_j		Firm j			
		Invest		Wait	
Firm i	Invest	-23,565.82	-24,906.69	-23,724.06	0.00
	Wait	0.00	-24,729.71	0.00	0.00

- At time 1 (the U status)

The payoff matrix of the status U at time 1 is summarized as

π_i, π_j		Firm j			
		Invest		Wait	
Firm i	Invest	41,091.46	22,572.19	66,065.14	4,092.79
	Wait	14,448.09	48,220.87	43,866.24	31,189.56

- At year 1 (the D status)

The payoff matrix of the status D at time 1 is summarized as

π_i, π_j		Firm j			
		Invest		Wait	
Firm i	Invest	-20,571.08	-25,094.71	-15,918.36	0.00
	Wait	0.00	-19,913.80	961.86	0.00

B.1.3 The NPV approach

The demand has an expected yearly growth rate of g = 8% based on the past project experience and experts' market observation. The current (inverse) demand function is given as $p_0 = 50 - 0.05Q_0$. Firm i has a cost advantage where Firm i's unit variable cost (c_i = \$10) is less than Firm j's (c_j = \$15). Assume that demand and supply are equivalent. The capacity of Firm i can be defined by the number of competitors and the unit variable costs. Hence, the capacity of Firm *i* is $q_i = (\frac{15}{10+15})Q = 0.6Q$. The current fixed investment cost is given as I_0 = $34,500. The project will operate for a finite service life of N = 4 years with the interest rate r = 12%. Therefore, with the above information, I can compute from equations (3.24) to (3.26) and get

$$\omega = \frac{10}{10+15} = 0.6, Q = \frac{a_0 - \bar{c}}{2b} = 375, G = \sum_{m=1}^{4} (\frac{1+0.08}{1+0.12})^m = 3.6554, \bar{c} = \frac{10+15}{2} = 12.5$$

$$\therefore \text{NPV}_i = -34,500 + \frac{(50-12.5)(50+12.5-20)(0.6)(3.6554)}{4(0.05)} = -17,022.6 \text{ with } q_i = 225$$

Finally, NPV is calculated as -$17,022.6 with an average annual planned capacity of 225 units.

B.1.4 Sensitivity analyses

Table B1 shows the payoffs and option values in each scenario when the expected growth rate decreases as 5% and increases as 11%. All other parameters are the defaults. Table B1 shows that the payoffs and option values of Firm *i* will increase when the expected growth rates increase.

Table B1 Sensitivity of project and option value to expected growth rate *g*

Scenario 1									
Firm *i*	*g* =	0.05	0.08	0.11	Firm *j*	*g* =	0.05	0.08	0.11
Payoff		-6,213.7	-4,583.8	-2,871.6	Payoff		-17,258.0	-16,028.8	-14,728.9
Scenario 2									
Firm *i*	*g* =	0.05	0.08	0.11	Firm *j*	*g* =	0.05	0.08	0.11
Payoff		12,179.4	17,220.7	22,721.9	Option value		0.0	0.0	0.0
Scenario 3 is the same concept as scenario 2									
Scenario 4									
Firm *i*	*g* =	0.05	0.08	0.11	Firm *j*	*g* =	0.05	0.08	0.11
Option value		15,756.6	17,178.7	18,652.9	Option value		8,158.7	9,147.5	10,176.2

Table B2 shows the payoffs and option values in each scenario when the expected standard deviation decreases as 25% and extends as 75%. All other parameters are the defaults. In most cases, the payoffs and option values will increase when the expected standard deviation is higher. In scenario 2, Firm *i*'s payoffs at σ = 0.5 and 0.75 are $17,220.7 and $11,554.7, a result which does not raise Firm *i*'s payoff with a higher standard deviation. The main reason for this result is that the higher standard deviation increases Firm *j*'s option value, an increase which makes Firm *j* invest the project at time 1 instead of abandoning the project as in the default setting. Hence, with the growing standard deviation in scenario 2, Firm *i* may gain a lower payoff from the next period of competitive outcome at time 1, since Firm *j* may change its investment decision due to the increasing option value.

Table B2 Sensitivity of project and option value to expected standard deviation σ

Scenario 1									
Firm *i*	σ =	0.25	0.5	0.75	Firm *j*	σ =	0.25	0.5	0.75
Payoff		-14,278.7	-4,583.8	15,976.4	Payoff		-23,692.7	-16,028.8	1,126.2
Scenario 2									
Firm *i*	σ =	0.25	0.5	0.75	Firm *j*	σ =	0.25	0.5	0.75
Payoff		3,011.3	17,220.7	11,554.7	Option value		0.0	0.0	4,620.1
Scenario 3 is the same concept as scenario 2									
Scenario 4									
Firm *i*	σ =	0.25	0.5	0.75	Firm *j*	σ =	0.25	0.5	0.75
Option value		6,225.82	17,178.7	45,132.3	Option value		1,142.98	9,147.5	35,237.9

Table B3 shows the payoffs and option values in each scenario when unit variable costs are either close as (12, 13), or diverged as (8, 17). All other parameters are the defaults. Overall, the payoffs and option values would increase for Firm *i* and decrease for Firm *j* when the unit variable costs are greatly varied.

Table B3 Sensitivity of project and option value to unit variable costs (c_i, c_j)

Scenario 1									
Firm *i*	*ci,cj*	12,13	10,15	8,17	Firm *j*	*ci,cj*	12,13	10,15	8,17
Payoff		-9,491.2	-4,583.8	763.4	Payoff		-11,780.2	-16,028.8	-19,837.9
Scenario 2									
Firm *i*	*ci,cj*	12,13	10,15	8,17	Firm *j*	*ci,cj*	12,13	10,15	8,17
Payoff		13,904.8	17,220.7	19,790.2	Option value		0.0	0.0	0.0
Scenario 3 is the same concept as scenario 2									
Scenario 4									
Firm *i*	*ci,cj*	12,13	10,15	8,17	Firm *j*	*ci,cj*	12,13	10,15	8,17
Option value		13,449.4	17,178.7	21,121.2	Option value		12,012.3	9,147.5	6,465.5

Table B4 shows the payoffs and option values in each scenario when product service life is reduced as two years and extended as six years. All other parameters are the defaults. Overall, the payoffs and option values of Firm *i* and *j* will increase when the product service life is longer. In scenario 2, Firm *i*'s payoffs at N = 4 and 6 are \$17,220.7 and \$2,792.5, a result which does not raise Firm *i*'s payoff with a longer service life. The main reason for this result is that the longer service life increases Firm *j*'s option value, an increase which makes Firm *j* invest the project at time 1 instead of abandoning the project as in the default setting. Hence, with the longer service life in scenario 2, Firm *i* may gain lower payoff from the next period of competitive outcome at time 1, since Firm *j* may change its investment decision due to the increasing option value.

Table B4 Sensitivity of project and option value to project service life N

Scenario 1									
Firm *i*	N =	2	4	6	Firm *j*	N =	2	4	6
Payoff		-24,714.0	-4,583.8	14,144.6	Payoff		-29,628.9	-16,028.8	-3,373.8
Scenario 2									

Firm *i*	N =	2	4	6	Firm *j*	N =	2	4	6
Payoff		-8,352.4	17,220.7	2,792.5	Option value		0.0	0.0	3,783.3
Scenario 3 is the same concept as scenario 2									
Scenario 4									
Firm *i*	N =	2	4	6	Firm *j*	N =	2	4	6
Option value		5,614.9	17,178.7	34,197.1	Option value		4,315.9	9,147.5	19,399.1

B.2 Section 4.3

B.2.1 For section 4.3.1

The summation of growth after product launch is obtained as

$$G_4 = \frac{1+0.21}{1.12} + \frac{(1.21)(1+0.04)}{(1.12)^2} + \frac{(1.21)(1.04)(1-0.13)}{(1.12)^3} + \frac{(1.21)(1.04)(0.87)(1-0.21)}{(1.12)^4}$$
$$= 3.4125$$

The values of $\tilde{\tilde{a}}_{22}, \tilde{\tilde{a}}_{21,}\ and\ \tilde{\tilde{a}}_{20}$ are

$$\tilde{\tilde{a}}_{22} = 0.54^2(149.51) + 2(0.54)(0.46)(90.68) + (0.46)^2(55) = 100.28$$
$$\tilde{\tilde{a}}_{21} = 0.54^2(90.68) + 2(0.54)(0.46)(55) + (0.46)^2(33.36) = 60.83$$
$$\tilde{\tilde{a}}_{20} = 0.54^2(55) + 2(0.54)(0.46)(33.36) + (0.46)^2(20.23) = 36.89$$
$$\Rightarrow \bar{a}_{00} = 0.54^2(100.28) + 2(0.54)(0.46)(60.83) + (0.46)^2(36.89) = 67.27$$

From equation (4.10),

$$\text{NPV}_{i00} = -I + \frac{G_4\omega}{(1+r)^4}\frac{(\bar{a}_{00} - \bar{c})(\bar{a}_{00} + \bar{c} - 2c_i)}{4b}$$
$$= -33,955.2 + \frac{3.41(0.6591)}{1.12^1}\frac{(67.27-11)(67.27+11-20)}{4(0.05)} = -1,036.61$$

$\therefore$ NPV (benchmark A) has a payoff value of -\$1,036.61, taking an action of "kill" .

From equations (4.20), the profit functions of Firm *i* at the second sub-gates are

$$\tilde{\pi}^{C}_{i22} = -25,000 + \frac{3.41}{1.12^{2/4}}\frac{[100.28 - 2(10) + 12]^2}{9(0.05)} = 36,023.17$$

$$\tilde{\pi}^{C}_{i21} = -25,000 + \frac{3.41}{1.12^{2/4}}\frac{[60.83 - 2(10) + 12]^2}{9(0.05)} = -5,004.79$$

$$\tilde{\pi}^{C}_{i20} = -25,000 + \frac{3.41}{1.12^{2/4}} \frac{[36.89 - 2(10) + 12]^2}{9(0.05)} = -19,018.50$$

The payoff matrices at statuses 22, 21, and 20:

At status 22	j go		j kill	
i go	36,023.17	46,128.04	106,415.29	0
i kill	0	142,543.3	0	0
At status 21	j go		j kill	
i go	-5,004.79	-4,052.07	16,647.04	0.00
i kill	0	26,245.13	0	0
At status 20	j go		j kill	
i go	-19,018.52	-19,993.2	-13,340.42	0
i kill	0	-11,680.3	0	0

The payoff matrices at statuses 11, 10, and 00 can be computed from equation (4.23) and (4.24) as

At status 11	j go		j kill	
i go	16,911.22	24,465.67	58,047.68	0
i kill	0	81,597.71	0	0
At status 10	j go		j kill	
i go	-1586.1894	958.6563	2,827.621	0
i kill	0	7,917.313	0	0
At status 00	j go		j kill	
i go	4,467.71	12,096.62	27,575.52	0
i kill	0	42,392.69	0	0

$\therefore$ Option game has SNPV of \$8,967.71(=4,467.71+4,500), Firm i takes an action of "go."

B.2.2 For section 4.3.2: Bayesian analysis

Given Table 4.2 and the sample collection of $\sum_{i=1}^{8}(x_i - 0.02)^2 = 0.30$,

From equation (4.11), we can compute

$\alpha' = 19.028 + \frac{8}{2} = 23.028$ and $\beta' = [\frac{1}{0.142} + \frac{1}{2}\sum_{i=1}^{8}(x_i - 0.02)^2]^{-1} = 0.139$

Hence, the updated customer requirement and preference x is then t distributed as

$\mathrm{m}(\mathrm{x}|z) = St[x|0.02, (23.028 \times 0.139)^{-1}, 46.056]$

with mean $E(x|z)=0.02, Var(x|z)=\frac{46.056(23.028\times 0.139)^{-1}}{46.056-2}=0.3265$

$\Rightarrow \xi' = 0.5714$

From equation (4.12), we can obtain σ'=0.4571

<u>Summary of prior and posterior distributions:</u>

	Prior	Posterior
g(ξ_x)	$IG(19.028, 0.142)$	$IG(23.028, 0.139)$
m(x)	$St(x\|0.02, 0.37, 38.056)$ $E(x)=0.02, Var(x)=0.39052$	$St(x\|0.02, 0.3124, 46.056)$ $E(x)=0.02, Var(x)=0.3265$
w(y)	$N(0.08, 0.5^2)$	$N(0.08, 0.4571^2)$
f(Q_1)	lognormal distribution $E(Q_1)=750(e^{0.08})=812.465$ $Var(Q_1)=750^2\cdot e^{2(0.08)}(e^{0.5^2}-1)$ $=187485$	lognormal distribution $E(Q_1)=750(e^{0.08})=812.465$ $Var(Q_1)=750^2\cdot e^{2(0.08)}(e^{0.4571^2}-1)$ $=153388.43$

Hence, the summation of the growth after launch is updated and obtained as

$$G_4' = \frac{1+0.1954}{1.12}+\frac{(1.1954)(1+0.04)}{(1.12)^2}+\frac{(1.1954)(1.04)(1-0.1154)}{(1.12)^3}$$
$$+\frac{(1.196)(1.04)(0.8846)(1-0.1886)}{(1.12)^4}=3.4083$$

I can update the values of $\tilde{\tilde{a}}'_{22}, \tilde{\tilde{a}}'_{21}, and\ \tilde{\tilde{a}}'_{20}$ as

$$\tilde{\tilde{a}}'_{22}=0.5438^2(140.19)+2(0.5438)(0.4562)(88.76)+(0.4562)^2(56.19)=77.09$$

$$\tilde{\tilde{a}}'_{21}=0.5438^2(88.76)+2(0.5438)(0.4562)(56.19)+(0.4562)^2(35.58)=48.81$$

$$\tilde{\tilde{a}}'_{20}=0.5438^2(56.19)+2(0.5438)(0.4562)(35.58)+(0.4562)^2(21.58)=30.70$$

(Benchmark B)

$$\tilde{\pi}_{i22}^{B'}=-25,000+\frac{3.4083(0.591)}{(1.12)^{2/4}}\frac{(77.09-11)(77.09+11-20)}{4(0.05)}=17,823.88$$

$$\tilde{\pi}_{i21}^{B'}=-25,000+\frac{3.4083(0.591)}{(1.12)^{2/4}}\frac{(48.81-11)(48.81+11-20)}{4(0.05)}=-10,678.90$$

$$\tilde{\pi}_{i20}^{B'}=-25,000+\frac{3.4083(0.591)}{(1.12)^{2/4}}\frac{(30.70-11)(30.70+11-20)}{4(0.05)}=-20,930.90$$

$$\begin{cases} SNPV_{i11}^{B'} = \dfrac{(0.5515)\max[17,823.88,0]+(0.4485)\max[-10,678.9,0]}{(1+0.05)^{1/4}} = \$9,711.4 \text{ (go)} \\ SNPV_{i10}^{B'} = \dfrac{(0.5515)\max[-10,678.9,0]+(0.4485)\max[-20,930.9,0]}{(1+0.05)^{1/4}} = \$0 \text{ (kill)} \end{cases}$$

The profit functions of Firm *i* by the option-game approach for the up and down at the first sub-gates of the development stages are:

$$\tilde{\pi}_{i22}^{C'} = -25,000 + \frac{3.4083}{(1.12)^{2/4}} \frac{[77.09-2(10)+12]^2}{9(0.05)} = 9,165.90$$

$$\tilde{\pi}_{i21}^{C'} = -25,000 + \frac{3.4083}{(1.12)^{2/4}} \frac{[48.81-2(10)+12]^2}{9(0.05)} = -13,081.90$$

$$\tilde{\pi}_{i20}^{C'} = -25,000 + \frac{3.4083}{(1.12)^{2/4}} \frac{[30.7-2(10)+12]^2}{9(0.05)} = -21,311$$

The updated payoff matrix at statuses 22, 21, and 20

At status 22	j go		j kill	
i go	9,165.902	6,655.196	47,487.29	0
i kill	0	50,811.24	0	0
At status 21	j go		j kill	
i go	-13,081.9	-15,365.4	-748.256	0
i kill	0	-759.464	0	0
At status 20	j go		j kill	
i go	-21,311	-22,781.3	-18,097.7	0
i kill	0	-18,740.9	0	0

The updated payoff matrix at statuses 11 and 10 can be computed from equation (4.26) as

At status 11	j go		j kill	
i go	-1,005.93	-2,373.9	19,873.59	0
i kill	0	21,684.66	0	0
At status 10	j go		j kill	
i go	-6,000	-6,000	-6,000	0
i kill	0	-6,000	0	0

$\therefore$ At the status of "11": the option-game approach has SNPV of \$12,936.8 [=(19,873.59+6,000)$\times$0.5],

Firm *i* takes an action of "go/kill," a Prisoner's Dilemma.

At the status of "10": the option-game approach has SNPV of \$0,

Firm *i* takes an action of "kill."

B.3 Section 5.3

B.3.1 For section 5.3.1

The summation of growth after product launch is obtained as

$$G_4 = \frac{1+0.21}{1.12} + \frac{(1.21)(1+0.04)}{(1.12)^2} + \frac{(1.21)(1.04)(1-0.13)}{(1.12)^3} + \frac{(1.21)(1.04)(0.87)(1-0.21)}{(1.12)^4}$$
$$= 3.4125$$

The values of $\tilde{\tilde{a}}_{22}, \tilde{\tilde{a}}_{21,}\ and\ \tilde{\tilde{a}}_{20}$ are

$$\tilde{\tilde{a}}_{22} = 0.54^2(184.84) + 2(0.54)(0.46)(112.11) + (0.46)^2(68) = 123.99$$
$$\tilde{\tilde{a}}_{21} = 0.54^2(112.11) + 2(0.54)(0.46)(68) + (0.46)^2(41.24) = 75.20$$
$$\tilde{\tilde{a}}_{20} = 0.54^2(68) + 2(0.54)(0.46)(41.24) + (0.46)^2(25.02) = 45.61$$
$$\Rightarrow \bar{a}_{00} = 0.54^2(123.99) + 2(0.54)(0.46)(75.20) + (0.46)^2(45.61) = 83.17$$

From equation (5.7), $\omega = 1 - \frac{12(0.95)+10(0.9)}{10+12+13} = 0.4171$

$$\bar{c} = \frac{c_i + \sum_{k=1}^{n-1} c_{jk}}{n} = \frac{10+12+13}{3} = 11.67$$

From equation (5.10),

$$\text{NPV}_{i00} = -I + \frac{G_4\omega}{(1+r)^1}\frac{(\bar{a}_{00} - \bar{c})(\bar{a}_{00} + \bar{c} - 2c_i - 2c_{il})}{4b}$$
$$= -33{,}955.2 + \frac{3.41(0.4171)}{(1.12)^1}\frac{(83.17-11.67)[83.17+11.67-2(10)-2(0.2)]}{4(0.05)} = -135.05$$

$\therefore$ The NPV method has payoff value of -\$135.05, taking an action of "kill".

From equation (5.26), the profit functions of Firm *i* in the 3-player Cournot competition at the second sub-gates are

$$\tilde{\pi}^{C}_{i22} = -25{,}000 + \frac{3.41}{(1.12)^{2/4}}\frac{[123.99 - 3(10)(1.02) + 25]^2}{4^2(0.05)} = 31{,}490.61$$
$$\tilde{\pi}^{C}_{i21} = -25{,}000 + \frac{3.41}{(1.12)^{2/4}}\frac{[75.10 - 3(10)(1.02) + 25]^2}{4^2(0.05)} = -5{,}474.12$$

$$\tilde{\pi}_{i20}^{C} = -25,000 + \frac{3.41}{(1.12)^{2/4}} \frac{[45.61 - 3(10)(1.02) + 25]^2}{4^2(0.05)} = -18,547.1$$

By applying Nash equilibrium with the best response analysis, the payoff matrices at statuses of “22,” “21,” and “20” are as follows:

“22”	i	**j go**	**k go**	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	**31491**	**27451**	**26453**	**72397**	0	**68187**	**70733**	66576	0	**183744**	0	0
i kill	0	71290	71313	0	0	195663	0	187833	0	0	0	0
“21”	i	**j go**	**k go**	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	-5474	-8479	-9725	**7940**	**0**	**3093**	**6976**	**3437**	**0**	**43121**	0	0
i kill	**0**	**6090**	**4822**	0	0	**44310**	0	**42790**	0	0	0	0
“20”	i	**j go**	**k go**	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	-18547	-20432	-21282	-14537	0	-17924	-15078	-17367	0	-4782	0	0
i kill	**0**	-15964	-17044	**0**	**0**	-5948	**0**	-5827	0	**0**	**0**	**0**

By applying Nash equilibrium with the best response analysis, the payoff matrices at the statuses of “11” and “10” are as follows:

“11”	i	**j go**	**k go**	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	**12974**	**10010**	**9235**	**36024**	0	**31574**	**34701**	**30877**	0	**111168**	0	0
i kill	0	34590	**34022**	0	0	**118032**	0	113185	0	0	0	0
“10”	i	j go	k go	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	-3363	-4316	-4601	-1789	**0**	-4360	-2301	-4177	**0**	**16866**	**0**	**0**
i kill	**0**	-2771	-3443	**0**	**0**	**17497**	**0**	**16691**	**0**	0	0	0

By applying Nash equilibrium with the best response analysis, the payoff matrix at time 0 is:

“00”	i	j go	k go	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	**4418**	**3031**	**2818**	18462	0	16246	17760	15692	0	62168	0	0
i kill	0	15754	15708	0	0	66097	0	63157	0	0	0	0

∴ The option-game has the SNPV of $8,918.17(=4,418.17+4,500), taking an action of "go" for Firm *i*.

B.3.2 For section 5.3.2: Determination of parameters (θ,ρ,α,β) in the prior distribution of customer requirements and preferences *x*

$$\begin{cases} E(\xi_x^2) = 0.1953 = \dfrac{1}{\beta(\alpha-1)} \\ Var(\xi_x^2) = 0.0029 = \dfrac{1}{\beta^2(\alpha-1)^2(\alpha-2)} \end{cases} \Rightarrow \alpha = 15.1524, \beta = 0.3618$$

$$\begin{cases} E(\mu_x) = 0.02 = \theta \\ Var(\mu_x) = 0.1953 = \dfrac{\rho}{(\alpha-1)\beta} = \dfrac{\rho}{14.1524(0.3618)} \Rightarrow \rho = 1 \end{cases}$$

$$\Rightarrow m(x) = St(x|\theta, \frac{\rho+1}{\alpha\beta}, 2\alpha) = St(x|0.02, 0.3648, 30.3)$$

with $E(x) = 0.02$, and $Var(x) = \dfrac{2}{14.1524(0.3618)} = 0.3906$

- Determination of parameters (θ',ρ',α',β') in the posterior distribution

Given the sample distribution $n = 6, \bar{x} = 0.05, \sum_{i=1}^{6}(x_i - \bar{x})^2 = 0.125$,

$$\alpha' = \alpha + \frac{n}{2} = 15.1524 + \frac{6}{2} = 18.1524$$

$$\beta' = [\frac{1}{\beta} + \frac{1}{2}\sum_{i=1}^{6}(x_i - \bar{x})^2 + \frac{n(\bar{x}-\theta)^2}{2(1+n\rho)}]^{-1} = 0.3537$$

$$\theta' = \frac{\theta + n\rho\bar{x}}{n\rho+1} = \frac{0.02 + 6(0.05)}{6+1} = 0.0457, \rho' = \frac{\rho}{1+n\rho} = 0.1429$$

Unknown parameters	**Moment**	**Value**
Mean μ_x	$E(\mu_x\|z)$	0.0457
	$Var(\mu_x\|z)$	0.0235
Variance ξ_x^2	$E(\xi_x^2\|z)$	0.1648
	$Var(\xi_x^2\|z)$	0.0017

$$\Rightarrow m(x|z) = St(x|\theta', [\frac{(\rho^{-1}+n)(\alpha+\frac{n}{2})\beta'}{\rho^{-1}+n+1}]^{-1}, 2\alpha+n) = St(x|0.0457, 0.1780, 36.3)$$

with $E(x|z) = \theta' = 0.0457$, and $Var(x|z) = \dfrac{\rho^{-1}+n+1}{(\alpha+\frac{n}{2}-1)(\rho^{-1}+n)\beta'} = 0.1884$

$$\Rightarrow y' = \gamma x' + \varepsilon \approx N(\gamma\mu_x' + \varepsilon, \gamma^2 \xi_x^{2'}) = N[0.8(0.0457) + 0.064, 0.8^2(0.1884)]$$
$$\therefore g' = 0.1006, \sigma^{2'} = 0.3472^2$$

$$lnN(6.72, 0.3472) \quad \therefore \begin{cases} E(Q_1) = 750(e^{0.1006}) = 829.38 \\ Var(Q_1) = 750^2 \cdot e^{2(0.1006)}(e^{0.3472^2} - 1) = 88125.4951 \end{cases}$$

- Bayesian analysis for product performance s

From equation (5.19), we can compute

$\alpha_s' = 15.0025 + \frac{8}{2} = 19.0025$ and $\beta_s' = [\frac{1}{0.3527} + \frac{1}{2}\sum_{i=1}^{8}(s_i - 0)^2]^{-1} = 0.345$

Hence, product perfprmance s' is then t distributed as

$m(s|z_s) = St[s|0, (19.0025 \times 0.345)^{-1}, 38.005]$

with mean $E(s) = 0, Var(s) = \frac{38.005(19.0025 \times 0.345)^{-1}}{38.005 - 2} = 0.161$

$\Rightarrow \xi_s' = 0.4012, \therefore \mu_l' = 0.0457, \xi_l' = 0.591$

- Hence, the summation of growth after launch is updated and obtained as

$$G_4' = \frac{1 + 0.1683}{1.12} + \frac{(1.1683)(1 + 0.0503)}{(1.12)^2} + \frac{(1.1683)(1 + 0.0503)(1 - 0.0678)}{(1.12)^3}$$
$$+ \frac{(1.1683)(1 + 0.0503)(1 - 0.0678)(1 - 0.1233)}{(1.12)^4} = 3.473$$

I can update the values of $\tilde{\tilde{a}}'_{22}, \tilde{\tilde{a}}'_{21}, and\ \tilde{\tilde{a}}'_{20}$ as

$$\tilde{\tilde{a}}'_{22} = 0.5724^2(146.98) + 2(0.5724)(0.4276)(103.87) + (0.4276)^2(73.4) = 90.68$$
$$\tilde{\tilde{a}}'_{21} = 0.5724^2(103.87) + 2(0.5724)(0.4276)(73.4) + (0.4276)^2(51.87) = 64.08$$
$$\tilde{\tilde{a}}'_{20} = 0.5724^2(73.4) + 2(0.5724)(0.4276)(51.87) + (0.4276)^2(31.46) = 44.34$$

(Benchmark B)

$$\tilde{\pi}_{i22}^{B'} = -25,000 + \frac{3.473(0.4)}{(1.12)^{2/4}} \frac{(90.68 - 11.67)[90.68 + 11.67 - 2(10) - 2(0.0457)]}{4(0.05)} = 49,838.25$$
$$\tilde{\pi}_{i21}^{B'} = -25,000 + \frac{3.473(0.4)}{(1.12)^{2/4}} \frac{(64.08 - 11.67)[64.08 + 11.67 - 2(10) - 2(0.0457)]}{4(0.05)} = 8,245.72$$

$$\tilde{\pi}_{i20}^{\mathrm{B'}} = -25,000 + \frac{3.473(0.4)}{(1.12)^{2/4}} \frac{(44.34-11.67)[44.34+11.67-2(10)-2(0.0457)]}{4(0.05)} = -11,866.71$$

$$\begin{cases} SNPV_{i11}^{\mathrm{B'}} = \dfrac{(0.6)\max[49,838.25,0]+(0.4)\max[8,245.72,0]}{(1+0.05)^{1/4}} = \$32,798.69 > \$6,000 \text{ (go)} \\ SNPV_{i10}^{\mathrm{B'}} = \dfrac{(0.6)\max[8,245.72,0]+(0.4)\max[-11,866.71,0]}{(1+0.05)^{1/4}} = \$4,887.45 < \$6,000 \text{ (kill)} \end{cases}$$

In equations (5.26), the profit functions of Firm *i* by option-game approach for the up and down at the first sub-gates are as follows:

$$\tilde{\pi}_{i22}^{\mathrm{C'}} = -25,000 + \frac{3.473}{(1.12)^{2/4}} \frac{[90.68-3(10)(1+0.0457)+25]^2}{0.05(3+1)^2} = 4,159.15$$

$$\tilde{\pi}_{i21}^{\mathrm{C'}} = -25,000 + \frac{3.473}{(1.12)^{2/4}} \frac{[64.08-3(10)(1+0.0457)+25]^2}{0.05(3+1)^2} = -11,337.8$$

$$\tilde{\pi}_{i20}^{\mathrm{C'}} = -25,000 + \frac{3.473}{(1.12)^{2/4}} \frac{[44.34-3(10)(1+0.0457)+25]^2}{0.05(3+1)^2} = -19,087.8$$

By applying Nash equilibrium with the best response analysis, the updated payoff matrices at the statuses of "22," "21," and "20" are as follows:

"22"	i	**j go**	**k go**	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	**4159**	**47**	**53**	24959	0	20749	23759	18395	0	80606	0	0
i kill	0	21303	22647	0	0	85020	0	76583	0	0	0	0
"21"	i	**j go**	**k go**	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	-11338	-14104	-14699	-1993	**0**	-5909	-2805	-6373	**0**	**22185**	**0**	**0**
i kill	**0**	-4451	-4676	**0**	**0**	**22573**	**0**	**19509**	**0**	0	0	0
"20"	i	**j go**	**k go**	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	-19088	-20854	-21479	-15326	0	-18283	-15850	-18085	0	-6168	0	0
i kill	0	-16896	-17543	0	0	-7098	0	-7844	0	**0**	**0.00**	**0**

By applying Nash equilibrium with the best response analysis, the updated payoff matrices at the statuses of "11" and "10" are as follows:

"11"	i	**j go**	**k go**	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	-613	-3403	-2995	**13177**	**0**	**10758**	**12466**	**8758**	**0**	**46896**	0	0
i kill	**0**	**14336**	**7423**	0	0	**49414**	0	**43538**	0	0	0	0

“10”	i	j go	k go	i	j kill	k go	i	j go	k kill	i	j kill	k kill
i go	-1617	-2146	-1540	**575**	**0**	**690**	**575**	-218	**0**	**5764**	**0**	0
i kill	**0**	-218	**690**	0	**0**	**5970**	0	**4345**	0	0	0	0

∴ At the status of "11": the option-game has SNPV of \$12,547.47 [=(13,176.81+6,000+12,645+6,000+0) / 3], taking the actions of "go/kill" for Firm *i*.

At the status of "10": the option-game has SNPV of \$6,574.79(=574.79+6,000), taking an action of "go" for Firm *i*.

Appendix C Validation

C.1 Firm *i*'s Equilibrium Profit of the Asymmetric Cournot

From equation (3.18), I have

$$C_{iuu}(q_i, q_j) = -I_2 + [-bq_i^2 + (\tilde{a}_{uu} - bq_j - c_i)q_i]G_2$$

$$\frac{\partial C_{iuu}(q_i, q_j)}{\partial q_i} = -2bq_iG + (\tilde{a}_{uu} - bq_j - c_i)G_2 = 0$$

$$\Rightarrow q_i = \frac{-1}{2}q_j + \frac{\tilde{a}_{uu} - c_i}{2b}$$

The same concept, I can get $q_j = \frac{-1}{2}q_i + \frac{\tilde{a}_{uu} - c_j}{2b}$

$$\therefore q_i = \frac{-1}{2}\left(\frac{-1}{2}q_i + \frac{\tilde{a}_{uu} - c_j}{2b}\right) + \frac{\tilde{a}_{uu} - c_j}{2b} = \frac{\tilde{a}_{uu} - 2c_i + c_j}{3b}$$

$$\Rightarrow q_j = \frac{\tilde{a}_{uu} - 2c_j + c_i}{3b}$$

Putting them to Firm *i*'s payoff function,

$$\therefore C_{iuu}(q_i, q_j) = -I_2 + \{[-b(\frac{\tilde{a}_{uu} - 2c_i + c_j}{3b})^2$$

$$+[\tilde{a}_{uu} - b(\frac{\tilde{a}_{uu} - 2c_j + c_i}{3b}) - c_i](\frac{\tilde{a}_{uu} - 2c_i + c_j}{3b})\}G_2$$

$$= -I_2 + \frac{(\tilde{a}_{uu}^2 - 4\tilde{a}_{uu}c_i + 2\tilde{a}_{uu}c_j + 4c_i^2 + c_j^2 - 4c_ic_j)G_2}{9b}$$

$$= -I_2 + \frac{(\tilde{a}_{uu} - 2c_i + c_j)^2 G_2}{9b}$$ as shown in equation (3.27)

C.2 Firm *i*'s Equilibrium Profit of Monopoly

From equation (3.19), I have

$$M_{iud}(q_i, q_j) = -I_2 + [-bq_i^2 + (\tilde{a}_{ud} - c_i)q_i]G_2$$

$$\frac{\partial M_{iud}(q_i, q_j)}{\partial q_i} = -2bq_i G_2 + (\tilde{a}_{ud} - c_i)G_2 = 0,$$

$$\Rightarrow q_i = \frac{(\tilde{a}_{ud} - c_i)}{2b}$$

Putting it to Firm *i*'s payoff function,

$$\therefore\ M_{iud}(q_i, q_j) = -I_2 + [-b(\frac{\tilde{a}_{ud} - c_i}{2b})^2 + (\tilde{a}_{ud} - c_i)(\frac{\tilde{a}_{ud} - c_i}{2b})]G_2$$

$$= -I_2 + \frac{(\tilde{a}_{ud} - c_i)^2 G_2}{4b} \quad \text{as shown in equation (3.28)}$$

C.3 Option Premium

$$\text{SNPV}_{i00} = \frac{\tilde{C}_{iuu} q_r^2 + 2\tilde{M}_{iud} q_r (1-q_r)}{(1+r_f)^2}$$

$$= (\frac{q_r}{1+r_f})^2[-I_2 + \frac{(\tilde{a}_{uu} - 2c_i + c_j)^2 G_2}{9b}] + \frac{2q_r(1-q_r)}{(1+r_f)^2}[-I_2 + \frac{(\tilde{a}_{ud} - c_i)^2 G_2}{4b}]$$

Let $c_j = \beta_{vc} c_i, \beta_{vc} > 1$

$$\Rightarrow \text{SNPV}_{i00} = (\frac{q_r}{1+r_f})^2\{-I_2 + \frac{[\tilde{a}_{uu} + (\beta_{vc} - 2)c_i]^2 G_2}{9b}\} + \frac{2q_r(1-q_r)}{(1+r_f)^2}[-I_2 + \frac{(\tilde{a}_{ud} - c_i)^2 G_2}{4b}]$$

From equation (3.26),

$$\text{NPV}_{i00} = -I_0 + \frac{G\omega(a_0 - \bar{c})(a_0 + \bar{c} - 2c_i)}{4b}$$

Finally, the option premium can be obtained as

$$\mathrm{SNPV}_{i00} - \mathrm{NPV}_{i00}$$

$$= \left(\frac{q_r}{1+r_f}\right)^2 \{-I_2 + \frac{[\tilde{a}_{uu} + (\beta_{vc} - 2)c_i]^2 G_2}{9b}\} + \frac{2q_r(1-q_r)}{(1+r_f)^2}[-I_2 + \frac{(\tilde{a}_{ud} - c_i)^2 G_2}{4b}]$$

$$+ I_0 - \frac{G\omega(a_0 - \bar{c})(a_0 + \bar{c} - 2c_i)}{4b}$$

$$= \frac{\tilde{C}_{iuu} q_r^2 + 2\tilde{M}_{iud} q_r (1-q_r)}{(1+r_f)^2} + I_0 - \frac{G\omega(a_0 - \bar{c})(a_0 + \bar{c} - 2c_i)}{4b}$$ as shown in equation (3.30)