

**ESSAYS ON KNOWLEDGE MANAGEMENT STRATEGIES IN NEW
PRODUCT DEVELOPMENT**

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ESSAYS ON KNOWLEDGE MANAGEMENT STRATEGIES IN NEW PRODUCT DEVELOPMENT

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*To my dad,
for making me who I am today,
and to my mom,
who never stopped believing in me.*

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SUMMARY

Management of knowledge involved in the new product development (NPD) projects is critical to the success of firms competing in environments that require rapid innovation. Unfortunately, many firms lack an understanding of how to develop knowledge management (KM) strategies that drive successful outcomes. In this thesis I develop a rich and multifaceted understanding of how KM strategies drive successful NPD outcomes. I examine KM strategies in the NPD domain at two different decision making levels of the firm. First I consider the KM strategies of a manager responsible for a single NPD project. Second, I consider KM at strategic level where a firm establishes strategies to transfer or share knowledge resources with a competitor. Each of these problems is summarized below.

First, I consider the how the manager of a single NPD project should develop knowledge (knowledge acquisition) of its product and process design teams and integrate that knowledge (knowledge transfer) over time throughout the development project. Ultimately, the ability to develop and integrate knowledge drives the net revenue earned at the product release time. I show that two different dynamic KM strategies arise for the creation and transfer of knowledge of the product and process design teams: a delay strategy and a front-loading strategy. I characterize drivers of each strategy as well as drivers of the market entry time strategy.

In contrast to the deterministic approach above, I introduce a related but stochastic model. In this formulation, the manager of a single NPD project focuses on maximizing expected net revenue which reflects the effectiveness of product development activities to meet market needs as well as the ability of process development activities to create efficient manufacturing processes. Also in contrast to the first model, I consider the effect of rework that occurs as a result of the KM activities. Again I find that the manager's strategies for knowledge creation satisfy either the delay or front-loading strategy. However, the drivers of each strategy in this model are substantially different from those in the first model reflecting the stochastic nature of the decision making environment as well as the effect of rework.

In a third model, I consider the strategic level question of how a firm engages in relationships with its competitor regarding the sharing or transfer of knowledge resources for NPD. I consider two cooperative mechanisms: knowledge transfer when both firms ultimately enter the market separately as competitors versus knowledge

sharing when both firms enter the market together following the joint development of a new product. In this thesis, I develop the KM strategies followed by the firms for each cooperation mechanism. In addition, I analyze the impact of firm and market characteristics on firms decision to whether to cooperate or not, and other KM decisions.

CHAPTER 1

INTRODUCTION

1.1 Overview

In today's dynamic marketplace, knowledge is key to gaining and sustaining competitive advantage (Webber 1993). Knowledge is information combined with experience, context, interpretation and reflection and may be embodied in documents, organizational routines, processes, practices, and norms (Davenport et al. 1998). Knowledge management is defined as the ability to retain, develop, organize and utilize knowledge.

Creation, utilization and management of knowledge is at the center of the new product development process (Clark and Fujimoto 1991). Firms pursuing NPD projects must know what they know and how to apply it in useful ways, and know what they don't know and how to close these gaps (Pitt and MacVaugh 2008). KM strategies for NPD impact the time to market, product and process functionality, manufacturing costs, and the match between customer requirements and final product features (Mihm et al. 2003, Ulrich and Eppinger 2003). Therefore, in a highly competitive and environment with changing customer needs as well as rapid changes in the underlying product and process technologies, NPD success is directly impacted by the firm's KM strategies (Lynn et al. 2000).

While some knowledge relevant to NPD already exists within the firm, new knowledge is created as the development process unfolds (Adams et al. 1998). The existing knowledge stored or embedded in the minds of people, in archives, in existing products and in procedures and equipment, needs to be recognized, retrieved and made available to the NPD teams. New knowledge is created through various knowledge creation activities, such as problem solving, testing or experimentation, knowledge transfer/sharing within the firm or from the outside the firm. The new and existing knowledge needs to be integrated to ensure a spiral of continuous expansion and development/refinement of knowledge for future use in the NPD process (Soderquist 2006, Nonaka and H. Takeuchi 1995).

Although there is agreement of its importance, there is a lack of general understanding and recommendations regarding KM strategies for successful NPD (Hargadon and Fanelli 2002). This thesis develops a rich and multifaceted

understanding of how KM strategies drive successful NPD outcomes. The research addresses the integration of KM and NPD at different decision making levels of the firm. First I consider the KM strategies of a manager responsible for a single NPD project. This research integrates key factors from the largely separate literatures of KM and NPD. Second, I consider KM at strategic level where a firm establishes strategies to transfer or share knowledge resources with a competitor. This research on NPD also reflects themes in the literature on strategic management. From this research, we are better able to understand the unique nature of KM in the context of NPD.

1.2 Knowledge Management for New Product Development Models

Chapters 2 and 3 introduce two normative models that explore how to manage the levels of knowledge of the product and process design teams throughout the development of a single new product. The timing and extent of knowledge embedded by both teams during the NPD project determine the features and functionality of the new product and process and thereby drive (expected) net revenue.

In chapter 2, we introduce a deterministic model to analyze the how the manager of a single NPD project should develop knowledge of its product and process design teams and integrate that knowledge over time throughout the development project. The manager determines the rates and directions of knowledge transfer (KT) between teams and the rates of knowledge acquisition (KA) for each team. The desirability of pursuing KA and KT changes throughout the NPD project for a variety of reasons. For example, as market and technological uncertainties are resolved over time, NPD efforts may be more effective later in the project. Also, KT may be more effective following the buildup of knowledge of either the source or recipient through KA. Moreover, by deploying product and process knowledge early in the NPD project the manager may realize an earlier product launch relative to the competition. Ultimately, the ability to develop and integrate knowledge drives the net revenue earned at the product release time which reflects the tradeoff between seeking early market entry benefits versus delaying the product release to develop superior product and process capabilities.

We simultaneously determine the optimal product launch time and the strategies for KA and KT throughout the NPD project. We provide conditions where the manager pursues a front-loading or a delay strategy for KT and KA. For example, if the initial levels of knowledge of both teams are high, (e.g. incremental development project), the manager initially pursues KA and KT at higher rates that decrease throughout the

development project (front-loading strategy). In contrast, if the initial levels of knowledge are low (e.g., “new-to-the-world” products) the manager pursues a delay strategy in which the peak efforts to increase knowledge occur later in the development project. Insights are given on the impact of additional benefits due to synergy or costs due to conflict associated with the simultaneous transfer of knowledge between the product and process design teams. Lastly, we explore forces that drive the optimal product launch time.

In contrast to the deterministic approach in Chapter 2, we introduce a related but stochastic model in Chapter 3. The manager determines the knowledge development (KD) strategy for the product design team, which includes the pursuit of problem solving activities such as testing and experimentation and other induced learning activities such as training. In addition, the manager determines the rates of KT between the product and process design teams. We explicitly recognize that the effectiveness of KD and KT are both interrelated and dynamic. While investments in KD and KT are pursued to increase the cumulative knowledge embedded in the product and process designs, in the short-term these investments may uncover errors that trigger rework. Naturally, the errors reduce the stock of knowledge embedded in the product and process designs, which drives expected net revenue. Overall, the expected net revenue is comprised of three components. First, the manager faces uncertainty regarding the time the product will be successfully launched in the marketplace. A success launch occurs when product design efforts result in a new product whose functionality meets the needs of the marketplace. Second, the expected net revenue earned reflects the ability to efficiently manufacture the product. This dimension of expected net revenue is driver by efforts of the process design teams. Third, expected net revenue is a function of time to capture the effect of time-based competition.

We outline conditions where the manager pursues a front-loading or a delay strategy for KT and KD. We show if the initial level of process design knowledge is small, the manager optimally delays her peak efforts of KT to the product design team until a later time when the process design team’s knowledge is larger. In addition, we show that rework associated with KD or KT impacts the rate and the timing of knowledge creation for both design teams. In particular, if a high rate of rework is triggered by KT from the process design team, the manager front-loads KD of the product design team and KT to the process design team but pursues the delay strategy for the KT to the product design

team. Lastly, we show drivers of expected net revenue that lead to a complementary relationship between the manager's pursuit of KD and KT versus a substitution strategy.

In Chapter 4, we consider the strategic level question of how a firm engages in a cooperative agreement with its competitor regarding the sharing or transfer of knowledge resources for NPD. We consider two cooperative mechanisms. Under competitive development (CD) knowledge transfer occurs between two firms who ultimately enter the market separately as competitors. In contrast, under joint development (JD), knowledge sharing occurs between two firms who ultimately enter the market together following the joint development of a new product. The models reflecting each of these cooperative mechanisms is described below.

We define the CD mechanism as a limited form of cooperation between two firms that pursue NPD projects individually and develop products that ultimately compete in the same market. We consider the knowledge transfer from one firm to the other which consists of the rights to use knowledge contained in licenses and patents, documentation about NPD activities, and access to other knowledge based resources. While the recipient firm benefits by deploying the additional knowledge, the source firm earns revenue from the sale of that knowledge. However, the source firm also suffers a loss in value of its proprietary knowledge. The extent of KT (decision variable) is determined based on, among other things, the price charged by the source firm (decision variable). In addition to KT, each firm pursues its own KD (decision variables) to increase the level of knowledge embedded into its own NPD project. Each firm's objective is to maximize its own expected profit. Expected net revenue is earned by each firm from the release of a new product whose value in the marketplace reflects the firm's level of NPD knowledge. The stochastic element of the net revenue captures the ability of the firm to introduce a product with functionality that meets the market needs over time. Expected net revenue is earned (source) and a cost is incurred (recipient) for the transfer of knowledge between teams. Lastly, costs are incurred for KD.

In contrast, the JD mechanism reflects a greater degree of cooperation between competing firms whereby both firms jointly enter into an NPD project and jointly release a new product to the marketplace. First, each firm determines the extent of knowledge to contribute to a joint NPD endeavor which we refer to as its rate of knowledge sharing (KS). Subsequently, each firm determines its investment in additional KD to be added to the pooled level of knowledge. The contribution each firm makes to the joint pool of knowledge drives the portion of total expected net revenue earned. While making the KS

decisions, each firm maximizes its individual expected profit, which consists of the portion of expected net revenue earned from the new product released to the marketplace, the reduction in expected net revenue from the loss in proprietary knowledge (i.e., the knowledge pooled in the JD), and the cost of KD. The firms make the joint KD decision that maximizes the joint profit, which consists of expected net revenue earned from the new products and the cost of joint KD.

Analysis of the above strategic models enables us to explore situations where a firm is better off to pursue KT or KS through CD or JD, rather than pursuing an NPD project without cooperation. In addition, we determine the conditions that determine the firms KT/KS and KD decisions for each cooperation mechanism.

Figure 1.1 illustrates the key points and the key decisions of models introduced in Chapters 2-4.

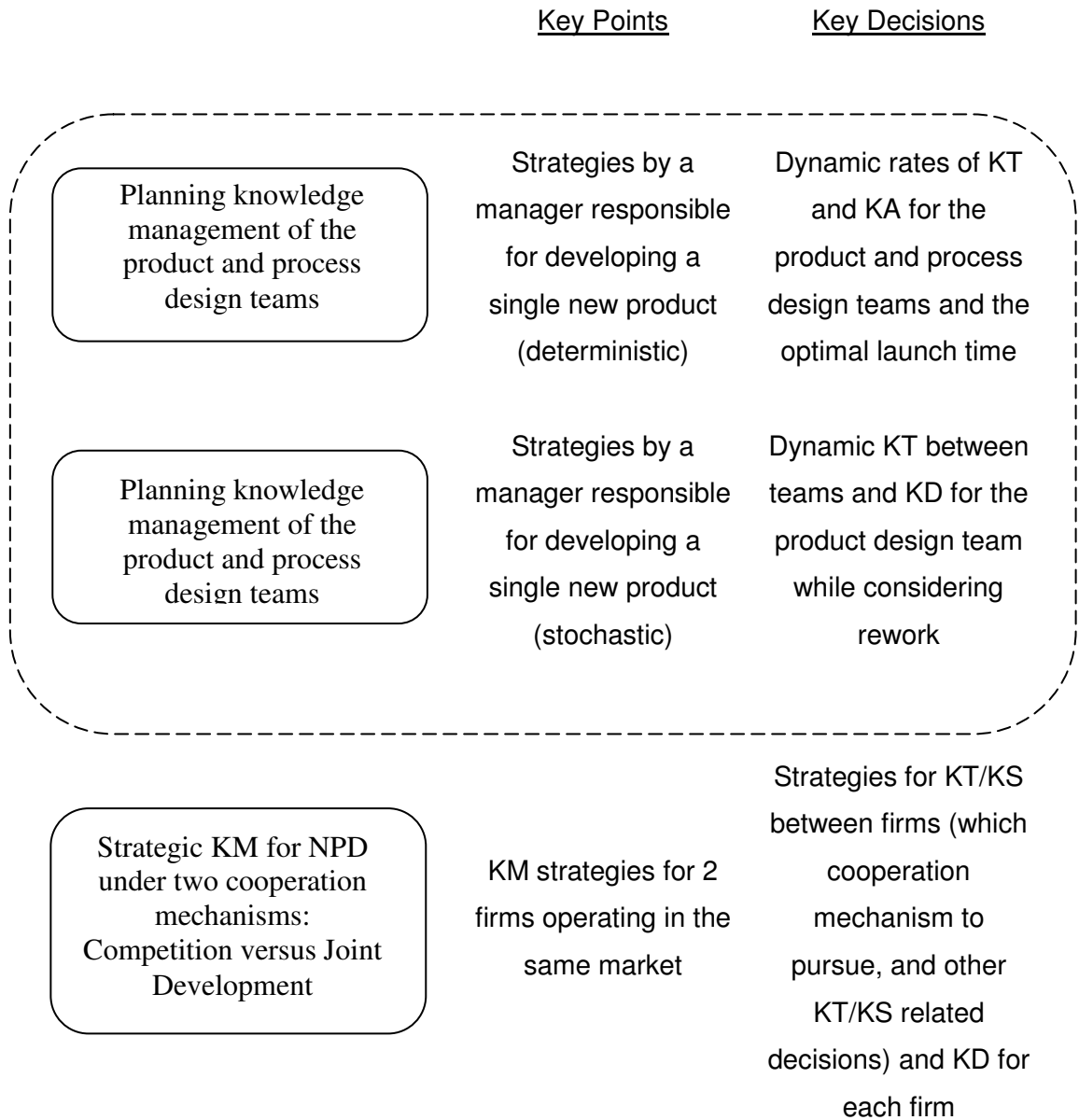


Figure 1.1 KM strategies for NPD at different decision making levels

CHAPTER 2

KNOWLEDGE MANAGEMENT STRATEGIES FOR PRODUCT AND PROCESS DESIGN TEAMS

2.1. Introduction

Today's highly competitive and dynamic marketplace has established knowledge as a main source of competitive advantage (Liebeskind 1996). According to Davenport and Prusak (1998), knowledge embodies experience, values, contextual information and expert insights that provide a framework for evaluating and incorporating new experiences and information. The scope of knowledge a firm must possess includes the customers' needs, the external business environment, and the skills and experience of its workforce. *Knowledge management* (KM) refers to the collection of processes that govern the creation, dissemination, and utilization of knowledge.

New product development (NPD) projects are among the most knowledge intensive endeavors in the modern corporation (Macher 2006). KM of the product and process development impacts the time to market, product and process functionality, manufacturing costs, and the match between customer requirements and final product features (Mihm et al. 2003, Ulrich and Eppinger 2003). Said differently, efficient and effective product and process design activities directly affect the commercial success of a product (Fine 1998, Fisher et al. 1999, Hatch and Macher 2005). Unfortunately, empirical evidence indicates that many firms lack an understanding of how to develop KM strategies that drive successful NPD outcomes (Döös et al. 2005, Terwiesch and Loch, 1999).

We introduce a model to understand how to manage the levels of knowledge of the product and process design teams throughout the development project. The timing and extent of knowledge embedded by the product and process design teams during the NPD project determine the features, functionality and manufacturing efficiency of the new product and process and thereby drive the *net revenue* earned over the product's life cycle. Moreover, net revenue is driven by the *product launch time* which reflects the tradeoff between seeking early market entry benefits (Hendricks and Singhal 1997) versus delaying the product release to develop superior product and process features (Bhuiyan et al. 2004, Carrillo and Franza 2006, Cohen et al. 1996, and Joglekar et al.

2001). We simultaneously determine the optimal product launch time and the optimal KM strategies throughout the NPD project.

The manager impacts the levels of knowledge of the product and process design teams during the NPD project by pursuing two forms of induced learning (Ittner et al. 2001, Pisano, 1994). First, the manager invests in *knowledge acquisition* (KA) for each team (Adler and Clark 1991). KA may take the form of personnel additions such as hiring new engineers or reassigning existing employees (Fine 1998). Also, KA occurs when team members participate in continuing education programs offered by universities or training programs offered by equipment or software vendors. Lastly, KA occurs when team members attend professional conferences (Biskup and Simons 2004, Jacobs 2006). The content of KA is broad including advancements in materials and technologies or improved design methods such as information technology support tools (Hatch and Mowery 1998, Lapre and Van Wassenhove 2001)

Second, the manager may invest in *knowledge transfer* (KT), which is the process by which one team's knowledge is affected by the experience of another (Argote and Ingram 2000). KT activities include the sharing of written documents and codified information about routines and practices, participation in meetings involving members of both teams, and the exchange of employees between teams (Boone 2008, Cummings and Teng 2003, Loch and Terwiesch 1998). KT from the product to the process design team conveys information such as consumer preferences and desirable product features (Blackburn et al. 1996, Hatch and Macher 2005). During the transfer of knowledge from the process to the product design team information on process constraints is communicated to ensure the manufacturability of the product (Adner and Levinthal 2001, Terwiesch et al. 2002).

We explicitly recognize that the effectiveness of KA and KT are both interrelated and dynamic (Epple et al. 1996). The benefits realized from KA at a particular time depend on the team's level of knowledge at that time since a higher skilled workforce is better able to comprehend and deploy new knowledge. Similarly, the effectiveness of KT at a particular time depends on the levels of knowledge of both teams since a higher skilled source has more knowledge to offer and a higher skilled recipient is better able to absorb and exploit new knowledge (Darr et al. 1995). Early investments in KA and KT are appealing since the benefits are sustained over the remainder of the NPD project (Terwiesch and Loch 1999). However, the contribution to net revenue from preliminary

team knowledge early in the development project may be limited since market and technical uncertainties are not yet resolved.

A team's level of knowledge also increases (autonomously) through *learning-by-doing* (LBD) (Ittner et al. 2001, Wright 1936). A substantial literature exists in KM describing drivers of LBD. In the context of NPD, the product and process design teams realize benefits from LBD due to testing, experimentation, and problem solving activities during the NPD project (Loch et al. 2001, Thomke 1998).

Beyond maximizing net revenue, the manager seeks to minimize the costs incurred for induced learning. Many costs are associated with KA including those from hiring and integrating new employees into the existing teams, salaries of consultants or specialists who offer training programs, tuition, travel, and conference registration fees. Furthermore, costs are incurred due to the disruption to ongoing development activities when members of the product or process design teams are engaged in KA. These disruption costs are substantial and may include overtime if the rate of development must be sustained during KA. Similarly, a substantial portion of the costs incurred for KT stem from the disruption to ongoing development activities (Carrillo and Gaimon 2004, Ha and Porteus 1995, Szulanski 1996, Zellmer-Bruhn 2003). In addition, we capture a key feature of the cost related dynamics of KT. The cost of KT for one team is impacted by the timing of KT pursued by the other team reflecting the potential for synergy or conflict if KT occurs in both directions simultaneously (Lado et al. 1997, Mihm et al. 2003).

We seek to contribute to the NPD literature on several dimensions. We introduce a model that provides a holistic view of KM of the product and process design teams throughout the NPD project. We consider the benefits realized by each team from LBD as well as the manager's pursuit of KA and KT. With few exceptions (Loch and Terwiesch 1998, Carrillo and Franza 2006) KA has received little attention in the NPD literature. Moreover, our model is general so that KT may occur in either or both directions during the development project, i.e., we do not a priori specify the nature of the dependency structure for KT between teams. Instead we observe the relationships obtained in the optimal solutions and identify conditions that drive those solutions. (Ha and Porteus 1995 consider communication in only one direction and Joglekar et al. 2001 consider tradeoffs related to communication but do not specify the optimal rates, directions and timing of KT.)

In contrast to much of the literature that focuses on early market entry, we capture the following key tradeoffs. To obtain time-to-market benefits, the manager may release an inferior product earlier or may accelerate the rate that knowledge is embedded in the development project so that the product is released earlier without degradation of quality. Alternatively, the manager may delay the launch to further develop product functionality and process capabilities. We show that under certain conditions the tradeoffs have less impact. We find that if either team realizes a higher rate of LBD or if the manager is better able to resolve market or technical uncertainty, then a superior product is launched earlier. Bhuiyan et al. (2004), Carrillo and Franza (2006), and Roemer et al. (2000) consider a tradeoff between early market entry and the additional design costs incurred with the an earlier launch. However, none of these authors provide the comprehensive view of KM presented in this chapter.

Terwiesch et al. (2002) analyze the flow of preliminary information, and consider the impact of the level of knowledge of the source team. We build upon this approach and express the effectiveness of KT as a function of the efforts expended and the levels of knowledge of both teams (i.e., the source and the recipient). Our results show that the marginal values of KA and KT are interrelated and change throughout the development project. Also, we recognize that transferring preliminary information may be of limited value since considerable market and technical uncertainty exists early in the development project. Analytically we prove that a manager who is better able to reduce the impact of market or technical uncertainty during the development project optimally pursues more KA and KT.

Based on analysis of the optimal solutions, we obtain important insights on a manager's strategy to invest in KA and KT. Conditions are given whereby the manager optimally pursues a *front-loading strategy*. For example, we show that if the initial levels of knowledge of the product and process design teams are relatively high, the manager initially pursues KA and KT at high rates that decrease throughout the NPD project. Despite the declining rates associated with induced learning, the levels of product and process design team knowledge continue to increase as the manager leverages LBD. In contrast, conditions are given whereby the manager optimally pursues a *delay strategy* in which the peak efforts to increase the levels of knowledge occur later in the development project. For example, we show that if the initial level of process design knowledge is small, the manager optimally delays her peak efforts of KT from the product team until the process team's knowledge has increased through KA and LBD.

This insight is in direct contrast with the existing literature that depicts the investments in knowledge creation as decreasing throughout the NPD project (Carrillo and Franza 2006, Terwiesch and Xu 2004).

We show that KA and KT are complementary strategies: higher KA efforts lead to higher KT, and vice versa. Moreover, we show how higher rates of KA or KT lead to an earlier product launch. With a higher rate of LBD of either the product or process design team, we show that the manager optimally pursues more KA for both teams, more KT in both directions (Hatch and Macher 2005) and realizes an earlier product launch. Therefore, we demonstrate the key role played by LBD for the competitive advantage in a NPD project.

We capture an important dynamic relationship that is ignored in the literature: the cost implications of either synergy or conflict associated with the simultaneous transfer of knowledge between the product and process design teams. We show that due to conflict the manager may pursue a lower rate of KT in one direction and a higher rate of KT in the reverse direction. Moreover, we find that synergy versus conflict affects, not only the rates of KT, but also the manager's pursuit of KA. In addition, the product launch time is affected when there is synergy or conflict. As expected, synergy leads to an earlier product launch. However, surprisingly, the impact of conflict is unclear.

The remainder of this chapter is structured as follows. Section 2 contains a review of the related literature. In Section 3, we introduce the objective and constraints of the model. We present analytic results in Section 4 and numerical results in Section 5. Section 6 contains the conclusions.

2.2 Literature Review

This chapter is grounded in two research streams: KM and NPD. The KM literature helps us to characterize the functional relationships that drive changes in the levels of knowledge of the product and process design teams over time. Knowledge is created both from autonomous and induced learning (Biskup and Simons 2004, Lapre and Van Wassenhove 2001). Autonomous learning, e.g., LBD, occurs naturally as the workforce gains experience. The actual rate of LBD achieved may be partially under managerial control (Dorroh et al. 1994, Pisano 1994). The phenomenon of LBD at the individual or organizational level has been discussed extensively in the empirical literature (Biskup and Simons 2004, Ittner et al. 2001, Lapre and Van Wassenhove 2001, Macher and Mowery 2003). LBD in teams has been shown to be analogous to the

phenomena observed with individuals and organizations (Darr et al. 1995, Schilling et al. 2003). We model the LBD in a manner that is consistent with the empirical literature. Carrillo and Franza 2006, Loch et al. 2001, and Thomke 1998 consider the benefits of LBD obtained through experimentation and problem-solving activities that occur during the NPD project.

In contrast, induced learning requires explicit managerial intervention and has cost implications (Carrillo and Gaimon 2000, 2004, Hatch and Macher 2005). For example, GM managers pursue KA provided by equipment makers to familiarize the product and process design teams with new features of CAD software, robots, and programmable controllers (Jacobs 2006). Managers also acquire knowledge on total quality management, project management and leadership skills (Biskup and Simons 2004, Ittner et al. 2001, Lapre and Van Wassenhove 2001) by hiring new employees, from consultants, or from faculty at educational institutions. KA costs are incurred from the associated disruption to ongoing activities of the workforce (Carrillo and Gaimon 2000, Chand et al. 1996). For example, overtime may be necessary if the levels of product and process development must be sustained during training. Our characterization of the cost incurred for KA reflects the above-mentioned features.

KT is another form of induced learning that has received considerable attention in the literature. In their study of 49 blockbuster product and process development teams, Lynn and Reily (2002) identify KT between teams as one of the five highest priority practices leading to a successful NPD project. In a case study, Loch and Terwiesch (1996) describe how knowledge of the product and process teams contributes to the development of the Jalopy sports car during the project's life cycle. The authors highlight the problems that arise when the design teams execute parallel development without sufficient transfer of knowledge between teams. Ultimately, they show that the project suffers from a substantial amount of engineering change orders issued late in the development leading to a delayed product launch.

Ha and Porteus (1995) examine KT from the product to the process design domain to determine the optimal number and timing of progress reviews during the development project to minimize the time-to-market. Loch and Terwiesch (1998) examine the amount of overlap of NPD activities as well as mechanisms to manage KT during the overlap. They determine the optimal meeting frequency and information batching policy. Roemer et al. (2000) explore the tradeoff between obtaining a shorter development time due to KT from the product to process design team versus the

additional rework and design costs caused by the transfer. Terwiesch et al. (2002) examine characteristics of the information that is transferred such as whether it is preliminary. Note, however, that in contrast to our approach, these authors consider either a one-directional information flow (from the product to the process design team), or do not specify the direction of KT between the teams. Also, these authors do not consider KA or LBD.

Most prior research considers KT strategies that reflect a particular dependency structure between design activities (Joglekar et al. 2001). The transfer of knowledge from the product to the process design team may be overlapped or may occur sequentially or simultaneously. The overlapping of activities in an NPD project has been studied in the concurrent engineering literature by Krishnan et al. (1997), Ha and Porteus (1995) and Loch and Terwiesch (1998). Smith and Eppinger (1997a), (1997b) and Eppinger (2001) have explored the sequencing of tasks within the product design. In contrast, we adopt a general approach that does not specify either the amount of overlap or the dependency between the product and process design activities. Rather, we observe the conditions that drive different optimal strategies for KT.

Blackburn et al. (1996) acknowledge that KT between the product and process development teams may occur in two directions simultaneously. According to Lado et al. (1997) and Luo et al. (2006), synergistic benefits are obtained with the simultaneous transfer of knowledge between the product and process design teams. In contrast, in the context of managing complex knowledge in NPD projects, Mihm et al. (2003) provide evidence of a conflict that occurs due to the difficulty of coordinating activities when the transfer of knowledge is simultaneous. Our approach is sufficiently general to capture the situations where there is either conflict or synergy due to KT that occurs in both directions simultaneously.

Lastly, our model captures complex and dynamic relationships that have not been taken into careful consideration in the literature. The effectiveness of KA is a function of a team's level of knowledge and is subject to diminishing returns. Similarly, the effectiveness of KT is a function of the efforts expended and the levels of knowledge of both teams (i.e., the source and recipient) and is subject to diminishing returns. We recognize that disruption costs are incurred from the pursuit of KA and KT (Loch and Terwiesch 1998, Mihm et al. 2003).

2.3 The Model Formulation

In this section, a model is presented to aid the manager determine a dynamic KM strategy for the product and process design teams throughout the development project for a new product. We describe how the levels of knowledge of the product and process design teams change over time. We characterize how the knowledge that is embedded into the new product over the development project impacts the net revenue earned when the product is released to the marketplace. Lastly, we consider the costs associated with increasing knowledge. A summary of our notation appears in Table A.1 of Appendix A.

2.3.1 Knowledge

Let $D(t)$ (state variable) denote the *level of product design team knowledge that is embedded in the NPD project at time t* . In other words, $D(t)$ is the level of knowledge at time t that is applied to the product design effort. Similarly, let $M(t)$ (state variable) denote the *level of knowledge that is embedded in the project by the process design team at time t* . The levels of knowledge of each team reflect their skills such as their understanding of diverse scientific and engineering information. The levels of knowledge may be inferred from the overall educational background of team members, years of work experience, and performance appraisals (Leonard-Barton et al. 1994, Epple et al. 1996, Carrillo and Gaimon 2004). The initial time levels of product and process design team knowledge are known and given by $D_0=D(0)\geq 0$ and $M_0=M(0)\geq 0$. As time passes during the development project, $D(t)$ and $M(t)$ increase and each team is able to apply more knowledge to the product and process design efforts.

Empirically it has been shown that a worker's level of knowledge autonomously increases over time through LBD. The levels of team knowledge may increase as a result of normal problem solving activities. Also, knowledge increases autonomously as teams gain proficiency with new software design tools through repeated use. According to Jacobs (2006), in the automotive industry the learning benefits of an inexperienced product or process design team may be substantial whereas the learning potential of a highly experienced team is limited. In other words, the ability of a team to generate new knowledge from LBD exhibits diminishing returns (Darr et al. 1995, Lapre and Van Wassenhove 2001, Schilling et al. 2003). From the above, the rates of increase in the levels of product and process design team knowledge due to LBD at time t are expressed as $\alpha[D(t)]^{\rho_1}$ and $a[M(t)]^{r_1}$, respectively, where $\alpha, a\geq 0$ and $0<\rho_1, r_1<1$. The

coefficients α and a scale the effects of LBD relative to other factors that increase team knowledge. The parameters ρ_1 and r_1 indicate the rates of diminishing returns.

In contrast to passive LBD, the manager invests in KA, which is a form of induced learning. For example, KA may take the form of hiring or sending team members to continuing education programs and conferences. Let $\gamma(t)$ and $g(t) \geq 0$ (control variables) denote the rates of efforts undertaken by the manager at time t for KA of the product and process design teams, respectively. The increase in team knowledge generated by KA at time t is related to the level of team knowledge at that time. A team with a higher level of knowledge requires less KA efforts to obtain the same increase in knowledge as a team with a lesser level of knowledge (Carrillo and Gaimon 2004, Jacobs 2006, Hatch and Macher 2005). Moreover, the increase in team knowledge due to KA exhibits diminishing returns (Terwiesch and Bohn 2001, Carrillo and Franza 2006, Jacobs 2006). From the above, the rates of increase in the levels of product and process design team knowledge due to KA at time t are given by $d_1\gamma(t)[D(t)]^{\rho_4}$ and $m_1g(t)[M(t)]^{r_4}$, respectively, where d_1 , m_1 , ρ_4 , and r_4 are exogenous parameters ($d_1, m_1 \geq 0$ and $0 < \rho_4, r_4 < 1$). The coefficients d_1 and m_1 scale the effects of KA efforts relative to other factors that increase team knowledge. The parameters ρ_4 and r_4 indicate diminishing returns.

The manager also increases the levels of team knowledge over time by investing in KT efforts. GM managers pursue KT through regularly scheduled meetings of the product and process design teams and by monitoring each team's response to entries by the other team into the computerized Engineering Change Request System (Jacobs 2006). Mathematically, capturing the impact KT on the level of team knowledge is complex. Empirical results show that the effectiveness of KT is related to the extent of efforts undertaken as well as the levels of knowledge of both teams participating in the transfer (Argote and Ingram 2000, Cummings and Teng 2003). We capture these as follows.

Let $\beta(t) \geq 0$ (control variable) represent the rate of efforts by the manager for the transfer of knowledge from the process to the product design team at time t . At any time, a process design team with a higher level of knowledge is capable of transferring more knowledge to the product design team. According to Jacobs (2006), a product design team is more willing to receive knowledge from a process design team that it perceives has a higher level of knowledge. However, the extent that more knowledge of the source enhances KT exhibits diminishing returns, as given by ρ_2 . Lastly, a product design team

with a higher level of knowledge is better able to comprehend and deploy knowledge transferred from the process design team. Said differently, the knowledge level of the recipient of KT impacts the effectiveness of that transfer, again with diminishing returns as given by ρ_3 (Dinur et al. 1998). The empirical results of Bhuiyan et al. (2004) suggest that consideration of diminishing returns is important.

From the above, we express the rate of increase in the product design team knowledge at time t due to KT from the process design team as $d_2\beta(t)[M(t)]^{\rho_2}[D(t)]^{\rho_3}$, with $0 \leq \rho_2, \rho_3 \leq 1$ and $d_2 \geq 0$. This representation of the gain in product design team knowledge satisfies a Cobb-Douglas function where the inputs are the rate of KT efforts and the levels of knowledge of the process and product teams.

Similarly, let $b(t) \geq 0$ denote the efforts undertaken by the manager for KT from the product to the process design team at time t (control variable). We express the increase in the process design team knowledge from KT at time t as $m_2b(t)[D(t)]^{r_2}[M(t)]^{r_3}$, with $0 \leq r_2, r_3 \leq 1$ and $m_2 \geq 0$. For example, as the product development advances, the knowledge transferred from the product design team may include information about product features that help define the appropriate process parameters (Loch and Terwiesch 1998). According to Jacobs (2006), the knowledge received by the process design team from the product design team substantially impacts the way the process design team conducts testing of the processes, selects materials, and specifies manufacturing procedures.

Equations (2.1) and (2.2) mathematically capture the way the levels of knowledge of the product and process design teams change over time, $t \in [0, T]$, where T indicates the end of the NPD project. Since the right sides of Equations (2.1) and (2.2) are positive, we know that $D(t)$ and $M(t)$ are positive and non-decreasing throughout the NPD project. (We denote the derivative of a function with respect to time by the subscript 't'.) Figure 2.1 illustrates how team knowledge changes over time.

$$D_t(t) = \alpha[D(t)]^{\rho_1} + d_1\beta(t)[M(t)]^{\rho_2}[D(t)]^{\rho_3} + d_2\gamma(t)[D(t)]^{\rho_4} \quad (2.1)$$

$$M_t(t) = a[M(t)]^{r_1} + m_1b(t)[D(t)]^{r_2}[M(t)]^{r_3} + m_2g(t)[M(t)]^{r_4} \quad (2.2)$$

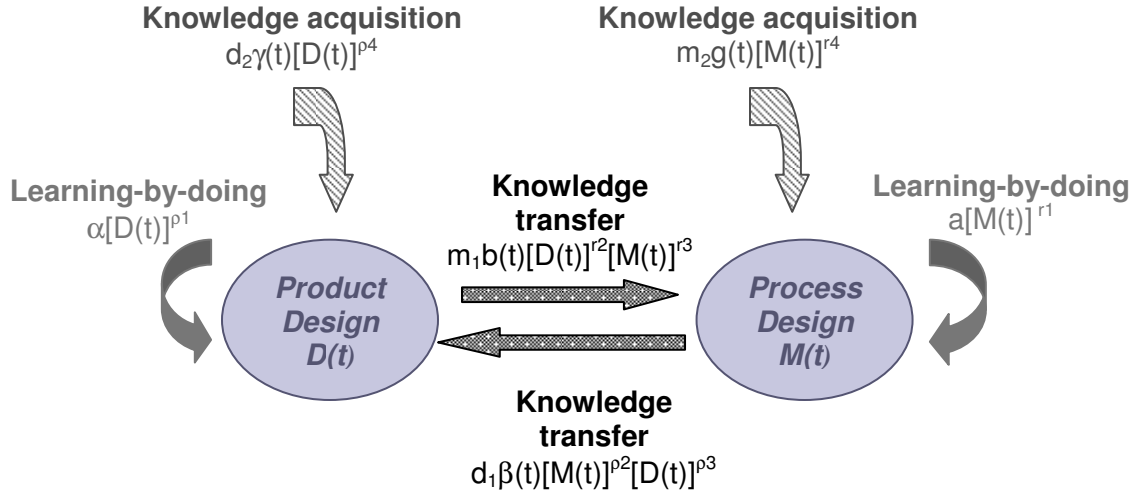


Figure 2.1 Dynamic knowledge management

The net revenue earned from the NPD project when it is released to the marketplace (time T) reflects the knowledge applied by both the product and process design teams throughout the development project. Through KA and KT, the manager impacts the levels of product and process design knowledge that are embedded in the development project over time. Let $X(t)$ and $Y(t)$ (*state variables*) represent the cumulative levels of useful knowledge embedded in the product and process design through time t of the development project, with the initial values $X(0) = X_0$ and $Y(0) = Y_0$. (A similar representation appears in Carrillo and Gaimon 2000.) The word *useful* is important. Due to technical or market uncertainty, team knowledge applied early in the development project may be less useful at driving net revenue at time T as knowledge embedded later. Our notion of useful knowledge is similar to the preliminary information concept, which appears in NPD literature (Terwiesch et al. 2002).

The cumulative levels of useful knowledge of the product and process design teams change over time. Let the exogenous functions $\delta_1(t)$ and $\delta_2(t)$ reflect the extent of technical or market uncertainty resolution associated with product and process development efforts at time t , respectively, $0 \leq \delta_1(t), \delta_2(t) \leq 1$. Since uncertainty is resolved naturally throughout the development project we know $\delta_{1t}(t), \delta_{2t}(t) \geq 0$. Thus, $\delta_1(t)D(t)$ and $\delta_2(t)M(t)$ denote the *impact* of uncertainty resolution at time t on the ability of product and process design efforts to contribute to net revenue. It is important to recognize that by pursuing knowledge creation at time t (increasing $D(t)$ or $M(t)$), the manager may reduce

the impact of uncertainty on the levels of useful knowledge. For example, a team may receive training on new materials to reduce the extent of technical uncertainty. This gives us Equations (2.3) and (2.4).

$$X_t(t) = \delta_1(t)D(t), \quad (2.3)$$

$$Y_t(t) = \delta_2(t)M(t). \quad (2.4)$$

2.3.2 The Objective

Having completed the presentation of the model constraints, we turn our attention to the profit-maximizing objective. Consistent with the NPD literature, we assume that the revenue from the new product is earned at its release time when development efforts are complete (Kim 1998, Santiago and Vakili 2005). Net revenue, denoted by $V[X(T), Y(T), T]$, is the difference between the revenue generated over the new product's lifetime in the marketplace less the associated manufacturing costs. Mathematically, net revenue is expressed as a function of the product release time, T , and the cumulative levels of useful knowledge that the product and process design teams embed in the development project through time T (Cohen et al. 1996).

The product and process design teams may contribute to net revenue at different rates (Joglekar et al. 2001). As the cumulative levels of useful product and process design team knowledge increase during the development project, the net revenue earned increases but at decreasing rates giving us $V_x, V_y \geq 0$ and $V_{xx}, V_{yy} \leq 0$ (Carrillo and Franza 2006). In some situations, the manager may purposely delay the launch of the new product in order to accumulate more useful product or process design knowledge. However in doing so, the manager forgoes some portion of net revenue since time based competition has the effect of penalizing a later product release, i.e., $V_T \leq 0$ and $V_{TT} \leq 0$ (Carrillo and Franza 2006). Note that the second order effect occurs since the benefits realized from earlier market entry are ultimately limited. Therefore, our characterization of net revenue captures the trade-off between the loss in net revenue from delaying the product launch and the additional net revenue earned from the greater amount of useful knowledge accumulated during the longer development project (Cohen et al. 1996).

$C_1[\beta(t)]$ and $C_2[b(t)]$ are the costs of KT efforts at time t . KT costs reflect the efforts of each team to document and codify knowledge and the relocation of employees between teams. Also, while engaging in KT, a portion of each team's efforts is diverted

from its usual activity of embedding knowledge into the product or process design (Loch and Terwiesch 1998, Mihm et al. 2003). Therefore, the costs of KT reflect the disruption to ongoing activities and include the costs of the overtime necessary to sustain team productivity during the transfer process. (See Carrillo and Gaimon 2000.) The cost of KT at time t increases at an increasing rate in relation to the efforts expended ($C_{1\beta}, C_{2b} \geq 0$ and $C_{1\beta\beta}, C_{2bb} \geq 0$) since increasing either $\beta(t)$ or $b(t)$ at any instant of time results in disproportionately large disruption costs.

It is interesting to consider the cost implications of simultaneously pursuing KT in both directions. Loebecke et al. (1999) describe a synergistic effect on costs. They state that the cost savings that occur during the simultaneous KT between the product and process design teams reflect the reduction in time, capital and rework. In contrast, Terwiesch et al. (2002) state that knowledge flowing in both directions at the same time may reduce the quality of information and may force one of the teams to use preliminary information. Such problems are more likely to occur if the knowledge transferred is sticky (Von Hippel 1994), ambiguous (Sorenson et al. 2005), particularly rich such as involving complex technologies (Hansen 1999), or requires intricate communication tools such as interactive technology (Fine 1998). Communication barriers such as cultural differences may also be the source of conflict during simultaneous KT (Loebecke et al. 1999, Sosa et al. 2004).

Let $C_3[\beta(t), b(t)]$ denote the impact on the cost of KT when the product and process design teams exchange knowledge simultaneously. Clearly, this term is non-zero only if both $\beta(t)$ and $b(t)$ are positive. If the impact of simultaneous KT reflects conflict (synergy) then $C_3[\beta(t), b(t)]$ is positive (negative). Naturally, the cost (benefit) of simultaneous KT increases with respect to the amount of efforts expended. This gives us $C_{3\beta}, C_{3b} > 0$ when conflict occurs and $C_{3\beta}, C_{3b} < 0$ in the case of synergy. Furthermore, as both $\beta(t)$ and $b(t)$ increase, we know the cost (benefit) increases at an increasing (decreasing) rate so that $C_{3\beta\beta} > 0$. Lastly, we assume that $C_{3\beta\beta} = C_{3bb} = 0$ so that all second order effects with respect to one directional KT are captured in $C_1[\beta(t)]$ and $C_2[b(t)]$.

The costs incurred for KA efforts of the product and process design teams at time t are denoted by $C_4[\gamma(t)]$ and $C_5[g(t)]$, respectively (Carrillo and Gaimon 2000). These costs include the salaries of trainers, consultants, attendance at conferences and workshops, and executive program tuition. Also, hiring costs (including those to integrate new employees into the existing teams) may be incurred. Finally, disruption costs such

as overtime are incurred to sustain team productivity levels during KA activities (Jacobs 2006). The cost of KA at time t increases at an increasing rate in relation to the efforts expended reflecting the increasing challenge of managing larger amounts of disruption at an instant of time ($C_{4\gamma}, C_{5g} \geq 0$ and $C_{4\gamma\gamma}, C_{5gg} \geq 0$) (Kim 1998, Biskup and Simons 2004).

The objective to be maximized is given in Equation (2.5) and captures the above discussion of net revenue earned at the terminal time (product release) and the costs incurred over the NPD project.

$$V[X(T), Y(T), T] - \int_0^T \{C_1[\beta(t)] + C_2[b(t)] + C_3[\beta(t), b(t)] + C_4[\gamma(t)] + C_5[g(t)]\} dt \quad (2.5)$$

In the remainder of the chapter, the notation depicting time is suppressed whenever possible. Proofs of the analytic results (Section 4) appear in Appendix A. "*" indicates optimal solutions.

2.4 The Optimal Solution

We solve the above model using optimal control methods (Sethi and Thompson (2000)). The Hamiltonian to be maximized is given in Equation (A.1) of the Appendix A. The variables $\lambda_1(t)$ and $\lambda_2(t)$ are introduced and represent the marginal values of the levels of knowledge of the product and process design teams at time t , respectively. Also, $\lambda_3(t)$ and $\lambda_4(t)$ represent the marginal values of the cumulative levels of useful product and process design team knowledge at time t , respectively. The necessary conditions for optimality of the marginal value functions are given in Equations (A.2)-(A.5).

Theorem 1, below, follows from analysis of the optimality conditions. From Theorem 1, we see that the marginal values of the levels of knowledge of the product and process design teams are non-negative and non-increasing functions of time. Also, we see that the marginal values of the cumulative levels of useful product and process design team knowledge are constant throughout the NPD project. Further interpretation of Theorem 1 is postponed until we present the optimal KA and KT policies.

THEOREM 1. *The marginal value functions satisfy the following conditions for $t \in [0, T]$.*

$$\lambda_1^*(t), \lambda_2^*(t) \geq 0 \text{ and } \lambda_{1t}^*(t), \lambda_{2t}^*(t) \leq 0; \lambda_3^*(t) = V_{X(T)} \text{ and } \lambda_4^*(t) = V_{Y(T)}, \lambda_{3t}^*(t), \lambda_{4t}^*(t) = 0.$$

Along with the non-negativity constraints, Equations (2.6)-(2.9) are the optimality conditions for the levels of KA and KT for both the product and process design teams.

To interpret these optimal policies, consider Equation (2.6). The first term represents the marginal cost of KT efforts from the product to the process design team at time t . The second term is the marginal reduction or increase in the transfer cost if both teams engage in KT simultaneously. The third term is the product of the value of another unit of product design team knowledge from time t through the remainder of the development project and the increase in knowledge realized from an additional unit of KT effort at t . Therefore, at time t , the optimal KT policy from the product to the process design team equates the additional marginal cost of transfer at t with the benefits realized from time t to T . A similar interpretation holds for (2.7). From Equation (2.8), we see that the optimal KA policy for the product design team equates the marginal cost at time t with the marginal value of the associated increase in product design knowledge from time t through the remainder of the development project. The interpretation of Equation (2.9) is analogous.

$$\partial H/\partial \beta = -C_{1\beta} - C_{3\beta} + d_1 \lambda_1 M^{p^2} D^{p^3} = 0 \quad (2.6)$$

$$\partial H/\partial b = -C_{2b} - C_{3b} + m_1 \lambda_2 D^{r^2} M^{r^3} = 0 \quad (2.7)$$

$$\partial H/\partial \gamma = -C_{4\gamma} + d_2 \lambda_1 D^{p^4} = 0 \quad (2.8)$$

$$\partial H/\partial g = -C_{5g} + m_2 \lambda_2 M^{r^4} = 0 \quad (2.9)$$

From Equations (A.2)-(A.5) and (2.6)-(2.9), we know the optimal strategies for KA and KT are non-negative over time until reaching zero when the product is released to the marketplace. In Theorem 2, we explore how the optimal rates of KA and KT change over time. With these insights, we find that the optimal solutions must satisfy one of the two cases given in Corollary 1. Figure 2.2 illustrates the two possible solutions described in Corollary 1. A complete discussion of Corollary 1 follows in Section 4.1.

***THEOREM 2.** The change in the rate that the manager optimally pursues KT from the process to the product design team at time t , (β_t^*) , satisfies Equation (2.10). Moreover, the change in the optimal rate of KA for the product design team at time t , (γ_t^*) , satisfies Equation (2.12). Analogous insights hold for b_t^* and g_t^* (see Equations (2.11) and (2.13)).*

$$C_{1\beta\beta}(\beta_t^*) + C_{3\beta b}(b_t^*) = d_1\lambda_{1t}M^{\rho_2}D^{\rho_3} + d_1\lambda_{1\rho_2}M^{\rho_2-1}M_tD^{\rho_3} + d_1\rho_3\lambda_1M^{\rho_2}D^{\rho_3-1}D_t \quad (2.10)$$

$$C_{2bb}(b_t^*) + C_{3\beta b}(\beta_t^*) = m_1\lambda_{2t}D^{r_2}M^{r_3} + m_1\lambda_{2r_2}D^{r_2-1}D_tM^{r_3} + m_1r_3\lambda_2D^{r_2}M^{r_3-1}M_t \quad (2.11)$$

$$C_{4\gamma\gamma}(\gamma_t^*) = d_2\lambda_{1t}D^{\rho_4} + d_2\lambda_{1\rho_4}D^{\rho_4-1}D_t \quad (2.12)$$

$$C_{5gg}(g_t^*) = m_2\lambda_{2t}M^{r_4} + m_2\lambda_{2r_4}M^{r_4-1}M_t \quad (2.13)$$

COROLLARY 1. *The rates the manager optimally pursues KA or KT during the NPD project satisfy one of the following (non-trivial) cases. (i) The optimal solution is positive and increasing, reaches a maximum, and then decreases until reaching zero at the product launch time (delay strategy). (ii) The optimal solution is positive and decreasing throughout the product development project until reaching zero at the product launch time (front-loading strategy).*

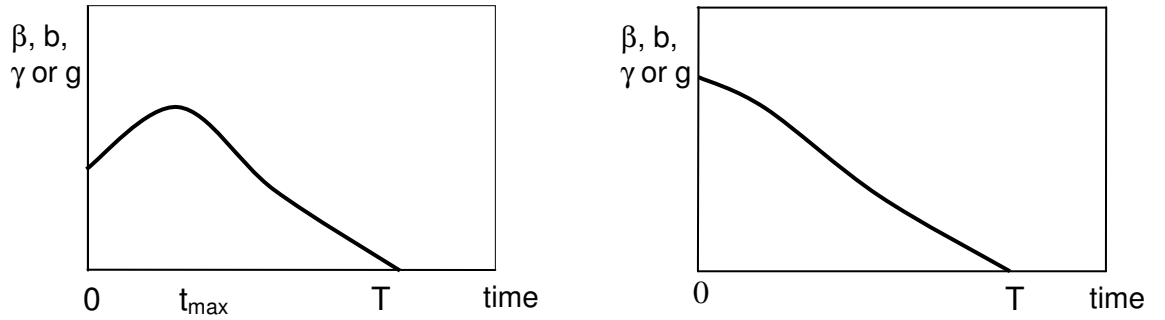


Figure 2.2 Case (i) Delay strategy and Case (ii) Front-loading strategy

2.4.1 Increasing Product Design Team Knowledge Through KA and KT

It is important to understand the conditions that lead to the solutions satisfying Cases (i) and (ii) of Corollary 1. In this section, we consider the manager's strategies to increase knowledge of the product design team (γ, β) noting that insights for the process design team (g, b) are analogous. Also, we focus on interpreting the optimal strategies for the KT from the process to the product design team since the interpretation for KA is analogous. Initially, we consider the situation where neither conflict nor synergy occurs

due to the simultaneous pursuit KT in both directions ($C_3[\beta,b]=0$). Later, we relax this assumption.

Case (i) of Corollary 1, illustrated in Figure 2.2, is referred to as the *delay strategy*. The delay strategy occurs when the effectiveness of KT from the process to the product design team is small early in the development project. This situation may arise if the initial levels of product and process design team knowledge are small, if there is considerable technical or market uncertainty early in the NPD project, or if the returns to KT are limited. Under any of these conditions, the manager pursues KT at a relatively small but increasing rate early in the development project. The rate increases since the effectiveness of KT is growing as the levels of product and process design team knowledge increase through LBD and knowledge creation and as technical and market uncertainty are resolved.

Eventually, the manager optimally reduces her pursuit of KT for several reasons. First, product design knowledge has already reached a sufficient level (diminishing returns). Second, over time less of the NPD project remains to accrue the benefits from an increase in the level of product team knowledge. Third, over time the manager is better able to leverage the team's level of knowledge to derive further additions through LBD which is free. Basically in Case (i), the manager optimally delays her peak investment in KT until a later time when such investments are more effective. In their case on the Jalopy sports car, Loch and Terwiesch (1996) describe the problems that occur when the NPD manager does not follow a delay strategy despite low initial levels of knowledge of the product and process design teams.

We refer to Case (ii) of Corollary 1 as the *front-loading strategy*, illustrated in Case (ii) of Figure 2.2. Front-loading occurs when the effectiveness of KT is high at the outset of the NPD project. This situation may arise if the levels of knowledge of both teams are relatively large at the initial time, there is limited technical or market uncertainty early in the development project, or the returns to KT are considerable. In the front-loading strategy, the manager pursues KT at a relatively high and decreasing rate throughout the NPD project. The manager has no incentive to delay investment in KT. The rate of KT decreases over time for several reasons. First, due to diminishing returns it is increasingly difficult to obtain further additions to the level of product design team knowledge through KT. Second, over time less of the NPD project remains to accrue the benefits from an increase in the level of team knowledge. Third, since the level of team knowledge is increasing, the manager's ability to leverage LBD increases.

The notion of a front-loading strategy has appeared in the literature (Terwiesch and Xu 2004, Thomke and Fujimoto 2000). Blackburn et al. (1996) describe the front-loading of KT in the context of concurrent engineering in software development. However, these authors do not obtain a timing strategy for KT or the rate and direction that transfer should occur during the NPD project. Carrillo and Franza (2006) find that the manager optimally invests in KA at the highest rate at the beginning of the NPD project. These authors do not, however, consider knowledge creation through KT or LBD. Moreover, in contrast to the existing literature which advocates only the front-loading strategy, we show that a delay strategy may optimally occur for KA of either team and KT between teams.

With two possible strategies for each of two decision variables, the manager chooses from eight combinations of solutions for the rates of KA and KT. For example, suppose the initial levels of both the product and process design teams' knowledge are small. The manager pursues the delay strategy for both her investment in KA of the product design team and KT from the process to the product design team. Moreover, suppose the impact of diminishing returns is larger for KA as compared to KT. Under these conditions, the manager optimally starts to decrease her pursuit of KA earlier in the NPD project (the peak efforts occur for smaller t) while still investing at an increasing rate in KT from the process design team. These insights are stated mathematically in Corollary 2.

COROLLARY 2. Suppose D_0 and M_0 are small and $\rho_3 \geq \rho_4$. Then $\gamma_i^(t) \geq 0$ for $t \in [0, t_\gamma]$ and $\gamma_i^*(t) < 0$ for $t \in (t_\gamma, T]$ whereas $\beta_i^*(t) \geq 0$ for $t \in [0, t_\beta]$ and $\beta_i^*(t) < 0$ for $t \in (t_\beta, T]$. Lastly, we have $t_\beta \geq t_\gamma$.*

So far, we have considered the situations where the initial levels of product and process team knowledge are both either large or small. Next, suppose at the initial time, the level of product design team knowledge is large but the level of process design team knowledge is small. With the substantial level of product team knowledge, the manager front-loads her pursuit of KA. In contrast, the manager optimally delays the peak pursuit of KT from the process design team until a sufficient level of that team's knowledge is reached. As a result, the initial pursuit of KT to the product design team is modest and increasing as the level of process design team knowledge grows. Eventually, the pursuit of KT declines as described above. These insights are stated in Corollary 3.

***COROLLARY 3.** Suppose D_0 is large and M_0 is small. Then $\gamma^*(0)$ is relatively large and $\gamma_t^*(t) < 0$ for $t \in [0, T]$ whereas $\beta_t^*(t) \geq 0$ for $t \in [0, t_\beta]$ and $\beta_t^*(t) < 0$ for $t \in (t_\beta, T]$.*

2.4.2 The Rates of KT between the Product and Process Design Teams

In Section 4.1, we analyzed KM strategies of either the product design team (β and γ) or the process design team (b and g). In contrast next, we view the manager's strategies from a different perspective: we compare the optimal rates of KT between the product and process design teams, β and b .

Suppose the initial level of the product design team knowledge is relatively large, whereas the initial level of the process team knowledge is relatively small. Also, suppose the level of knowledge of the source team is more effective at driving benefits from KT compared to the recipient team. Under these conditions, the manager optimally delays the peak transfer of knowledge from the process to the product design team. The delay strategy occurs since the effectiveness of KT is driven by the source team and the initial level of process team knowledge is small. In contrast, the manager pursues a front-loading strategy for the transfer of knowledge from the product to the process team. The front-loading strategy is undertaken, in part, to accelerate the increase in the relatively low level of process design knowledge. As the level of knowledge about the manufacturability (process) of the product grows, the rate of KT from the process to the product team increases. At some point, due to diminishing returns, less time remaining in the product development project, and the increasing opportunity for LBD, the rate of KT from the process to the product design also team declines. These insights are summarized below in Corollary 4.

***COROLLARY 4.** Suppose D_0 is large and M_0 is small; ρ_2 and r_2 are relatively large; and ρ_3 and r_3 are relatively small. Then $b^*(0)$ is relatively large and $b_t^*(t) < 0$ for $t \in [0, T]$ whereas $\beta_t^*(t) \geq 0$ for $t \in [0, t_\beta]$ and $\beta_t^*(t) < 0$ for $t \in (t_\beta, T]$.*

The situation depicted in Corollary 4 where the KT is front-loaded in one direction while delayed in the reverse direction is similar to the sequential development of the product and process design (i.e., Loch et al. 2001). Hence, while the literature prescribes the dependency structure of the design activities (Ha and Porteus 1995), in our approach, the dependency structure is an outcome of the optimal solution.

The above analytic results depicted in Corollaries 2, 3 and 4 did not consider the additional cost or benefit due to conflict or synergy that occurs when the transfer of knowledge between design teams occurs simultaneously. Earlier, we described how the benefit from synergy versus the cost from conflict are captured by the function $C_3(\beta, b)$. Whether or not there is conflict or synergy, the optimal rates of KT satisfy either a front-loading or a delay strategy as given in Corollary 1. However, the conditions driving the solutions given in Corollaries 2, 3 and 4 are slightly different. In Corollary 5, analytic results are presented describing the impact of synergy versus conflict on the manager's optimal pursuit of KT.

COROLLARY 5. *Suppose $C_3[\beta, b] \neq 0$. First, if $C_3[\beta, b] < 0$, then large β^* (b^*) is associated with larger b^* (β^*). Alternatively, if $C_3[\beta, b] > 0$, then large β^* (b^*) is associated with smaller b^* (β^*). Lastly, if $C_3[\beta, b] > 0$, it is also possible that both β^* and b^* are smaller.*

In the first part of Corollary 5, the simultaneous transfer of knowledge embodies synergy ($C_3[\beta, b] < 0$) which drives larger rates KT in both directions as compared to the case where $C_3[\beta, b] = 0$. As a result, the levels of knowledge of both the product and process design teams increase faster. While $C_1(\beta)$ and $C_2(b)$ are larger for larger β and b , the total cost of KT may be smaller since $C_3(\beta, b) < 0$. In contrast, suppose the simultaneous transfer of knowledge is the source of conflict ($C_3[\beta, b] > 0$). Here, compared to the case where $C_3[\beta, b] = 0$, conflict may lead to smaller rates of KT in both directions. As a result, the levels of product and process design team knowledge increase more slowly during the NPD project. While $C_1(\beta)$ and $C_2(b)$ are smaller for smaller β and b , the total cost of KT may be larger since $C_3(\beta, b) > 0$. Alternatively, conflict may lead to the situation where KT is pursued at a higher rate in one direction but at a lesser rate in the other. As a result, the levels of knowledge of the product and process design teams may increase faster or slower and the full cost of KT may be larger or smaller.

2.4.3 Analytic Sensitivity Results

We now present results of analytic sensitivity analysis to provide additional insights on the manager's KM strategies. Corollary 6 shows how the effectiveness of KT in *either* direction impacts the optimal rates of transfer in *both* directions as well as the KA strategies for *both* teams. Corollary 6 depicts how the effectiveness of KA for *either*

team impacts the optimal rates of KA for *both* teams and the rates of KT in *both* directions. A discussion of some of the key managerial implications follows.

COROLLARY 6. *If any of the following measures of effectiveness are larger for either team, then the manager optimally pursues (i) more KT efforts in both directions (β and b) and (ii) more KA for both teams (γ and g).*

- (i) *Effectiveness of LBD (α , ρ_1 , a or r_1);*
- (ii) *Effectiveness of KT (d_1 , ρ_2 , ρ_3 , m_1 , r_2 , or r_3);*
- (iii) *Effectiveness of KA (d_2 , ρ_4 , m_2 or r_4).*

One might have expected that a high rate of LBD reduces the need for induced learning. However, from (i) we see the opposite result: there is a complementary relationship between the rate of LBD and the manager's pursuit of knowledge creation. We obtain this result because any investment in KA or KT has greater impact when there is a high rate of LBD. Kim (1998) also examines LBD and KA, but does not consider the possibility of KT. In addition, we extend the literature since we describe how the effectiveness of LBD for *either* team increases the manager's pursuit of any form of knowledge creation for *both* teams. Clearly, these results show that, to the extent possible, the NPD manager should undertake efforts to increase the rates of LBD of her product and process design teams.

From (ii), we see a key result: there is a complementary relationship between the manager's pursuits of KT in both directions. In particular, if process team knowledge drives substantial benefits for the transfer of knowledge to the product design team, then the manager pursues higher rates of KT in *both* directions. To see this result, note that with a greater rate of return, more KT is advocated from the process (source) to the product (recipient) design team. The subsequently higher level of product (source) knowledge makes the transfer of knowledge to the process design team (recipient) more beneficial. Therefore, if the transfer of knowledge from one team to the other is highly effective, then there is a direct benefit to the recipient team and an indirect benefit to the source team.

A complementary relationship also exists between the optimal rates of KA and KT. Suppose KA is more effective for the product design team. Naturally, the manager optimally pursues more KA for that team. With the higher level of product team knowledge (recipient), the value of KT from the process design team is enhanced and

occurs at a higher rate. The higher level of product team knowledge (source) enhances the value of KT to the process team (recipient). Finally, the higher level of process team knowledge increases the returns from KA for that team. Hence, if KA for either team is highly effective, from (iii), the manager optimally pursues more KA for both teams and more KT in both directions.

In Corollary 7, we describe how drivers of revenue impact the manager's pursuit of KA for *both* teams and the pursuit of KT in *both* directions. The interpretation of Corollary 7 follows.

COROLLARY 7. *Suppose the marginal net revenue earned from the cumulative level of useful knowledge of either team is large ($V_{X(T)}$ or $V_{Y(T)}$). Then the manager optimally pursues (i) more KT efforts in both directions (β and b) and (ii) more KA for both teams (γ and g).*

From Corollary 7, if the manager anticipates a higher market response for product-related features then she pursues more knowledge creation to increase the level of knowledge that the product design team embeds in the development project over time. (Also see Cohen et al. 1996.) In other words, the rate of KA for the product design team and the rate of KT from the process design team are both higher. Following our earlier logic, we conclude that beyond the effects on the product design team, the rate of KA for the process design team and the rate of KT to the process design team are larger, as well. This result is consistent with Joglekar et al. (2001) who state that to improve the overall performance a manager should consider investing in both the product and process teams rather than over-investing in one team.

COROLLARY 8. *Suppose a manager is better (less) able to resolve market or technical uncertainty associated with the product or process development (δ_1 or δ_2). Then the manager optimally pursues (i) more (less) KT efforts in both directions (β and b) and (ii) more (less) KA for both teams (γ and g).*

Suppose early in the development project there is considerable uncertainty associated with the product or process development. From Corollary 8, the manager's response is to reduce her initial pursuit of KA for both teams and KT between teams. However, while smaller in magnitude, KA and KT are still desirable early in the NPD project for the following reasons. First, higher levels of knowledge reduce the impact of

uncertainty on the accumulation of useful product and process design team knowledge. In other words, the manager can endogenously reduce the impact of uncertainty through knowledge creation. Second, the benefits from increasing the levels of knowledge of the product and process design teams early in the development project are sustained until the product release time. Third, knowledge creation increases the benefits derived from LBD. Fourth, higher levels of knowledge enhance the future gains from KA and KT. Finally, the manager wants to avoid the disproportionately higher disruption costs incurred if larger rates of KA and KT are pursued at any particular time later in the development project.

The above insight has some relation to the Kittyhawk project undertaken by Hewlett-Packard (Rogers and Christensen 1998). Despite considerable technical and market uncertainty at the outset of the NPD project, the general manager set very aggressive goals: the creation of a 1.3" disk drive within 12 months, a break-even in 36 months, and a target revenue of \$100 million two years after the product launch. While the design teams were able to resolve many technical challenges, identifying the appropriate target market proved daunting. Driven by the project deadline and despite the considerable market uncertainty that remained, the HP teams committed all of their efforts to creating the 1.3" disk drive for the personal digital assistant (PDA). Unfortunately, the anticipated high-volume demand for PDA's did not materialize. In hindsight, it seems that the NPD manager seriously underestimated the market uncertainty ($\bar{\delta}_1$ and $\bar{\delta}_2$ were overestimated). As a result, the NPD teams pursued intense design efforts too early in the development project. In the next section, we extend these results and explore the effect of market or technical uncertainty on the optimal product launch time.

2.4.4 The Optimal Product Launch Time

In this section, we determine the optimal length of time during which the product and process design teams should continue to embed knowledge into the development project, i.e. the product launch time. We show that the optimal product launch time and the manager's knowledge creation strategies are interrelated so that a simultaneous solution is needed.

The optimal product launch time, T^* , satisfies the transversality condition in Theorem 3. The first and second order conditions on $V[X(T), Y(T), T]$ (see Section 3.2) drive a tradeoff. To realize an earlier market entry, the manager may release an inferior

product or may accelerate the rate that knowledge is embedded into the product and process design. Alternatively, despite the loss in time-to-market benefits, the manager may delay the product release to fine tune product features or process capabilities. (Similar tradeoffs are described in Bhuiyan et al. 2004, Carrillo and Franza 2006, Cohen et al. 1996, and Joglekar et al. 2001.) Reflecting the above, we have T^* as illustrated in Figure A.2 in Appendix A.

THEOREM 3. *The optimal product launch time (T^*) satisfies:*

$$\delta_1(T)D(T)V_{X(T)} + \delta_2(T)M(T)V_{Y(T)} \stackrel{\sim}{=} V_T . \quad (2.14)$$

It is helpful to delve more deeply into Equation (2.14) to fully understand the product release time decision. We refer to the left and right hand sides of Equation (2.14) as LHS and RHS, respectively. (Simply by the way in which the variables are defined, we can reasonably assume that the direct effects of $V_{X(T)}$ or $V_{Y(T)}$ on LHS dominate the indirect effects observed through $D(T)$ or $M(T)$.) Suppose the extent of time-based-competition in the marketplace is more pronounced. Here, the curve representing the adverse effect on net revenue due to delaying the product release (RHS) shifts up. As a result, profit is maximized with an earlier product release (T_1^*). Alternatively, suppose the knowledge embedded by the product design team has a more dramatic effect on increasing net revenue. From Figure A.2, the curve representing the marginal contribution to net revenue from embedding more useful knowledge (LHS) into the NPD project shifts up. As a result, delaying the product launch (T_2^*) is desirable to afford the manager additional time to improve product features and process functionality and thereby enhance profit.

The relationship between the optimal product launch time and the manager's pursuit of knowledge creation for the product and process design teams is the focus of Corollary 9. While the corollary is stated in terms of efforts to increase the product team's knowledge, analogous results hold for the process team. Intuitively, if more knowledge creation occurs during the development project, then the marginal contributions to net revenue from any additional cumulative useful knowledge ($V_{X(T)}$ and $V_{Y(T)}$) are smaller (diminishing returns) so that the curve in Figure A.2 shifts down and T^* is smaller.

COROLLARY 9. *The optimal product release time (T^*) occurs earlier (is delayed) if the rate of KT from the process to the product design team (β) or the rate of KA for the product design team (γ) is larger (smaller) during the development project.*

Taken together, Corollaries 6, 7, 8 and 9 provide powerful insights. For example, if the rate of LBD is larger for either team, then from Corollary 6 the manager optimally undertakes more KA for both teams and more KT in both directions. As a result, the rates that the product and process design teams embed useful knowledge during the NPD project are higher. From Corollary 9, we see that this leads to an earlier product launch time. Therefore, with a higher rate of LBD for either team, the manager is able to achieve an earlier product launch. This analytic result confirms insights from the case study by Thomke and Fujimoto (2000) on NPD projects at Toyota. The authors describe how increasing the rate that NPD teams identify and solve design problems leads to a reduction in the development project timeline.

Insights on the effect of the rate of uncertainty resolution on the optimal launch time are particularly interesting. Suppose technical or market uncertainty are resolved rapidly during the development project. From Corollary 8 we know that the manager invests in higher rates of knowledge creation for both teams. From Corollary 9 this gives us an earlier product launch. Essentially, a faster rate of uncertainty resolution drives faster rates of increase in the levels of cumulative useful knowledge of both the product and process design teams during a shorter development time period. A related result is obtained by Loch and Terwiesch (1998) and Terwiesch and Loch (1999) who find that a high rate of uncertainty resolution impacts the duration of overlapping of product and process design efforts during an NPD project. We extend this result by obtaining, not only the duration, but also the directions and rates at which KT optimally occur when uncertainty is resolved faster in the NPD project.

Lastly, we consider the effect of synergy versus conflict when the transfer of knowledge occurs in both directions simultaneously. Suppose there is a cost reduction due to synergy. From Corollary 5, we know that synergy drives larger rates of KT in both directions as compared to the case where $C_3[\beta, b]=0$. From Corollary 9, the faster rates at which the product and process design teams embed knowledge into the NPD project lead to an earlier product launch. Therefore, synergy allows the manager to achieve an earlier product launch.

In contrast, there are two possible outcomes if the simultaneous KT is a source of conflict (higher cost). Again, from Corollary 5, relative to the case where $C_3[\beta, b]=0$, conflict may lead to smaller rates of KT in both directions. Here, the cumulative levels of useful knowledge increase more slowly throughout the development project and the product launch time is optimally delayed. Therefore, conflict in the simultaneous transfer

of knowledge between the product and process design teams may drive a delayed product launch. Alternatively, conflict may cause a higher rate of KT in one direction and a lower rate in the other. In this situation, we do not know whether the cumulative useful levels of product or process team knowledge are larger or if the optimal product launch time occurs earlier or later.

2.5 Numerical Analysis

In this section, we introduce results based on numerical sensitivity analysis. We present two base examples (Examples 1 and 2), each reflecting a substantially different decision-making environment, as well as three variations of each base example. The purpose of the numerical examples is to illustrate some key analytical results and to extend those results by providing insights on profit. We compare the situation where the manager is given a mandate regarding the product launch time versus the situation where the manager has the authority to optimally determine the product launch. Also, our numerical results extend our analytic results on the effect of conflict or synergy when KT occurs in both directions simultaneously.

The particular functions and input parameters we employ are inspired by the KM literature, interviews with managers from the automotive industry, and articles from academic and practitioner publications. Appendix A contains a detailed account of all functional forms and input parameter values. Most input parameters are the same for Examples 1 and 2. However, due to different input values for D_0 , M_0 , $V_{X(T)}$, $V_{Y(T)}$, V_T , and T , we obtain dramatically different solutions. Tables A.3 and A.5 summarize the results of Examples 1 and 2. Figures 2.3 and 2.4 illustrate key managerial insights.

2.5.1 Example 1 and Its Variations

The situation reflected in Example 1 is based on the following parameter settings. The product launch time is given ($T=10$). The product and process design teams have a solid foundation of knowledge at the outset of the NPD project due to recent training and past experience from related projects ($D_0= M_0=8$). The product design team knowledge is more effective at driving KT benefits to the process team compared to the ability of the process design team knowledge to drive KT benefits to the product team ($r_2=5\rho_2$). The level of product design team knowledge enhances the effectiveness of KA significantly more than the level of process team knowledge enhances the effectiveness of KA ($\rho_4=2r_4$). The remaining input parameter settings are identically defined for both teams.

Since the initial levels of knowledge of the product and process design teams are relatively large, the optimal rates of KA and KT decrease throughout the NPD project for both teams (front-loading strategy). As illustrated in Figures 2.3a and 2.3b, earlier in the NPD project, the level of knowledge of the product design team optimally increases faster than that of the process design team. Hence, as shown in Figure 2.3c, the level of knowledge embedded by the product design team during the development project is much larger than the knowledge contributed by the process design team. The manager focuses more efforts on increasing product design team knowledge due to its significant impact on the effectiveness of both KA and KT. It is interesting to note that rather than directly acquiring more process design knowledge, the manager optimally increases that knowledge by investing in more product design knowledge which is then transferred to the process design team. The total profit earned is \$12,023.

Example 1a is identically defined as Example 1 except that we optimally determine the product launch time, $T_{1a}^*=8.7$. As illustrated in Figures 2.3a and 2.3b, compared to Example 1, the manager realizes an earlier product launch while investing in higher rates of knowledge creation for both teams throughout the development project. As a result, despite the earlier launch time, the accumulated useful levels of product and process design team knowledge are higher at time 8.7 in Example 1a than at time 10.0 in Example 1. Therefore, by permitting the manager to derive T, we find that she optimally introduces a superior product to the marketplace at an earlier time. This leads the manager in Example 1a to realize a 12.0% higher (\$13,460) profit relative to Example 1.

Example 1b is identically defined as Example 1a except that the simultaneous transfer of knowledge between the product and process design teams incurs an additional cost due to conflict ($c_3=0.5$). As a result, the manager in Example 1b pursues smaller rates of KT in both directions. The smaller rates of transfer drive smaller rates of KA. With the more limited pursuit of knowledge creation, the levels of product and process design team knowledge embedded in the NPD project are smaller. To ensure that sufficient levels of design knowledge are embedded during the development project, the manager in Example 1b delays the product launch time by 5.4% ($T_{1b}^*=9.2$) compared to Example 1a. Due to the later market entry and the lesser amounts of cumulative useful knowledge at the launch time, profit is 10.8% lower (\$12,001) than in Example 1a.

In contrast in Example 1c ($c_3 \approx 0.5$) when there are benefits due to synergy for the simultaneous transfer of knowledge between teams, the optimal launch time is 10.6% earlier ($T_{1c}^* = 7.8$) than in Example 1a. The manager optimally pursues greater rates of KT in both directions which leads to greater rates of KA for both teams. As a result, higher rates of product and process design team knowledge are embedded during the development project. Ultimately, profit is 9.4% higher (\$14,718) as compared to Example 1a. These results demonstrate the importance of developing KT strategies that embody synergy as opposed to conflict.

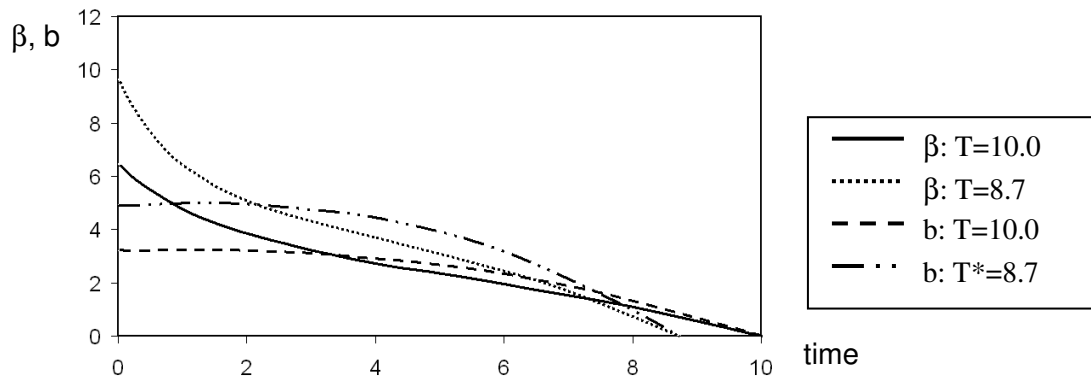


Figure 2.3a Optimal KT for $T=10.0$ (Example 1) and $T^*=8.7$ (Example 1a)

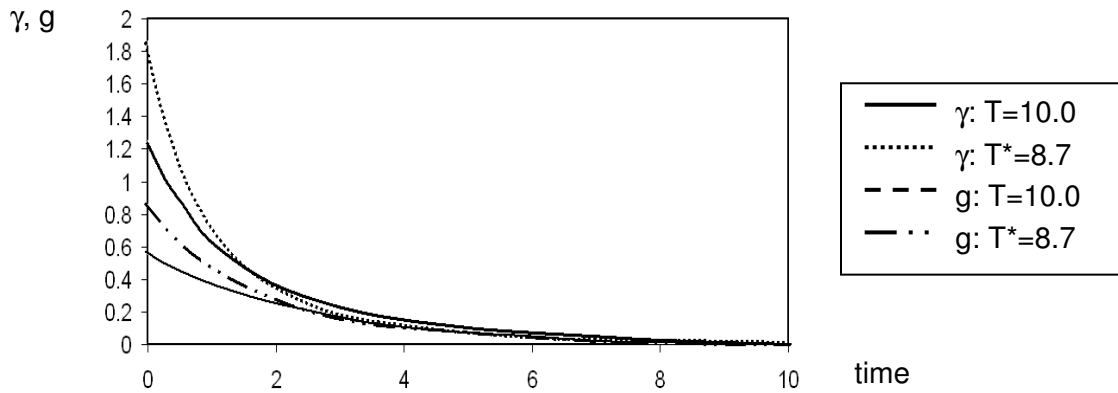


Figure 2.3b Optimal KA for $T=10.0$ (Example 1) and $T^*=8.7$ (Example 1a)

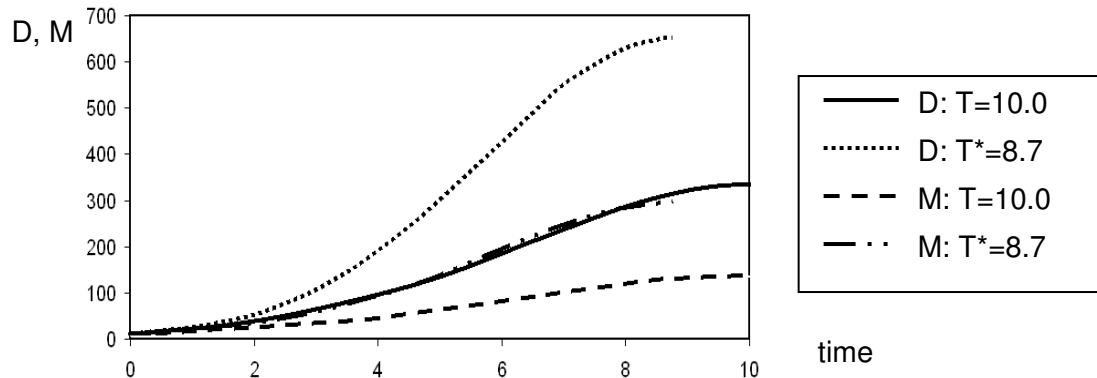


Figure 2.3c Optimal levels of product and process design team knowledge for $T=10.0$ (Example 1) and $T^*=8.7$ (Example 1a)

2.5.2 Example 2 and Its Variations

The second base example is identically defined as Example 1 except for the following. We consider an NPD project in which the initial knowledge levels of both teams are small ($D_0=M_0=0.01$) and the product release time is given ($T=3$). The marginal revenue earned from embedding process design knowledge during the development project is twice as large as the corresponding value for product design knowledge ($V_{Y(T)}=2V_{X(T)}$). Lastly, the manager incurs additional conflict costs when the transfer of knowledge between teams occurs simultaneously ($c_3=0.5$).

Despite the initially low levels of product and process design team knowledge, the manager undertakes front-loading strategies for KA for both teams. KA is high early in the NPD project because of the need to increase the levels of knowledge and since the rates of return on KA are considerably higher than those for KT. In contrast, with the initially small levels of product and process team knowledge and the additional cost due to conflict, KT provides limited benefits relative to the costs early in the NPD project. Therefore, the manager undertakes the delay strategies in both directions of KT. The peak pursuit of KT is delayed until later in the NPD project when the levels of product and process team knowledge are larger due to KA and LBD so that the effectiveness of KT is larger.

Throughout the NPD project of Example 2, the manager pursues considerably more KT from the product to the process design team than transfer in the reverse direction (Figure 2.4a). This result occurs due to the higher contribution to net revenue from process design knowledge and the additional costs incurred when KT is pursued in

both directions simultaneously. Also, the substantial contribution to net revenue from process design knowledge leads to a higher rate of KA by the process design team compared to the product team. The profit earned in Example 2 is \$5,909.

The inputs to Examples 2 and 2a are identical except that in Example 2a we optimally determine the product launch time, $T_{2a}^*=2.8$. We find that the optimal rates of knowledge creation for both the product and process design teams are smaller throughout the NPD project in Example 2a compared to Example 2. As a result, the cumulative useful levels of knowledge embedded into the development project by both the product and process design teams are smaller at the earlier launch time (Figures 2.4a-2.4c). Nevertheless, the strategy depicted in Example 2a leads to profit of \$6,431, which represents an 8.8% increase compared to Example 2. Here, the impact of time-based competition on net revenue is substantial and drives the manager to launch an inferior product at an earlier time.

The input for Example 2b is identical to Example 2a except that the manager does not incur additional costs due to conflict ($c_3=0$) from the simultaneous transfer of knowledge. The manager's knowledge creation strategy is illustrated in Figures 2.4d and 2.4e. Due to the conflict cost in Example 2a, the optimal KT from the process to the product design team is lower whereas the KT in the reverse direction is higher compared to Example 2b. This is consistent with Corollary 5. Furthermore, the rates of KA for both teams are higher in Example 2a relative to Example 2b. Therefore, in Example 2a, KA is used to compensate for the lower rate of KT that occurs from the process to the product design team. Overall, the levels of knowledge of both teams increase slower in Example 2a relative to 2b. Ultimately, due to the cost conflict in Example 2a, the manager optimally launches an inferior product 8.8% later ($T_{2b}^*=2.6$) and earns 7.5% less profit as compared to Example 2b where profit is \$6,956.

Lastly, instead of conflict, in Example 2c the simultaneous transfer of knowledge exhibits synergy ($c_3=\tilde{0.5}$). Here, the manager optimally launches a superior product earlier ($T_{2c}^*=2.4$) and earns 17.5% higher profit (\$7,559) compared to Example 2a. Again, these results demonstrate the importance of developing KM strategies that embody synergy as opposed to conflict.

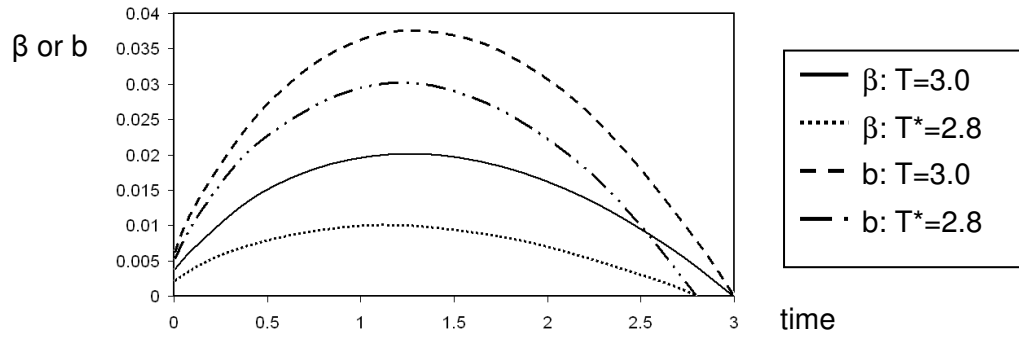


Figure 2.4a Optimal KT for $T=3.0$ (Example 2) and $T^*=2.8$ (Example 2b)

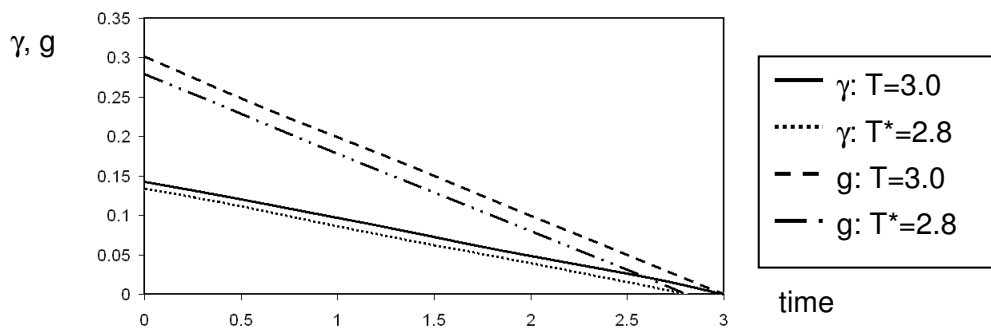


Figure 2.4b Optimal KA for $T=3.0$ (Example 2) and $T^*=2.8$ (Example 2b)

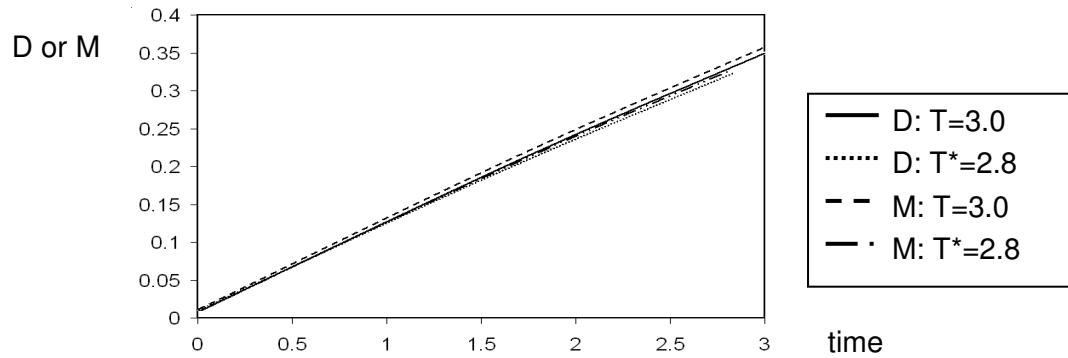


Figure 2.4c Optimal levels of product and process design team knowledge for $T=3.0$ (Example 2) and $T^*=2.8$ (Example 2b)

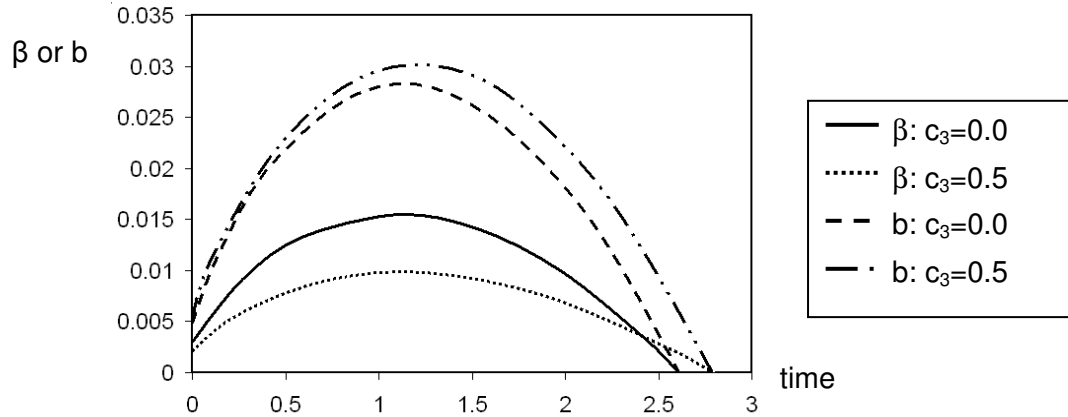


Figure 2.4d Optimal KT for $c_3=0.5$ (Example 2a) and $c_3=0.0$ (Example 2b)

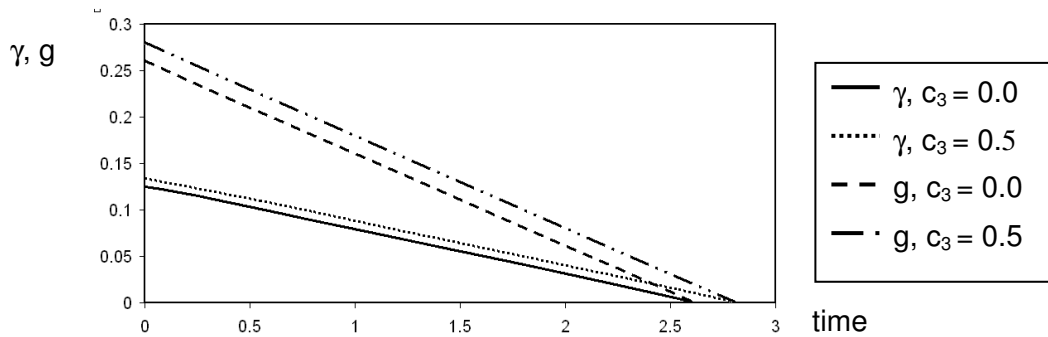


Figure 2.4e Optimal KA for $c_3=0.5$ (Example 2a) and $c_3=0.0$ (Example 2b)

2.6. Conclusions

We develop a normative model to aid the manager of an NPD project determine her KM strategy for the product and process design teams. The timing and extent of knowledge embedded by each team during the development project determine the features, functionality, and manufacturing efficiency of the product and process. Thus, the manager's KM strategy drives the net revenue earned when the product is launched. The manager impacts the knowledge levels of the product and process design teams through knowledge creation. The manager determines the optimal rates of KA for each team and the rates of KT between teams. Also, the manager may determine the optimal product launch time, which reflects the tradeoff between early market benefits versus the development of superior product and process features.

2.6.1 The Delay or Front-Loading Strategies

We show that there are two possible strategies that the NPD manager may follow when pursuing KA for each team or KT between teams. First, we introduce the *delay strategy*, which occurs when the effectiveness of KA or KT is small early in the development project. A low level of effectiveness may occur if the initial level of product and process design team knowledge is small, if there is considerable technical or market uncertainty early in the NPD project, or if the returns to KA or KT are small. Due to the limited effectiveness, the manager pursues KA or KT at a relatively small but increasing rate early in the development project. The rate increases for two reasons. First, over time, the levels of product and process design team knowledge increase through LBD and knowledge creation. Second, technical and market uncertainty are resolved over time. As a result, the effectiveness of KA or KT increases early in the development project. Eventually, the rate of KA or KT reaches a peak and declines thereafter. The decline occurs for several reasons. First, the level of product or process team knowledge reaches a point where additional gains are difficult to achieve (diminishing returns). Second, over time less of the NPD project remains to accrue the benefits KA or KT. Third, over time the manager is better able to increase knowledge by leveraging LBD which is free. Basically, in the delay strategy, the manager optimally delays her peak investment in KA or KT until a later time when the investment is more effective.

Second, we introduce the *front-loading strategy*, which occurs when the effectiveness of KA or KT is high at the outset of the NPD project. This situation may arise if the levels of knowledge of the product or process design teams are relatively large at the initial time, if there is limited technical or market uncertainty early in the development project, or if the returns to KA or KT are considerable. In the front-loading strategy, the manager pursues KA or KT at a relatively high and decreasing rate throughout the NPD project. Therefore, the manager has no incentive to delay the peak investment in KA or KT. The rate of KA or KT decreases over time for several reasons. First, further additions to the level of product or process design team knowledge are more difficult to realize as a result of diminishing returns. Second, as time passes, less time remains in the NPD project to accrue the benefits from an increase in the level of product design team knowledge. Third, since the level of knowledge of the product or process team increases over time, the manager's ability to leverage LBD increases.

The above analytic results are extended numerically (details not given here) to observe how the delay versus front loading strategy impact the optimal product launch

time and profit. Consistent insights are obtained in extensive sensitivity analysis. We first set the initial levels of knowledge of both teams at low levels and then increase them to observe the effect on the optimal solution. When the initial levels of knowledge are small, the manager optimally pursues the delay strategy. As the initial levels of knowledge increase, the peak rate of KT or KA occurs earlier. Eventually, when the initial levels of knowledge are sufficiently large, the manager optimally switches and pursues the front-loading strategy for KT or KA. Moreover, we find that as the initial levels of product and process team knowledge increase, the manager launches a superior product earlier and earns higher profit. Analogous results are obtained for the other drivers of effectiveness of KA or KT.

Since the manager has some control over the effectiveness of pursuing knowledge creation, the above insights are particularly important. In particular, we demonstrate that the manager must carefully assemble her product and process design teams so that the full potential of each team's knowledge is realized at the outset of the NPD project. To do so, the manager must understand the nature of the knowledge that will be required as well as the talents of potential team members. Naturally, if a key skill is not available internally, the manager should acquire the skill, perhaps, through hiring or engaging consultants. It is interesting to note that when a manager assembles teams for a more radical (incremental) development project, the initial levels of team knowledge are likely to be low (high) relative to the levels reached by the product launch time. Therefore, it is especially important as well as more challenging for the manager of a radical NPD project to form teams that embody the necessary skills.

In addition, the rates of return on KA or KT also drive the levels of effectiveness. To the extent possible, the manager should create an environment that fosters higher rates of return. Incentives may be put into place to encourage the sharing of knowledge within a team so that any increase in knowledge by some team members (e.g., through LBD, executive education, etc.) is shared with other team members. Similarly, if a manager introduces an IT system to facilitate the sharing of knowledge within a team, then the returns to any investment in knowledge creation are higher.

Lastly, the effectiveness of knowledge creation is impacted by the rates of technical and market uncertainty. To the extent possible, the manager should take action to reduce uncertainty early in the development project. Technical uncertainty may be reduced, in part, by selecting team members with the ability to anticipate future developments. Alternatively, forming alliances with university research labs may provide

insights on technology advancement. Similarly, selecting team members with extensive experience in marketing research may reduce uncertainty about the marketplace. Also, employing consulting firms that specialize in market research may be helpful. Lastly, KA or KT efforts that occur early in the development project may focus on reducing the impact of uncertainty.

2.6.2 Complementary Relationships

Another important insight from the model is that the manager should consider key complementary relationships among the KA and KT strategies and the impact of these strategies on the optimal product launch time. We show that if KT in *either* direction or KA for *either* team is higher, the manager pursues higher rates of knowledge creation for *both* teams. The higher rates of KA and KT enable the design teams to embed more knowledge into the development project over time. Thus, the manager optimally launches the product earlier. A larger rate of KA or KT optimally occurs if the effectiveness is larger or the cost is smaller. To increase the effectiveness, the manager should follow the suggestions given in Section 6.1. To reduce the cost, the manager should lessen any potential conflict when KT occurs in both directions simultaneously and enhance synergy, as described in Section 6.4.

Analytically, we show that if the rate of LBD for *either* team is larger, then the manager optimally pursues more KA for *both* teams and more KT in *both* directions. Numerically we show that if the rate of LBD of either team is larger, then the manager earns higher profit by releasing a superior product at an earlier time. Therefore, a high rate of LBD reduces the tradeoff between time-to-market benefits and developing a superior product and process. Clearly, we show that LBD is a key source of competitive advantage. This is important since, to some extent, the manager can influence the rate of LBD. Pisano et al. (2001) describe several actions that can be taken to enhance the rate of LBD associated with the deployment of new cardiac procedures. In general, the manager may enhance the rate of LBD by creating an environment that values and rewards learning. The manager can encourage and facilitate KT between team members so that LBD realized by some team members benefits the entire team. Also, the investment in technical support systems may enhance the ability of a team to benefit from LBD.

2.6.3 Uncertainty Resolution

We analyze the effect of uncertainty resolution that occurs during the development project. The rate of technical and market uncertainty is exogenous reflecting external market conditions and technology change. Analytic results are obtained demonstrating that if uncertainty is relatively small early in the development project or if uncertainty is resolved quickly over time then the manager pursues higher rates of KA and KT for both teams. As a result, higher levels of design team knowledge are embedded in the development project over time and an earlier product launch occurs resulting in a higher profit. Alternatively, suppose the extent of uncertainty is large early in the development project or decreases slowly. As a result, KA and KT are less effective and are pursued at lesser rates. However, we also find that by undertaking more KA and KT, and thereby increasing the levels of product and process design knowledge, the manager may *endogenously* reduce the *impact* of technical and market uncertainty. Therefore, the extent to which the manager reduces her pursuit of KA or KT is moderated by the ability of the product and process design teams to apply their knowledge to reduce uncertainty. In Section 6.1, we describe actions a manager may pursue to reduce the impact of uncertainty.

2.6.4 Synergy or Conflict

We analyze the impact of costs due to conflict or benefits from synergy when KT between the product and process design teams occurs simultaneously. Our results reveal that the benefits related to synergy lead to higher rates of KT in both directions. Due to the complementary relationships, this gives us higher rates of KA for both teams. With higher levels of product and process design knowledge embedded in the development project, the manager realizes an earlier launch of the product, although the product may not always be superior. Beyond these analytic results, numerical results show that synergy leads to higher profit.

In contrast, there are two possible outcomes if additional costs occur due to conflict when the transfer of knowledge for both teams occurs simultaneously. First, the conflict may cause the manager to pursue less KT in both directions, which leads to less KA over time. Moreover, product and process design knowledge are embedded in the development project at a slower rate and the product launch time is delayed. Second, the manager may undertake a higher rate of KT in one direction and a lower rate in the other. In this case, the levels of knowledge embedded by the design teams may be

larger or smaller so we do not know whether the product launch is earlier or delayed. Beyond these analytic results, numerically we find that conflict always leads to lower profit.

These results demonstrate that the manager should take actions to avoid conflict and to exploit synergy when KT occurs in both directions simultaneously. The literature provides examples of NPD projects where synergy and conflict occur (Loebecke et al. 1999, Terwiesch et al. 2002). To the extent possible, the manager should reduce the sources of conflict including the transfer of knowledge that is sticky (Von Hippel 1994) or ambiguous (Sorensen et al. 2005). It is also important to reduce or manage the complexity in the content of the knowledge transferred (Hansen 1999). The NPD manager should establish incentives for collaboration and cooperation and should reward teams for the quality and clarity of the knowledge they share. Teams should be given support tools (information technology) to make documentation and communication more straightforward. Training teams to apply methods such as concurrent engineering is also useful. To reduce conflict and enhance synergy, basic principles of project management should be followed. At the outset, the goals of the KT activity should be established and the roles of individual team members should be clear. A project manager should be identified with the responsibility to coordinate and monitor the KT activities and to modify the original plan as needed. Lastly, through sensitivity training, the manager should reduce conflict and enhance synergy caused by communication barriers due to cultural differences (Loebecke et al. 1999, Sosa et al. 2004).

CHAPTER 3

A STOCHASTIC MODEL FOR THE MANAGEMENT OF KNOWLEDGE FOR PRODUCT AND PROCESS DESIGN TEAMS

3.1. Introduction

Today's highly competitive and dynamic marketplace has established knowledge as a main source of competitive advantage (Liebeskind 1996). According to Davenport and Prusak (1998), knowledge embodies experience, values, contextual information and expert insights that provide a framework for evaluating and incorporating new experiences and information. The scope of knowledge a firm must possess includes the customers' needs, the external business environment, and the skills and experience of its workforce. *Knowledge management* (KM) refers to the collection of processes that govern the creation, dissemination, and utilization of knowledge.

New product development (NPD) projects are among the most knowledge intensive endeavors in the modern corporation (Macher 2006). KM of product and process development impacts the time to market, product and process functionality, manufacturing costs, and the match between customer requirements and final product features (Mihm et al. 2003, Ulrich and Eppinger 2003). Said differently, efficient and effective product and process design activities directly affect the commercial success of a product (Fine 1998, Fisher et al. 1999, Hatch and Macher 2005). Unfortunately, empirical evidence indicates that many firms lack an understanding of how to develop KM strategies that drive successful NPD outcomes (Döös et al. 2005).

We introduce a model to develop insights on managing the levels of knowledge of the product and process design teams throughout the NPD project. The timing and extent of cumulative knowledge embedded in the development project by the product and process design teams determine the features, functionality, manufacturing efficiency, and launch time of the new product and process and thereby drive the *expected net revenue* earned over the product's life cycle. The expected net revenue is comprised of three components. First, the manager faces uncertainty regarding the time the product will be successfully launched in the marketplace. Second, the expected net revenue earned reflects the ability for early market entry deploying efficient manufacturing processes. While the first dimension of expected net revenue is driven by product development efforts, the latter is driven by efforts for process development and

the extent of time-based competition. As such, the expected net revenue derived from the NPD project captures the trade-off between seeking early market entry benefits (Hendricks and Singhal 1997) versus delaying the product release to develop superior product and process features (Bhuiyan et al. 2004, Carrillo and Franza 2006, Cohen et al. 1996, and Joglekar et al. 2001).

The above establishes the critical role of the NPD manager who determines the levels of knowledge of the product and process design teams throughout the development project. Specifically, the manager determines the optimal rate and timing of knowledge creation, which includes two types of induced learning (Ittner et al. 2001, Pisano, 1994). First, investment in *knowledge development* (KD) increases the level of knowledge of the product design team (Iansiti and Clark 1994). KD reflects problem solving activities undertaken by the product design team including testing, simulation, prototyping and experimentation (Thomke 1998). Also, KD occurs when team members participate in training programs offered by equipment or software vendors. KD may take the form of personnel additions such as hiring new engineers or reassigning existing employees. Finally, KD occurs when team members attend professional conferences (Biskup and Simons 2004, Jacobs 2006).

Second, the manager invests in *knowledge transfer* (KT) to increase the knowledge levels of the product and process design teams. KT is the process by which one team's knowledge is affected by the experience of another (Argote and Ingram 2000). KT activities include the sharing of codified information about routines and practices, participation in meetings involving members of both teams, and the exchange of employees between teams (Cummings and Teng 2003, Loch and Terwiesch 1998). KT from the product to the process design team conveys information such as the consumer preferences and desirable product specifications (Blackburn et al. 1996, Hatch and Macher 2005). During the transfer of knowledge from the process to the product design team, information on process capabilities and constraints are communicated to ensure the manufacturability of the product (Terwiesch et al. 2002).

We explicitly recognize that the effectiveness of KD and KT are both interrelated and dynamic (Epple et al. 1996). Early investments in KD and KT are appealing since the benefits are sustained over the remainder of the NPD project (Terwiesch and Loch 1999). Moreover, the benefits realized from KD at a particular time depend on the level of knowledge of the product design team at that time since a higher skilled workforce is better able to comprehend and deploy new knowledge. Similarly, the effectiveness of KT

at a particular time depends on the levels of knowledge of both teams since a higher skilled source has more knowledge to offer and a higher skilled recipient is better able to absorb and exploit new knowledge (Darr et al. 1995).

While investments in KD and KT are pursued to increase the levels of knowledge of the product and process design teams and ultimately drive net revenue, in the short-term these investments may uncover errors that reduce the value of the cumulative knowledge previously embedded. For example, KD during CAD experiments undertaken by the product design team may reveal that an element of the product concept has been specified incorrectly (Terwiesch et al. 2002, Yassine 2008). Similarly, KT may cause the recipient team to uncover errors in its conception of product or process characteristics (Loch and Terwiesch 1998). The manager may respond to the reductions in embedded knowledge triggered by the errors by deploying more knowledge. This may occur in the form of design changes, i.e., activities whose implementation alters elements of the product or process design that were previously developed (Mitchell and Nault 2007).

While maximizing the net expected benefits from the development project, the manager needs to account for the costs incurred for induced learning. Many costs are associated with KD including those from equipment and materials required for experimentation, or from integrating new employees (new knowledge) into existing teams. The costs of KT reflect the considerable efforts undertaken by members of both teams to codify knowledge (either manually or using information technology). Furthermore, disruption costs are also incurred when members of the product or process design teams are engaged in KT. The disruption costs are substantial and may include overtime if the rate of development must be sustained during knowledge creation (Carrillo and Gaimon 2004, Ha and Porteus 1995).

We obtain important insights on a manager's strategy to invest in KD and KT to maximize expected profit over the development project. Conditions are given whereby the manager optimally pursues a *front-loading strategy*. For example, we show that if the initial level of knowledge of the product design team is relatively high, the manager initially pursues KD and KT for the process design team at high rates that decrease throughout the NPD project. In contrast, we provide conditions whereby the manager optimally pursues a *delay strategy* in which the peak efforts to increase the level of knowledge occur later in the development project. For example, we show that if the initial level of process design knowledge is small, the manager optimally delays her peak efforts of KT to the product design team until the process design team's knowledge has

increased. This insight extends the existing literature that depicts the investments in knowledge creation as decreasing throughout the NPD project (Carrillo and Franza 2006).

Our findings characterize the key impact of design changes on the manager's knowledge management strategies throughout the NPD project. We show that design changes triggered by uncovering errors during KD or KT impacts the rate and the timing of knowledge creation for both design teams. For example, suppose there is a high rate of design changes triggered by KT from the process design team. We show that the manager front-loads KD of the product design team and KT to the process design team but pursues the delay strategy for KT to the product design team. Lastly, we show that the drivers of expected net revenue lead to a complementary relationship between the manager's pursuits of KD and KT in some cases, and to a substitutability in other cases.

The remainder of this chapter is structured as follows. Section 3.2 contains a review of the related literature. In Section 3, we introduce the objective and constraints of the model. We present analytic results and sensitivity analysis in Section 3.4. Section 3.5 contains the conclusions.

3.2 Literature Review

This chapter is grounded in two research streams, KM and NPD. In the context of NPD, two forms of induced learning have appeared in the literature. First, KD is comprised of problem solving undertaken by the product design team that involves testing, simulation, prototyping and experimentation (Thomke 1998, Iansiti and Clark 1994). Thomke and Fujimoto (2000) emphasize the importance of pursuing activities that identify and solve problems early to reduce the lead time and costs of product development. Second, the NPD literature clearly establishes the importance of managing the rate and timing of KT between the product and process design teams. In their study of 281 blockbuster product and process development teams, Lynn et al (2000) identify KT between teams as one of the five highest priority practices leading to a successful NPD project. Clark and Fujimoto (1991) have analyzed the worldwide automotive industry, and introduced the concept of "integrated problem solving," which refers to exchanging preliminary product design information to achieve overlap and intensive communication between product and process design efforts. In a case study, Loch and Terwiesch (1996) describe how knowledge exchange between the product and process teams impacts the development of the Jalopy sports car.

Much of the NPD literature characterizes KT in the context of concurrent engineering. Ha and Porteus (1995) examine KT from the product to the process design domain for a project where the product and project design processes are carried out in parallel. They determine the optimal number and timing of progress reviews during the development project that minimize the time-to-market. Krishnan et al. (1997) consider the general case of partially overlapping sequential design activities. They show that the timing of KT from the product to process design team depends on two characteristics of the NPD project: (i) “upstream evolution” i.e., the rate at which the product design team converges to the final product attributes and features, and (ii) “downstream sensitivity” i.e., the extent of engineering changes generated by KT from the product design team. They optimize the overlap between the product and process design efforts in order to minimize time-to-completion. Loch and Terwiesch (1998) examine the amount of overlap of sequential NPD activities as well as mechanisms to manage communication policies, which refer to the KT from the product to the process design domain during overlap. The authors determine the optimal meeting frequency and information batching policy that maximizes the benefits from an earlier product launch realized by overlapping product and process development activities less the additional indirect costs of KT incurred.

Roemer et al. (2000) develop an algorithm to determine the optimal overlap between multiple sequential activities and apply it in a real example. Joglekar et al. (2001) develop insights on optimal concurrency strategies between coupled product and process design activities under a deadline. They find that concurrency is not always the optimal design structure, depending on factors such as KT effectiveness and design errors. With the objective of minimizing the time-to market of an NPD project, Roemer and Ahmadi (2004) determine the optimal overlapping and crashing strategies of design activities for KT from the product to the process design team. In a comprehensive field study, Terwiesch et al. (2002) document properties of the information exchange and the modes of KT in automotive projects. In the context of larger and more complex engineering projects, Mihm et al. (2003) show how misaligned objectives of different sub-teams drive coordination problems and delay project completion. In a study of redesign and development projects in healthcare and telecommunications, Mitchell and Nault (2007) examine the impact of KT and uncertainty on rework for product and process design teams. They find that communication between teams reduces the impact of design changes, and thereby leads to earlier project completion.

Relative to the above-mentioned literature, our research is unique in its comprehensive treatment of dynamic knowledge management strategies for the product and process design teams throughout the NPD project. In contrast to much of the NPD literature, we permit the NPD manager to increase the level of knowledge of the product design team over time through KD as well as KT. Moreover, we explicitly permit the NPD manager to determine the dynamic rates of KT in both directions. As a result, we capture the value of efforts to improve the design for manufacturability, design efficient manufacturing processes, and ultimately launch a product with features that meet market demand.

The existing literature considers the errors and subsequent design changes that occur during an NPD project as exogenous. In contrast, we capture the endogenous nature of detecting errors triggered by knowledge creation activities during the development project. Thus, we provide insights on the impact of the extent of errors uncovered on both the rate and timing of the knowledge creation for both of the product and process design teams. As such, we are able to extend the earlier work by Clark and Fujimoto (1991), Adler (1995) and Terwiesch et al. (2002) and explore the advantage of delaying KD or KT until later in the development project to minimize the impact on expected profit when design changes and rework are triggered by the detection of errors.

We capture the uncertain nature of the value earned from NPD projects. The probability of releasing a successful product is impacted by the product design knowledge. Thus, we extend the past literature which have acknowledged the product design as an essential ingredient in the of NPD projects, and explicitly capture the importance of product design in the value earned from a development project. Meanwhile the net revenue earned from the marketplace is impacted by the process design knowledge, and the time-to-market. Thus, unlike most studies in the NPD area, that focuses on early market entry, our maximization of expected net revenue also captures the value of delaying a product launch to improve the efficiency of manufacturing processes as well as to develop product features and functionality that enhance the likelihood of releasing a product that meets market needs.

Most prior research considers KT strategies with a particular dependency structure between design activities (Joglekar et al. 2001). In contrast, we adopt a general approach that does not specify either the amount of overlap or the dependency between the product and process design activities. In our research, KT between the product and

process design teams may be overlapped or may occur sequentially or simultaneously. Moreover, we characterize conditions that drive different dynamic strategies for KD and KT as well as different dependency structures. Finally, in contrast to the previous literature which assumes all knowledge is transferred during KT, we endogenously determine the optimal rates of KT in both directions throughout the project.

3.3 The Model Formulation

In this section, we present a model to aid the manager determine a KM strategy for the product and process design teams throughout a development project. We describe how the knowledge levels of both teams vary over time and the impact of rework that is triggered both by knowledge development of the design team, and knowledge transfer between teams. Moreover, we show how the knowledge embedded into the new product during development determines the probability of designing a functional product that returns positive net revenue in the marketplace. A summary of our notation appears in Table B.1 of the Appendix B.

3.3.1 Knowledge

We consider the time horizon $t \in [0, T]$, where 0 is the initial time of the development project and T is sufficiently large so that the end of the product lifecycle has been reached. Let $D(t)$ denote the *level of knowledge of the product design team that is relevant to the NPD project at time t* . Similarly, $M(t)$ is the *level of knowledge of the process design team that is relevant to the NPD project at time t* . Each level of knowledge reflects the team's competence about the scientific and engineering information that is relevant to the development project. The initial levels of knowledge are known, given by $D_0 = D(0) \geq 0$ and $M_0 = M(0) \geq 0$. The initial levels of knowledge may be inferred from the overall educational background of team members, years of work experience, performance appraisals, and past experience in similar scientific and engineering domains (Leonard-Barton et al. 1994, Epple et al. 1996, Carrillo and Gaimon 2004). While a team may possess a considerable amount of knowledge in general, the level of knowledge relevant to the development project under consideration may be small due to its novelty. As described below, the manager increases $D(t)$ and $M(t)$ so that each team is able to apply more knowledge to the NPD project.

The knowledge level of the product design team increases as the manager allocates resources towards KD efforts. Let $\gamma(t)$ denote the *rate of efforts directed by the*

manager at time t for KD of the product design team. KD efforts include problem-structuring, goal-setting for the problem-solving process, and experimenting with working prototypes of different design alternatives (Thomke 2000, Clark and Wheelwright 1992). KD also occurs when team members undergo training such as participation in continuing education programs and conferences. In addition, KD may take the form of hiring and integrating new employees into the existing teams.

The extent that KD efforts increase product team knowledge is related to the team's existing level of knowledge as well as and the effect of diminishing returns. A product design team with a higher level of knowledge it is better able to comprehend and deploy new knowledge so that the impact of KD efforts is larger (Carrillo and Gaimon 2004, Hatch and Macher 2005). However, the extent that the existing level of product design team knowledge drives gains from KD exhibits diminishing returns. Mathematically, the rate of increase in the level of product design team knowledge at time t due to KD is $\gamma(t)[D(t)]^{\rho_1}$, where ρ_1 ($0 < \rho_1 < 1$) indicates the rate of diminishing returns. Our representation of the gain in product design team knowledge parallels the widely used Cobb-Douglas function in Economics.

In addition to KD for the product design team, the manager increases the knowledge levels of both the product and process design teams by investing in KT. Knowledge transfer may take place in either or both directions through sharing codified information, participation in meetings, and exchanging employees. For example, in GM KT takes place through regularly scheduled meetings between teams and is monitored through a computerized Engineering Change Request System (Jacobs 2006). The recipient's increase in knowledge due to KT is two dimensional. First, there is the direct value of the knowledge that is transferred and applied from the source team. Second, there is an indirect increase in the recipient's level of knowledge because KT inspires the recipient to conduct additional experimentation and problem solving .

Empirical results show that the effectiveness of KT is related to the extent of efforts undertaken as well as the levels of knowledge of both teams participating in the transfer (Argote and Ingram 2000, Cummings and Teng 2003). While a source team with a higher level of knowledge is capable of transferring more knowledge to the recipient team, the benefits to the recipient exhibits diminishing returns. Similarly, the recipient team with a higher level of knowledge is better able to comprehend, deploy and respond to knowledge transferred from the source team. Said differently, the knowledge level of

the recipient team impacts the effectiveness of KT, again with diminishing returns (Dinur et al. 1998).

We capture these relationships as follows. Let $\beta(t) \geq 0$ be the *rate of efforts allocated by the manager to the transfer of knowledge from the process to the product design team at time t*. Let ρ_2 and ρ_3 ($0 \leq \rho_2, \rho_3 \leq 1$) indicate the rates of diminishing returns associated with the levels of product and process design knowledge, respectively. Therefore, $\beta(t)[M(t)]^{\rho_2}[D(t)]^{\rho_3}$ is the rate of increase in product design team knowledge at time t due to KT from the process design team. Similarly, with $b(t) \geq 0$ representing the *effort allocated by the manager to KT from the product to the process design team at time t*, $b(t)[D(t)]^{r_1}[M(t)]^{r_2}$ denotes the increase in the level of process design team knowledge, with $0 \leq r_1, r_2 \leq 1$. Again, our formulation reflects the general Cobb-Douglas function.

Equations (1) and (2) summarize how the levels of knowledge of the product and process design teams change over time (the subscript 't' denotes the derivative with respect to time.) Clearly, $D(t)$ and $M(t)$ are positive and non-decreasing throughout the NPD project. The product design team increases knowledge through KD and KT, whereas the process design team increases knowledge only through KT. In other words, KT from the product design team provides the impetus for knowledge creation activities to be undertaken by the process design team throughout the development project.

$$D_t(t) = \gamma(t)[D(t)]^{\rho_1} + \beta(t)[M(t)]^{\rho_2}[D(t)]^{\rho_3} \quad (3.1)$$

$$M_t(t) = b(t)[D(t)]^{r_1}[M(t)]^{r_2} \quad (3.2)$$

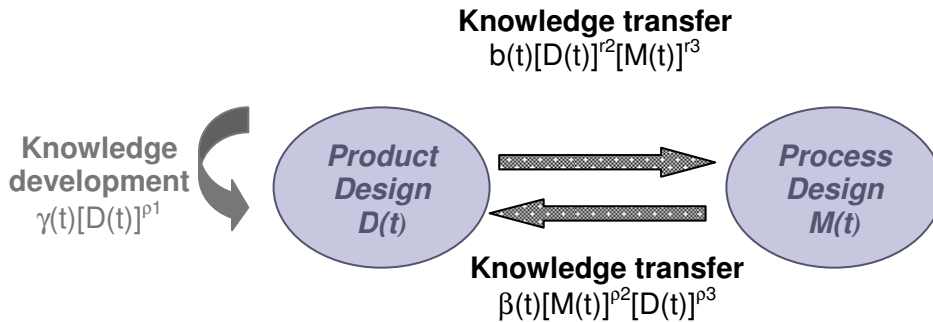


Figure 3.1 Dynamic knowledge management

Bhuiyan et al. (2004) suggest the importance of diminishing returns on the increase in knowledge derived from knowledge transfer. The extent that the level of knowledge of the source team increases the knowledge level of the recipient team may be different for the product and process design teams depending on characteristics of the NPD project. Thus we do not specify an a priori relationship between the parameters ρ_2 and r_1 . However, we do reasonably assume $\rho_3 < \rho_1$ indicating that, when increasing the level of knowledge of the product design team, the returns from KD are larger than the returns from KT (Darr et al. 1995).

The expected net revenue earned from the NPD project when it is released to the marketplace is driven by the knowledge applied by both the product and process design teams at each instant of time throughout the development project. Let $X(t)$ and $Y(t)$ represent the cumulative levels of useful knowledge embedded in the product and process designs, respectively, through time t of the development project for $t \in [0, T]$. For simplicity (and without loss of generality) since time $t=0$ represents the start of the development project we let $X(0)=0$ and $Y(0)=0$. This characterization of the accumulation of useful product and process design knowledge is similar to the evolution concept introduced by Krishnan et al. (1997). (Also see Carrillo and Gaimon 2000.)

Two forces drive the cumulative levels of useful knowledge over time. $X(t)$ and $Y(t)$ increase as the product and process design teams ($D(t)$ and $M(t)$, respectively) embed knowledge into the development project. Thus, if the manager pursues knowledge creation activities at time t to increase the knowledge levels of the product or process design team, she is able to embed more knowledge into the NPD project thereafter.

In contrast, $X(t)$ and $Y(t)$ may decrease at time t when knowledge creation activities ($\gamma(t)$ and $\beta(t)$) or ($b(t)$) identify mistakes in prior development efforts that necessitate design changes. Suppose CAD experiments undertaken by the product design team reveal that an element of the product concept assumed prior to time t is specified incorrectly. As a result, a portion of the knowledge the product design team had embedded in the development project is useless ($X(t)$ is reduced). Similarly, KT may cause the recipient team to uncover errors rendering a portion of the knowledge it had previously embedded in the development project useless (Mitchell and Nault 2007).

From the above, we see a conflict in the way that knowledge creation activities impact the cumulative levels of useful product and process design team knowledge. The

pursuit of KD and KT directly increases $D(t)$ and thereby indirectly increases the cumulative level of useful product design knowledge from time t through T . Similarly, KT indirectly increases the cumulative level of useful process design team knowledge starting at time t . At the same time investments in KD and KT ($\gamma(t)$ and $\beta(t)$) may uncover errors that directly reduce the cumulative useful level of knowledge previously embedded in the product design ($X(t)$). Similarly, the pursuit of KT to the process design team ($b(t)$) may uncover errors that directly reduce the cumulative useful level of knowledge previously embedded in the process design, $Y(t)$. Naturally, a small (large) rate of KD or KT provides less (more) opportunity to uncover errors. Over time as the manager continues to apply product and process design knowledge (including rework and design changes), the reductions in the cumulative levels of useful product and process design knowledge recover (Loch and Terwiesch 1998).

To formalize the above discussion mathematically, let $\theta_1 \geq 0$ indicate the extent that KD triggers design errors and reduces the cumulative level of useful product design knowledge. Similarly, let θ_2 and θ_3 ($\theta_2, \theta_3 \geq 0$) indicate the extent that design errors triggered by KT reduce the cumulative levels of useful product and process design knowledge, respectively (Yassine et al. 1999). Equations (3) and (4) summarize the above discussion regarding how the cumulative levels of useful product and process design team knowledge change over time. While it is possible for $X(t)$ and $Y(t)$ to decrease at time t , conditions are given (Appendix B) ensuring the non-negativity of these variables in any optimal solution.

$$X_t(t) = D(t) - \theta_1 \gamma(t) - \theta_2 \beta(t), \quad (3.3)$$

$$Y_t(t) = M(t) - \theta_3 b(t). \quad (3.4)$$

3.3.2 The Objective

Having completed the presentation of the model constraints, we turn our attention to the objective: to maximize expected profit. We denote the expected net revenue earned by a product released to the marketplace at time t as $F[X(t)]R[Y(t),t]$. Our conceptual representation of expected net revenue captures efforts of the product and process design teams as well as elements in the marketplace, as described below.

The probability that the new product has been successfully developed by time t , denoted by $F[X(t)]$, increases as the cumulative level of useful knowledge embedded into

the product design through that time increases (Lynn et al 2000, Christensen and Raynor 2003a). A product is deemed *successful* if it embodies the features and functionality demanded by the marketplace. Implicitly, the probability of developing a successful product represents a threshold acceptance the manager aims to achieve by accumulating product design knowledge. Naturally, as the cumulative level of useful product design team knowledge increases (decreases), the probability of developing a successful product increases (decreases) but at a decreasing rate giving us $\partial F/\partial X \geq 0$ and $\partial^2 F/\partial X^2 \leq 0$ (Krishnan et al. 1997, Bhuiyan et al. 2004).

The second component of the expected revenue function, $R[Y(t),t]$, denotes the revenue earned less the associated manufacturing and distribution costs incurred for the product that is released to the marketplace at time t (Zirger and Maidique 1990, Smith and Reinertsen 1998, Ulrich and Eppinger 2003). At each instant of time, as the cumulative level of useful knowledge embedded by the process design team increases, the margin that is achieved by cost effective manufacturing processes increases. Thus, the net revenue earned at time t increases (at a decreasing rate) in relation to the cumulative level of useful knowledge embedded by the process design team, giving us $\partial R/\partial Y \geq 0$ and $\partial^2 R/\partial Y^2 \leq 0$ (Armstrong and Lévesque 2002).

The time the new product is launched to the marketplace also impacts the net revenue earned. In some situations, the manager may purposely delay the launch of the new product in order to increase the net revenue earned (increase $Y(t)$) or generate a higher probability of success in the marketplace (increase $X(t)$). However, in doing so, the manager forgoes a portion of net revenue since time based competition has the effect of penalizing a delayed product release. This gives us $\partial R/\partial t \leq 0$ and $\partial^2 R/\partial t^2 \leq 0$ (Dhebar 1996, Christensen and Raynor 2003b). The second order effect occurs since the benefits realized from earlier market entry are bounded. Therefore, our characterization of expected net revenue captures the trade-off that occurs from delaying the product launch: the loss in expected net revenue due to time-based competition versus the additional expected net revenue earned from a superior product that is manufactured more efficiently (Cohen et al. 1996).

Beyond the manufacturing and distribution costs captured in net revenue, costs are incurred for knowledge creation (Clark and Fujimoto 1991, Roemer et al 2000). The cost for KD pursued by the product design team at time t is denoted by $C_1[\gamma(t)]$. This cost includes the wages of the design team and the costs for materials and equipment associated with modeling, experimentation, testing, prototyping and simulation (Jacobs

2006). Also, the cost of KD includes the salaries of trainers and consultants, expenses associated with attending conferences and workshops, and executive program tuition. The cost of KD at time t increases at an increasing rate in relation to the efforts expended at that particular time (Krishnan and Zhu 2006). While the first order effect is obvious, consider the second order effect. As more and more KD efforts are undertaken at a particular time, the costs for integration, coordination, and supervision increase at an increasing rate. Similarly, as the number of employees who divert their attention from development activities to pursue training increases, the costs (such as overtime) incurred to sustain team productivity levels increase at an increasing rate. This gives us $\partial C_1/\partial \gamma$ and $\partial^2 C_1/\partial \gamma^2 \geq 0$.

The cost of KT from the process (product) design team at time t is given by $C_2[\beta(t)]$ ($C_3[b(t)]$). This cost reflects the wages of the team members as they document and codify knowledge and pursue activities that are triggered by the transfer of knowledge. Costs are also incurred for the relocation of process and product design team members to facilitate the face to face transfer of knowledge. Analogous to the above discussion on KD, the cost of KT increases at an increasing rate as the extent of KT increases due to the overall disruption to ongoing activities as well as the difficulty of integrating and coordinating larger amounts of knowledge at a single instant of time (Loch and Terwiesch 1998, Mihm et al. 2003, Carrillo and Gaimon 2000). This gives $\partial C_1/\partial \beta$, $\partial C_2/\partial b$, $\partial^2 C_1/\partial \beta^2$, and $\partial^2 C_2/\partial b^2 \geq 0$.

Lastly, at the terminal time, the cumulative levels of useful product and process design knowledge provide a foundation for future development projects and are therefore another source of profit. Let $\Phi_1 X(T)$ ($\Phi_2 Y(T)$) denote the future value of the cumulative level of useful product (process) design knowledge with $\Phi_1 \geq 0$ ($\Phi_2 \geq 0$).

The objective to be maximized is given in Equation (5) and captures the above discussion of the expected net revenue and the costs incurred over the NPD project.

$$\int_0^T \{F[X(t)]R[Y(t), t] - C_1[\gamma(t)] - C_2[\beta(t)] - C_3[b(t)]\} dt + \Phi_1 X(T) + \Phi_2 Y(T) \quad (3.5)$$

3.4 The Optimal Solution

In the remainder of the chapter, the notation depicting time is suppressed whenever possible. Equations, tables and figures beginning with “B” refer to the Appendix. The symbol “*” indicates an optimal solution. Proofs of the analytic results appear in the Appendix B.

For mathematical completeness, we must consider the non-negativity constraints for the cumulative levels of useful knowledge of the product and process design teams. The effect of the non-negativity constraints are straightforward: If the constraint on $X(t)$ ($Y(t)$) is binding, then the manager decreases the rates of KD or KT (KT) thereby forcing $X(t)$ ($Y(t)$) to zero. The complete solution and the conditions on $\gamma(t)$, $\beta(t)$ and $b(t)$ that ensure $X(t)$ and $Y(t)$ remain positive are given in the Appendix B. However, it is reasonable to assume that the manager would not optimally pursue KD or KT that would drive the cumulative level of useful product or process design team knowledge to zero. Moreover, the results in the chapter hold regardless of whether a non-negativity constraint is binding. Therefore, for simplicity hereafter, we assume the non-negativity constraints on $X(t)$ and $Y(t)$ hold in an optimal solution.

The Lagrangian to be maximized is given in the Equation A.2. To obtain optimal solutions, we introduce the variables $\lambda_1(t)$ and $\lambda_2(t)$ to represent the marginal values of the levels of knowledge of the product and process design teams at time t , respectively. Also, $\lambda_3(t)$ and $\lambda_4(t)$ represent the marginal values of the cumulative levels of useful product and process design team knowledge at time t , respectively. The necessary conditions for optimality of the marginal value functions $\lambda_1(t)$, $\lambda_2(t)$, $\lambda_3(t)$ and $\lambda_4(t)$ are given in the Equations (A.5)-(A.8).

Theorem 1 states that the marginal values of the levels of knowledge of the product and process design teams are non-negative and non-increasing functions of time. Also from Theorem 1, the marginal values of the cumulative levels of useful product and process design team knowledge are non-negative throughout the NPD project. Further interpretation of Theorem 1 is postponed until we present the optimal policies for KD and KT. Theorem 1 follows directly from the optimality conditions.

THEOREM 1. *The marginal value functions satisfy the following conditions for $t \in [0, T]$.*

$\lambda_1^*(t), \lambda_2^*(t) \geq 0$ and $\lambda_{1t}(t), \lambda_{2t}(t) \leq 0$; $\lambda_3^*(t) = \Phi_1 + \int_t^T F_X R d\tau$ and $\lambda_4^*(t) = \Phi_1 + \int_t^T F_R Y d\tau$, $\lambda_{3t}(t), \lambda_{4t}(t) \geq 0$.

Along with the non-negativity constraints γ , β and $b \geq 0$, Equations (6)-(8) are the optimality conditions for the rate of KD for the product design team and the rates of KT to both the product and process design teams. The first term Equation (6) represents the marginal cost of KD for the product design team at time t . The second term is the marginal value of the associated increase in the level of product design knowledge from time t through the remainder of the development project. Therefore, at time t , the optimal KD policy for the product design team equates the additional marginal cost at t with the benefits realized from time t through T . Similarly, from Equation (7) (Equation (8)), we see that the optimal policy for KT from the process (product) to the product (process) design team equates the marginal cost at time t with the net marginal value of the associated increase in the level of product (process) design knowledge from time t through the remainder of the development project. Note that the net marginal value of KT reflects the loss in value associated with uncovering errors (third terms in Equation (7) and (8)).

$$\partial H / \partial \gamma = -C_{1\gamma} + \lambda_1 D^{\rho_1} - (\lambda_3) \theta_1 = 0 \quad (3.6)$$

$$\partial H / \partial \beta = -C_{2\beta} + \lambda_1 M^{\rho_2} D^{\rho_3} - (\lambda_3) \theta_2 = 0 \quad (3.7)$$

$$\partial H / \partial b = -C_{3b} + \lambda_2 D^{\rho_1} M^{\rho_2} - (\lambda_4) \theta_3 = 0 \quad (3.8)$$

3.4.1 The Dynamic Rates of KD and KT

Theorem 2 describes how KD and KT change throughout the development project. From the results in Theorem 2, we find that the optimal solutions for KD and KT must satisfy one of the two cases given in Corollary 1. Each case corresponds to different project, team, and market characteristics. Figures A.2 and A.3 illustrate the two possible solutions described in Corollary 1. A complete discussion of Corollary 1 follows.

THEOREM 2. *The change in the optimal rate of KD for the product design team at time t , (γ_t) , satisfies Equation (3.9). Moreover, the change in the rate that the manager optimally pursues KT from the process to the product design team at time t , (β_t) , and from the product to the process design team at time t (b_t) satisfy Equations (3.10) and (3.11), respectively.*

$$C_{1\gamma\gamma}(\gamma_t) = \lambda_{1t}D^{\rho_1} + \lambda_{1\rho_1}D^{\rho_1-1}D_t - F_X R\theta_1 \quad (3.9)$$

$$C_{2\beta\beta}(\beta_t) = \lambda_{1t}M^{\rho_2}D^{\rho_3} + \lambda_{1\rho_2}M^{\rho_2-1}M_tD^{\rho_3} + \lambda_{1\rho_3}M^{\rho_2}D^{\rho_3-1}D_t - F_X R\theta_2 \quad (3.10)$$

$$C_{4bb}(b_t) = \lambda_{2t}D^{r_1}M^{r_2} + \lambda_{2r_1}D^{r_1-1}D_tM^{r_2} + \lambda_{2r_2}D^{r_1}M^{r_2-1}M_t - FR_V\theta_3 \quad (3.11)$$

COROLLARY 1. *The rates the manager optimally pursues KD or KT during the NPD project satisfy one of the following (non-trivial) cases. (i) The optimal solution is positive and decreasing until reaching zero at or before the end of the development project (front-loading strategy). (ii) The optimal solution is positive and increasing, reaches a maximum, and then decreases until reaching zero at or before the end of the development project (delay strategy).*

In the *front loading strategy*, the manager pursues KD or KT at a rate that is initially high and decreases throughout the NPD project. Front-loading of KD or KT occurs when the effectiveness of KD or KT is high at the outset of the NPD project. The effectiveness of KD may be larger if: (i) the extent of errors uncovered by $\gamma(t)$ is small; (ii) the initial level of product design team knowledge is large; (iii) the marginal probability of developing a successful product is large; or (iv) the marginal expected net revenue from embedding process design knowledge is small. Similarly, the effectiveness of KT from the process (product) to the product (process) design team is larger if: (i) the rate of errors detected by $\beta(t)$ ($b(t)$) is small; (ii) the initial level of process (product) team knowledge is large; or (iii) the marginal probability of developing a successful product is small (large) (iv) the marginal expected net revenue from embedding process design knowledge is large (small). Nevertheless, the pursuit of knowledge creation decreases over time in the front-loading strategy for two reasons. First, due to diminishing returns it is increasingly difficult to obtain further additions to the level of knowledge through KD or KT. Second, over time less of the NPD project remains to accrue benefits from embedding more product or process design team knowledge.

The notion of a front-loading strategy has appeared in the literature. Blackburn et al. (1996) conceptually describe the front-loading of KT in the context of concurrent engineering in software development. In their study of design projects in the automotive industry, Thomke and Fujimoto (2000) advocate front-loading of problem solving to reduce the impact of late product design changes and thereby lower the development cost. In contrast, we show conditions whereby the rate of errors uncovered during

knowledge creation (KD or KT) drive either a front-loading strategy or a delay strategy. Moreover, we extend the literature by characterizing conditions on various facets of our model, such as the marginal probability of developing a successful product, that drive the manager to pursue a front-loading or delay strategy for KD or KT.

In contrast, at the core of the *delay strategy* is the manager's desire to postpone the peak rate of knowledge creation until a later time in the NPD project when such activity will be more effective at driving expected profit. Specifically, in the delay strategy, the rate that the manager pursues KD or KT is relatively small and increasing early in the development project, reaches a peak value, and then occurs at a decreasing rate thereafter. For example, if the initial level of product design team knowledge is small then KT to the process design team may follow the delay strategy. In general, the delay strategy may occur if the effectiveness of knowledge creation is relatively small early in the development project. Therefore, the conditions that drive the delay strategy are the opposite from those that lead to the front-loading strategy.

At some point in the delay strategy, the rate of KD or KT peaks after which the manager optimally reduces her pursuit of KD or KT for two reasons. First, the level of product or process design knowledge has become sufficiently large so that any further pursuit of KD or KT adds little to $D(t)$ or $M(t)$ (diminishing returns). Second, over time less of the NPD project remains to capture the benefits from an increase in the level of product or process team knowledge. Loch and Terwiesch (1996) describe the challenges faced by the NPD manager who does not follow a delay strategy despite the low initial levels of knowledge of the product and process design teams. In addition, according to the literature, if product design knowledge is evolving quickly then KT to the process design team may be more intense later in the project (Adler 1995, Ha and Porteus 1995, Loch and Terwiesch 1998). While previous research has advanced our understanding of KT during NPD projects, it has not captured the impact on the manager's KM strategy due to factors such as the endogenous design changes triggered by knowledge creation activities.

In Corollary 2 we observe an important relationship between the rates of KT of the product and process design teams. A manager who optimally pursues a delay strategy for KT in one direction is driven to undertake a front-loading strategy for KT in the other direction. For example, suppose the ability of product design knowledge to increase the probability of developing a successful product is large. In contrast, suppose the extent that process design knowledge drives manufacturing efficiency thereby

improving net revenue is small. Under these conditions, the manager is driven to follow the delay strategy for KT from the process to the product design team and to front-load KT from the product to the process design team. Thus, she increases process design knowledge early in the development project through KT from the product design team but delays the pursuit of KT to the product design team until later when process design knowledge is more developed.

COROLLARY 2. The conditions that drive KT to the product (process) design team β (b) to follow a delay strategy also drive KT to the process design team b (β) to follow a front-loading strategy.

Knowledge management of the product and process design teams is comprised of three solutions: KD for the product design team and KT between teams. With two possible strategies (front-loading or delay) for each of the three decision variables, it appears that the manager chooses from eight combinations of solutions. However, from Corollary 2, we know that whenever conditions occur that drive the manager to pursue the delay strategy for KT in one direction, then under the same conditions the manager is driven to pursue the front-loading strategy for KT in the other direction. This allows us to eliminate two combinations of KD and KT strategies. Note that the reverse of Corollary 2 does not hold; if KT in one direction satisfies the front-loading strategy then the KT in the other direction may satisfy either the delay or front-loading strategy. The six remaining strategies are described in the Appendix B. In Sections 3.4.3-3.4.4, we explore two possible combinations of KD and KT strategies.

3.4.2 Reflecting on the literature: KT only from the Product to the Process Design Team

The traditional view in the NPD literature is that KT occurs only from the product to process design team (Ha and Porteus 1995, Krishnan et al. 1997, Loch and Terwiesch 1998, Terwiesch et al. 2002). To benchmark our model against the existing literature, we consider the situation where KT from the process to the product design team is exogenously restricted ($\beta=0$). Some of our results are consistent with the literature. However, we obtain three major insights that capture the complex and dynamic relationships driving the evolution of knowledge during development projects, which have not been considered in the NPD literature.

First, we find that if KT occurs only from the product to the process design team then KD for the product design team is always front-loaded. Moreover, the level of process design team knowledge increases faster early in the development project since more advanced knowledge is transferred from the product design team (source). Second, we are able to determine the conditions that drive high or low rates of KD. We find that if the effectiveness of KT to the process design team is large the manager is driven to pursue a higher rate of KD throughout the development project. Recall that the effectiveness of KT to the process design team is larger if, for example, the extent of errors detected by KT is smaller or the ability to develop manufacturing processes that enhance net revenue is large. These results are important since they extend the literature by linking the optimal KD and KT strategies and show that a complementary relationship exists between efforts to increase the knowledge levels of the product and process design teams. Third, we identify characteristics of the project, teams, and marketplace that drive KT to the process design team to be either front-loaded or delayed. We find that the manager is driven to front-load KT to the process design team if the marginal revenue of embedding process design knowledge is large or the initial level of process design team knowledge is small. In contrast, the manager is driven to delay the peak rate of KT when the marginal probability of developing a successful product is large or the effectiveness of KD is large early in the project.

***COROLLARY 3.** If $\beta=0$ for $t \in [0, T]$, the manager optimally pursues the front-loading strategy for KD of the product design team (γ). Moreover, KT from the product to the process design team follows the front loading-strategy if the conditions that drive $b_t(0) \leq 0$ hold (i.e. if R_γ or M_0 is large or F_x or D_0 is small) . In contrast, KT follows the delay strategy if the conditions drive $b_t(0) > 0$.*

3.4.3 Product Oriented Development

In this section, we focus on a particular combination of KM strategies. Suppose the following three conditions hold. (i) The initial level of product design team knowledge is relatively large whereas (ii) the initial level of process design team knowledge is relatively small. (iii) The level of knowledge of the process design team has a greater impact on the effectiveness of knowledge transfer to the product team than the level of product design team knowledge has on the effectiveness of KT to the process team ($\rho_2 > r_1$).

The optimal solution is illustrated in Figure A.4. Driven by the large initial level of product team knowledge, the manager optimally front-loads KD activities. Clearly, there is no incentive for the manager to delay KD since it is highly effective at the start of the development project. However, the manager delays the peak efforts of KT from the process to the product design team for two reasons. First, KT from the process design team is more effective later in the NPD project when the level of process design knowledge is larger. Second, note that the level of process design knowledge has a substantial impact on the effectiveness of KT to the product team. As a result, the manager delays the peak rate of KT to the product design team until later in the project when process design knowledge is more advanced.

Interestingly, while the manager pursues the delay strategy for the transfer of knowledge to the product design team, she front-loads the transfer of knowledge to the process design team for two reasons. First, higher rates of KT to the process design team increase the initially low level of process team knowledge. Second, driven by the high initial level of knowledge of the product design team (source), KT to the process design team is effective at the outset of the NPD project.

In conclusion, we term this case as *product oriented development* since it illustrates the how the manager leverages product design team knowledge throughout the development project to maximize expect profit. These insights are summarized in Figure 3.2 and Corollary 4, below. Note that Figure 3.2 is given for illustrative purposes only. ¹

¹ For example, the solution in Case (i) may begin convex increasing, become concave increasing, and then is concave decreasing by T. Or, the solution in Case (ii) may start convex decreasing and change to concave decreasing by T.

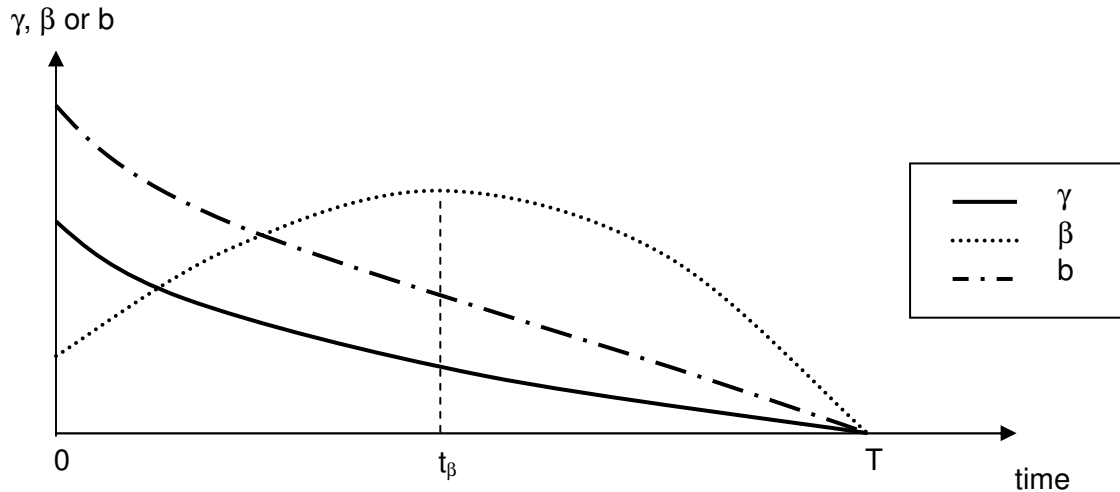


Figure 3.2 KD and KT for the scenario depicted in Corollary 4a and 4b

COROLLARY 4a. Suppose D_0 is large and M_0 is small. Then, the manager is driven to pursue (i) the front-loading strategy for KD (γ).

COROLLARY 4b. Again, suppose D_0 is large and M_0 is small. In addition, suppose $\rho_2 > r_1$. Then, the manager is driven to pursue (i) the delay strategy for KT to the product design team (β) and (ii) the front-loading strategy for KT to the process design team (b).

We may interpret the above analytic results in the context of industry practice. Consider the NPD project pursued by Advanced Micro Devices (AMD) to develop the K6 microprocessor. The K6 was created while leveraging a considerable amount of product design knowledge based on the K5 (Slater 1996). The product team designed a chip with 8.8 million transistors in 350 nm, which was twice the number of transistors in the K5 (Morrison and DeTar 1998). Due to the new product features, the manufacturing processes for the K6 chip were substantially different from those that already existed. Moreover, since the details of the microchip architecture of K6 were relatively complex, KT from the product to the process design team was difficult (Wilson 1996). Ultimately, AMD faced manufacturing challenges with K6 that led to the reduction in output volume and a delayed product launch (DeTar 1997, Takahashi 1997). As an aside, AMD's slow ramp-up afforded Intel the opportunity to first introduce the Pentium MMX (Willcox 1999).

One possible explanation for AMD's performance is that the NPD manager overestimated the knowledge level of the process design team at the outset of the development project. In fact, initially it appeared that the process design team would design the manufacturing system for the K6 chip employing the same die size as the one that had been used in the previous generation of microprocessors. The process design team planned on taking advantage of the additional metal layers and tighter physical design to pack more transistors into one area (Slater 1997). However, serious problems developed while designing the high yield process technology to build the small chips with such a high density of transistors (DeTar 1997). It would seem that by overestimating the initial level of knowledge of the process design team, the NPD manager did not recognize the importance of front-loading KT from the product design team. As a result, the ability of the process design team to embed useful knowledge into the NPD project was limited. Moreover, it seems that AMD placed little value on KT from the process to the product design team. As a result, it appears that product development proceeded without knowledge about manufacturability and early signals of insufficient process knowledge were not detected. Overall, AMD's problems may be explained by its pursuit of a knowledge management strategy that did not properly leverage product design knowledge at the outset of the development project.

3.4.4 Process Oriented Development

Next, we assume the reverse conditions stated in Section 3.4.3 hold. Thus, the manager optimally pursues a front-loading strategy for KT to the product design team but delays the peak rates of KD of the product design team and KT to the process design team.

Since the initial level of product team knowledge is small, the effectiveness of KD early in the development project is limited leading to the delay strategy. However, KT from the process to the product design team is effective at the outset of the development project due to the initially large level of process design team knowledge (source). Thus, the NPD manager leverages the process design team's knowledge to drive the development of product design knowledge. This approach to NPD is generally referred to as design for manufacturability. Moreover, from the outset of the NPD project, the manager pursues KD and KT from the product design team at increasing rates. Eventually, when product team knowledge is sufficiently developed, the manager reaches the peak rates of KD and KT to the process design team.

In conclusion, we term this case as *process oriented development* since it illustrates the how the manager leverages process design team knowledge throughout the development project to maximize expect profit. These insights are summarized in Figure 3.3 and Corollary 5, below.

γ, β or b

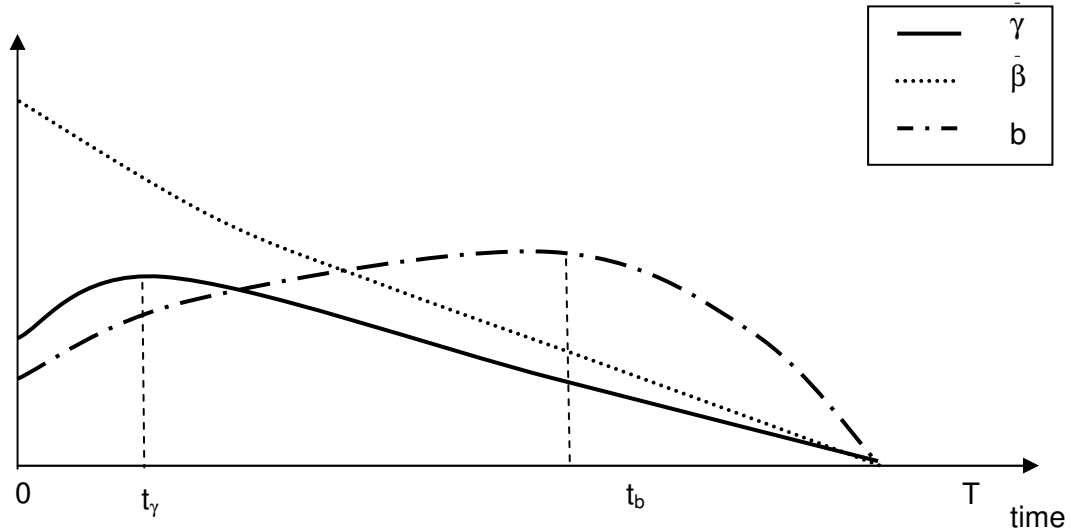


Figure 3.3 KD and KT for the scenario depicted in Corollary 5a and 5b.

COROLLARY 5a. Suppose D_0 is small and M_0 is large. Then, the manager is driven to pursue (i) the delay strategy for KD (γ).

COROLLARY 5b. Again, suppose D_0 is small and M_0 is large. In addition, suppose $\rho_2 < r_1$. Then, the manager is driven to pursue (i) the front-loading strategy for KT to the product design team (β) and (ii) the delay strategy for KT to the process design team (b).

We may interpret the above analytic results in the context of industry practice. Consider the development of the first commercially mass produced and marketed hybrid automobile (Nonaka and Peltokorpi 2006), the Toyota Prius, which uses both a gasoline engine and an electric motor for propulsion. The product design of the Prius entails a complex electrical architecture for the power train, including the designs of electric motors, electric inverters and converters, high-voltage batteries, electronic control units, as well as semiconductors and sensors (Tilin 2005). Despite substantial innovations in

the product attributes of the Prius, Toyota manufactured and assembled it in the same factories as conventional (gasoline powered) vehicles (Weber 2006). Thus, we can reasonably assume that the initial level of knowledge of the process design team was large.

The development of Toyota's Prius demonstrates how process design expertise may shape product design objectives. Throughout the NPD project, the product and the process design teams collaborated closely through face-to-face KT from the process to the product design team (Magnusson and Berggren, 2001). Moreover, Toyota created the Unit Production Technology Department (UPTD) to facilitate KT from the process design team (including the drive system and chassis) regarding the manufacturability of the hybrid vehicle. At the same time, once the manufacturing process constraints were reliably addressed in the product design, the product design team intensified experimentation to converge to the final design (e.g. fuel infrastructure, battery powered design, engine system). This suggests that a delay strategy was used for KD (Nonaka and Peltokorpi 2006). Overall, it seems that Toyota's success with the Prius may be explained by its ability to leverage a considerable level of process design knowledge from the outset of the development project.

3.4.5 The Impact of Errors Detected during Knowledge Creation

In this section we explore the impact of errors that are detected by KD or KT activities that reduce the cumulative level of useful product or process design knowledge. Suppose the initial knowledge levels of the product and process design teams are relatively similar. In addition, suppose the extent of errors detected by KD is large. As expected, we find that the manager pursues KD at a smaller rate throughout the NPD project. Moreover, we find that the manager is driven to pursue the delay strategy for KD. Essentially, if the extent of errors detected is large, then the manager delays the peak rate of KD until a later time when more advanced product design knowledge is available to reduce the impact of those errors. Said differently, with more knowledge later in the NPD project, the product design team is better able to respond to errors that are uncovered. Meanwhile, in order to recover the loss in the cumulative level of useful knowledge, the manager continues to apply product and process design knowledge, which takes the form of design changes and rework. Analogous results hold for the pursuit of KT in either direction.

We also find that if the effect of errors detected by KT to the process or process design team is large, then the manager front loads KD of the product design team. For example, suppose KT from the product to the process design team uncovers considerable errors. By intensifying KD early in the NPD project, the product design team is able to communicate more advanced knowledge to the process design team and thereby reduce the impact of the errors detected in KT. Similarly, suppose KT to the product design team triggers considerable design changes. In this situation, the manager front loads KD to better prepare product design team to absorb KT from the process design team and thereby reduce the impact of the errors that are uncovered.

Lastly, if the extent of errors detected by KT in one direction is large, the manager front-loads KT in the other direction. To interpret this result, suppose the extent errors uncovered by KT to the process design team is large. The manager is driven to front-load KT to the product design team to increase the level of knowledge of the source. In this way, the manager leverages the enhanced product design team knowledge later in the NPD project and thereby reduces the impact of the errors detected during KT to the process design team.

COROLLARY 6a. *A high (low) rate of errors detected by a particular means of knowledge creation $(\theta_1, \theta_2, \theta_3)$ drives the manager to pursue less (more) of that type of knowledge creation over the development project (γ, β, b) .*

COROLLARY 6b. *Suppose the extent errors uncovered by KD for the product design team (θ_1) is large (small). Then, the manager is driven to (i) delay (front-load) KD (γ) , (ii) front-load (delay) KT to the product design team (β) and (iii) delay (front-load) KT to the process design team (b) .*

COROLLARY 6c. *Suppose the extent of errors uncovered by KT to the product design team (θ_2) is large (small). Then, the manager is driven to (i) front-load (delay) KD (γ) , (ii) delay (front-load) KT to the product design team (β) and (iii) front-load (delay) KT to the process design team (b) .*

COROLLARY 6d. *Suppose the extent of errors uncovered by KT to the process design team (θ_3) is large (small). Then, the manager is driven to (i) front-load (delay) KD (γ) , (ii)*

front-load (delay) KT to the product design team (β), and (iii) delay (front-load) KT to the process design team (b).

3.4.6 The Impact of Drivers of Expected Net Revenue

In this section we consider how the determinants of the expected net revenue impact the KM strategies. First, suppose the cumulative level of useful product design knowledge substantially increases the probability that the new product will have the features and functionality leading to success in the marketplace. As expected, we find that KD and KT to the product design team are larger throughout the NPD project. In a result that is not obvious, we find that the rate of KT to the process design team is also larger throughout the development project. Second, suppose the cumulative level of useful process design knowledge drives a substantial increase in net revenue when the product is released. As expected, we find that a higher rate of KT to the process design team is pursued throughout the development project. In a result that is not obvious, we find that KD and KT to the product design team are higher throughout the NPD project. Therefore, we demonstrate that a complementary relationship exists between the three means of knowledge creation. This result is consistent with Joglekar et al. (2001) who state that to improve performance a manager should consider investing in both the product and process teams rather than over-investing in one team.

Drivers of net revenue not only impact the rates of knowledge creation activities but also the timing. Again, suppose the cumulative level of useful product design knowledge substantially enhances the probability of a successful product launch. We find that KD for the product design team is front-loaded to accelerate the accumulation of useful product design knowledge. Moreover, KT to the process design team is front-loaded so that process design knowledge increases rapidly early in the development project. However, the manager is driven to delay the peak rate of KT to the product design team until a later time when process knowledge is more refined. Therefore, when product design knowledge is a key driver of expected net revenue, to increase the level of product design knowledge the manager relies more on KD early and KT from the process design team later in the development project. In addition, by delaying the KT to the product design team, the manager transfers more advanced knowledge from the process design team about design for manufacturability.

Similarly, suppose the cumulative level of useful process design knowledge substantially increases net revenue. We find that the manager optimally, front-loads KT

from the process design team to accelerate the increase in product design knowledge but delays KT to the process design team. The delay strategy is advocated so that KT from the product design team occurs after it has become more refined. The peak rate of KD for the product design team occurs later when product design knowledge is more advanced from earlier KT from the process design team. Therefore, KD is delayed reflecting the relatively high desirability of investing in process design knowledge as a means of maximizing expected net revenue.

Time-based competition is another driver of expected net revenue. Specifically, the net revenue earned from the product release is driven by the level of useful process design knowledge as well as the amount of time based competition. We show that the manager's pursuit of knowledge creation is smaller throughout the NPD project if the marginal impact of time-based competition on net revenue is larger. Therefore, time-based competition reduces the potential gains realized from introducing the new product to the marketplace. However, while smaller in magnitude, the manager does pursue knowledge creation during the NPD project. We find that the manager is driven to front-load KT to the process design team to accelerate the rate of increase in the cumulative level of useful process design knowledge. Moreover, KD is front-loaded so that the knowledge that is transferred from the product design team is more refined. Lastly, the manager delays KT to the product design team in order to transfer more advanced knowledge about the manufacturability of the product.

COROLLARY 7a. Suppose any of the following conditions hold: (i) the marginal probability that the new product is successfully developed by time t ($F_{X(t)}$) is large (small); (ii) the marginal net revenue from embedding useful process design knowledge ($R_{Y(t)}$) is large (small); or (iii) the marginal reduction in net revenue from a delayed product launch (R_t) is small (large). Then, the manager is driven to pursue more (less) knowledge creation for both the product and process design teams (γ , β and b) throughout the NPD project.

COROLLARY 7b. Suppose any of the following conditions hold: (i) the marginal probability that the new product is successfully developed by time t ($F_{X(t)}$) is large (small); (ii) the marginal net revenue earned from embedding useful process design knowledge ($R_{Y(t)}$) is small (large); (iii) the marginal reduction in net revenue from a delayed product launch (R_t) is large (small). Then, the manager is driven to: (a) front-load (delay) KD (γ),

(b) delay (front-load) KT to the product design team (β), and (c) front-load (delay) KT to the process design team (b).

3.5. Discussion and Conclusions

We develop a normative model to aid the manager of an NPD project determine her KM strategy for the product and process design teams. The timing and extent of knowledge embedded by each team during the development project determine the features, functionality, and manufacturing efficiency of the product and process. The manager determines the optimal rate and timing of knowledge creation, which includes KD for the design team and KT between the product and process design teams. The optimal dynamic rates of knowledge creation are obtained to maximize the expected profit, which consists of the expected net revenue when the product is released less the costs for knowledge creation during development.

3.5.1 The Delay or Front-Loading Strategies

We show that each knowledge creation solution satisfies one of two possible strategies over the development project. First, in the *front-loading strategy* the manager pursues KD or KT at an initially high rate that decreases throughout the remainder of the NPD project. The rate of KD or KT decreases over time because further additions to the level of product or process design team knowledge are more difficult to realize (diminishing returns), and because as time passes less time remains in the NPD project to accrue the benefits from KD or KT.

In particular, KD is front-loaded when its effectiveness is high at the outset of the NPD project. The effectiveness of KD is high if the initial level of product design knowledge is large, or if the extent of errors detected while pursuing KD is small. Also, KD is front-loaded if the manager estimates that the cumulative level of useful product design knowledge substantially enhances the probability of a successful product launch. Moreover, what is not obvious is that KD is front-loaded when the cumulative level of useful process design knowledge is not a key driver of net revenue. In this situation, the manager focuses on developing product design knowledge as a means of maximizing expected net revenue.

Similarly, KT to the product (process) design team is front-loaded if the initial level of process (product) team knowledge is large, or if the rate of errors detected by KT to the product (process) design team is small. In addition, if the ability of process design

knowledge to drive net revenue is large (small) early in the NPD project, the manager follows front-loading strategy for KT to the product (process) design team. Lastly, in a result that is not so apparent, the manager front-loads KT to the product design team if the cumulative product design knowledge is not a key driver of the probability of successful launch of the new product early in the NPD project. Under this condition, the manager accelerates the increase in the product design knowledge to increase the probability of developing a successful product.

Second, in the *delay strategy* the manager optimally delays her peak investment in KD or KT until a later time when the investment is more effective. If the effectiveness of KD or KT is small at the initial time, then it is pursued at a relatively small but increasing rate early in the development project. The rate increases over time because as the levels of knowledge grow the effectiveness of investments in KD and KT increase. Eventually, the rate of KD or KT declines when the level of product or process design team knowledge reaches a point where additional gains are difficult to achieve (diminishing returns) and since less of the development project remains to reap the benefits from knowledge creation. The conditions that drive the delay strategy are the opposite from those that lead to the front-loading strategy.

Since the manager has some control over the effectiveness of pursuing knowledge creation, the above insights are particularly important. In particular, we demonstrate that the manager must carefully assemble her product and process design teams so that the full potential of each team's knowledge is realized at the outset of the NPD project. To do so, the manager must understand the nature of the knowledge that will be required as well as the talents of potential team members. On the one hand, the knowledge embodied by team members should reflect some degree of differentiation, since such teams are more likely to develop novel solutions (Bonabeau et al. 2008, Sosa et al. 2007). On the other hand, a certain amount of overlap in the knowledge of team members positions them to better understand each other's expertise and draw links between their stocks of knowledge (Clark and Fujimoto 1991).

The rates of return on KD or KT are key drivers of their effectiveness at building the levels of product and process design knowledge. To the extent possible, the manager should create an environment that fosters higher rates of return. Incentives may be put into place to encourage the sharing of knowledge within a team so that any increase in knowledge by some team members (e.g., through executive education, etc.) is shared with other team members. Similarly, if a manager introduces an IT system to

facilitate the sharing of knowledge either within or between teams, then the returns to any investment in knowledge creation are higher.

We discuss two of the six combinations of KM solutions that can occur. Figure 3.4 illustrates the KM strategies driven by the initial levels of knowledge of the product and process design teams. First, suppose the initial knowledge level of the product design team is large, the initial knowledge level of the process design team is small, and the effectiveness of KT to the product design team is larger than the effectiveness of KT in the other direction. Under these conditions the manager is driven to pursue a product oriented development strategy whereby the KD for the product design team and the KT to the process design team is front-loaded and the KT to the product design team is delayed. Second, suppose the above conditions are reversed. Here, the manager is driven to pursue a process oriented development strategy, in which the manager is driven to front-load KT to the product design team and delay KD for the product design team and the KT to the process design team. These product and process oriented strategies are illustrated in the first and fourth quadrants of Figure 3.4, respectively. Third, suppose that initial levels of knowledge of both product and process design teams are large. This condition drives the manager to purpose a *front-loaded development* strategy, where all the knowledge creation efforts follow a front-loading strategy (given at the second quadrant of Figure 3.4).

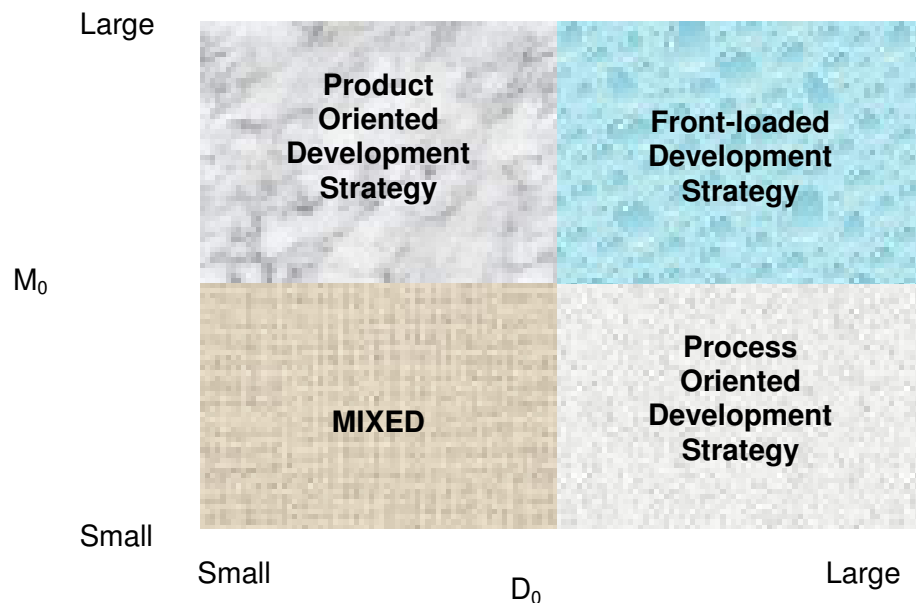


Figure 3.4 Optimal KM strategies

The KM strategies that constitute the first, second and fourth quadrants of Figure 3.4 are driven by the initial knowledge levels of the product and process design teams. Suppose the initial levels of the product and process design teams are small. The manager's strategy for under these conditions is driven by two other factors: (i) the extent of errors uncovered by KD for the product design team and KT between the teams and (ii) the drivers of expected net revenue. In sections 3.5.2 and 3.5.3, we describe the KM strategies driven by these drivers. In addition, we depict the actions a manager may pursue to reduce the impact of errors detected during knowledge creation, and increase the impact of the drivers of expected net revenue.

3.5.2 The Impact of Errors Detected during Knowledge Creation

We analyze the impact of errors that are detected by KD or KT activities on the KM strategy of the manager. We show that if the extent of design changes triggered by KD for the product design team, then the manager pursues KD at a smaller rate throughout the development project. Analogous results hold for the pursuit of KT in either direction.

In addition, our results reveal three key insights with respect to the impact of errors uncovered on the timing of KD and KT. First, if the extent of errors uncovered by KD for the product design team is large, then the manager is driven to pursue product oriented development strategy (strategy depicted at the first quadrant of Figure 3.4). Second, the manager is driven to pursue process oriented development strategy if the extent of errors uncovered by KT to the product design team is large. Finally, if KT to the process design team uncovered large extent of errors, then the manager is driven to pursue *front-loaded product development* strategy. According to this strategy, the manager front-loads the KD and KT to the product design team and delays KT to the process design team. Thus, the manager accelerates the increase in the knowledge level of the product design team and transfers knowledge related to the attributes and features of the product later in the project. Thus, more effective KT to the process design team mediates the impact of the errors uncovered by KT from the product design team.

The extent of errors uncovered by KD and KT during the project is may be related to the complexity of the NPD project. According to Mitchell and Nault (2007), project scope, which stems from the number of subsystem interactions impacts the extent of errors uncovered for product and process design. Thus, it is crucial for managers to span the units, components and functional areas covered by the NPD

projects to identify the system interdependencies, and decompose the design problem if necessary to reduce design complexity. However, decomposing the NPD project, and pursuing product and process designs with less knowledge input from the other may not be preferable due to reduced system performance, increased manufacturing cost, or an increased development budget (Terwiesch et al. 2002).

Finally, the types of processes and activities undertaken by the manager for KD or KT also drive the extent of errors uncovered by knowledge creation. To the extent possible, the manager should carefully assess the project and team characteristics and should determine the most effective form of KD and KT activities. For example, if the complexity in the content of knowledge transferred between the design teams is large, then detailed documentation of the design activities may be the form of KT with smaller extent errors uncovered compared to face-to-face meetings between teams. In addition, use of support tools, such as IT may be useful to make communication between teams more straightforward.

3.5.3 The Impact of Drivers of Expected Net Revenue

We analyze the impact of drivers of expected net revenue on the manager's KD and KT strategies. We find that if the product design knowledge substantially increases the probability of releasing a successful product early in the development project, then the manager pursues larger rates of KD for the product design team *and* larger rates of KT to both the product and process design teams. Similarly, the rates of knowledge creation for both teams are pursued at a larger rate if the process design knowledge substantially increases the net revenue generated by the new product early in the project, or the impact of time-based-competition in the market is large. Therefore, with respect to these drivers of expected net revenue, we observe a complementary relationship between the KD and KT.

Our results also reveal that the drivers of expected revenue impact the timing of the knowledge creation for the product and the process design teams. Specifically, we show that if the product design knowledge significantly increases the probability of developing a successful product, or the time-based competition in the marketplace is large, then the manager is driven to pursue product oriented development strategy. Meanwhile the manager is driven to pursue process oriented development strategy if the ability of the process design knowledge to enhance net revenue is large.

These results demonstrate that the manager should carefully assess the drivers of expected net revenue due to their impact on the manager's KM strategy, and take actions to influence them to the extent possible. For example, projects with radical versus incremental product or process designs vary significantly with respect to their drivers of expected net revenue. The development project of a drug based on radically new compounds may have a low probability of a successful release to the marketplace while expected net revenue from manufacturing the product may be large. Thus, it is crucial for the manager to identify the product/process design of new product development project as processes involving radical changes or incremental improvements to existing designs.

In addition, the manager may influence the probability of releasing a successful product or the impact of process design on the net revenue (e.g. through by forming alliances with university research labs may provide insights on scientific and technological advancements, etc.). The impact of delaying the product launch in the marketplace on the net revenue earned from the product may be reduced by selecting team members with extensive experience in marketing research. Also, employing consulting firms that specialize in market research may be helpful.

CHAPTER 4

KNOWLEDGE MANAGEMENT FOR NEW PRODUCT

DEVELOPMENT: COMPETITION VERSUS JOINT DEVELOPMENT

4.1 Introduction

In today's highly competitive marketplace, a firm's success is driven by its ability to successfully launch new products in the marketplace (Deeds and Hill 1996). Various domains of knowledge are required for successful new product development (NPD), including scientific and technology related expertise, as well as knowledge about the marketplace and manufacturing processes. Recent studies demonstrate that many firms are unable to rely solely on internal knowledge-based capabilities to develop new products (Arora and Gambardella 1990, Rigby and Zook 2002). To gain access to the full scope of knowledge necessary for NPD, these firms tap into external pools of knowledge (Cassiman and Veugelers 2006) by entering into various forms of cooperative agreements (Appleyard 1996, Samaddar and Kadiyala 2006).

Ironically, the knowledge sought by a firm may only be available from competitors developing similar products (Arora and Fosfuri 2003). The traditional view suggests that the unique knowledge possessed by a firm provides the maximum benefit if it remains proprietary, i.e., if the firm does not share or transfer this knowledge to competitors (Teece 1986). However, under certain conditions, knowledge transfer (KT) or knowledge sharing (KS) between competing firms has its advantages. In particular, a firm may transfer or share knowledge with a competitor to generate revenue that may be used for other NPD projects. In addition, KT or KS may be beneficial if the ultimate value of that knowledge in the marketplace is uncertain (Appleyard 1996, Kulatikala and Lin 2006). Thus, firms considering cooperative agreements with competitors face complicated decisions. Moreover, since the firms entering into cooperative agreements ultimately compete in the same market, the decisions made by one firm generally influence the decisions of the other (Ulrich and Eppinger 2003, Klastorin and Tsai 2004). Structures of cooperative agreements range from those in which the expected gains from developing new products is maximized individually for each firm, to those in which the joint gain of both firms is maximized.

In this chapter, a framework for analyzing the knowledge flow between two competing firms engaged in cooperative agreements is provided. We introduce a two-period game theoretic model that explores knowledge management (KM) strategies that drive NPD for two profit maximizing firms. KM strategies include the KT or KS between firms and the knowledge development (KD) each firm pursues either independently or jointly with its competitor. We examine two mechanisms of cooperation between the competitors: competitive development (CD) and joint development (JD) agreements. Through analysis of these models, we seek to provide insights to the following questions: (1) Under what conditions should competing firms enter into CD or JD agreements? (2) More specifically, what conditions drive each firm's KT, KS and KD decisions? (3) What are the effects of market specific factors such as the drivers of expected net revenue? (4) What are the effects of the unique capabilities of a firm to integrate the knowledge it receives through transfer or sharing? (5) What is the effect of the loss of competitive advantage by the source firm due to KT or KS with its competitor? (6) What is the impact of uncertainty associated with the marketplace and the ability to integrate knowledge on the firms KM decisions?

The remainder of this chapter is structured as follows. Section 4.2 provides an overview of the key terms and concepts guiding this research. Section 4.3 provides a review of the related literature. In Section 4.4, two models depicting the CD and JD mechanisms are introduced. Optimal solutions, analytic sensitivity analysis and numerical analysis for each mechanism are presented in Section 4.5. Conclusions and areas of future research are given in Section 4.6.

4.2 Mechanisms of Cooperation

In this research, we introduce a two-period game to examine two mechanisms of cooperation between competitors: competitive development (CD) and joint development (JD) agreements. CD and JD arrangements offer a particularly good venue within which to examine the KM strategies since collaboration through transferring or sharing knowledge is one of the most common forms of cooperation between competing firms (Anand and Khanna 2000b).

We define the CD mechanism as a form of cooperation between two firms developing new products that ultimately compete in the same market. The flow of knowledge-based resources from one firm (the source) to the other (the recipient) may take many forms including giving the rights to use licenses and patents, documentation

about scientific or technical expertise, or the transfer of employees who possess unique knowledge. An example of one such CD approach is the licensing agreement between Hitachi, Ltd. and Sony Corp., in which Sony purchased the rights to use the CPU cores of the Hitachi's SuperH™ RISC engine family (SuperH) in its development projects for electronic goods (Sony Corporation 1998). Both firms use the SuperH microprocessors for the development of digital AV electronics and information technology related electronic appliances, and, therefore, compete in the same markets. Another example of the CD mechanism is the agreement between Procter and Gamble (P&G) Co. and Glaxo Wellcome PLC, through which P&G Co. sold patents pertaining to ulcer therapy to Glaxo PLC. Both P&G and Glaxo embed the knowledge embodied in the patents into their ulcer-eradication treatments (Tritec and Helidac) that compete in the same end markets (The Wall Street Journal 1996).

In contrast, cooperation through the JD mechanism involves the joint development and market entry of a new product by the two firms. When competing firms cooperate through the JD mechanism, each firm dedicates a portion of its knowledge to the NPD project that is jointly pursued to develop the single product. As an example of one such agreement, in 2005, Olympus Corporation and Matsushita Electric (more commonly known as Panasonic) agreed to jointly develop interchangeable lens type digital SLR cameras (Hug 2005). As a result, the firms were able to bring Olympus's industry-leading SLR camera technology with Panasonic's advanced digital AV technology to the market, and develop innovative new design concepts for next-generation digital SLR cameras. As another example of firms pursuing NPD projects jointly, Phillips and Lucent formed a JD while developing PCS wireless phones and later shared the revenues from the sales of the new products (Business Wire, 10 September 1997).

4.2.1 Evolution of Knowledge

The level of knowledge possessed by each firm that is related to the development project includes an understanding of diverse scientific and engineering information. The initial levels of knowledge may be inferred from the overall educational background of the employees working on the development project, years of work experience, performance appraisals, and past experience in similar research, development and engineering domains. While a firm may possess a considerable amount of knowledge in general, the level of knowledge relevant to the development

project under consideration may be small due to its novelty. As described below, the firms increase their level of knowledge throughout the development project so that they apply more knowledge to the NPD project. Specifically, the extent of knowledge embodied by the firms at the end of the NPD project is embedded into the new product, and determines the features, functionality and manufacturing efficiency of the new product. Throughout the rest of this Chapter, we use the level of knowledge of a firm at the end of the NPD project as a proxy for the knowledge embedded into the new product by the firm.

We consider firms that pursue two forms of *knowledge creation* to increase the levels of knowledge they embed into the design of their new product and process (Ittner et al. 2001, Pisano 1994). First, in the initial period of the game, one or both of the firms may increase its level of NPD-related knowledge by entering into a cooperative agreement with its competitor. Firms engage in *knowledge transfer (KT)* that may take form of giving the rights to use licenses and patents, or documentation about component technologies or modules. We assume that, in the case of CD, KT occurs in one direction, and the source firm gives the recipient firm the rights to use the knowledge in exchange for revenue. The benefits the recipient realizes from the knowledge it buys are uncertain since its integration may prove difficult. Alternatively, the firms may engage in *knowledge sharing (KS)* whereby both firms share a portion of their knowledge in a joint NPD project and ultimately share the revenue earned when the new product is released. Again, the capability of the firms to integrate the shared knowledge dedicated to the joint NPD project is uncertain. Therefore, reflecting the challenges associated with knowledge integration, the level of knowledge after knowledge transfer (CD) or sharing (JD) is uncertain.

The other means by which firms pursue knowledge creation is through *knowledge development (KD)* (Iansiti and Clark 1994), which occurs in the second period of the game. KD is a form of knowledge creation whereby the firm's employees expend efforts resulting in advancements in materials, technologies, processes, or product designs (Hatch and Mowery 1998, Lapre and Van Wassenhove 2001). KD undertaken by product and process design developers may take the form of problem-structuring and goal-setting for the problem-solving process teams; building working models of design alternatives through simulation or creating a physical prototype and analyzing, testing and evaluating these models (Clark and Wheelwright 1993). Knowledge creation activities are often supported by technologies such as computer-

aided design and simulation software (Thomke 1998, Thomke and Fujimoto 2000). In addition to the above means of KD focusing on activities inside the firms, KD also occurs when members of design teams participate in continuing education programs offered by universities or training programs offered by equipment or software vendors. In addition, KD occurs when design team members attend professional conferences (Biskup and Simons 2004, Jacobs 2006). For the CD case, each firm individually makes a KD decision to maximize its individual profit. Alternatively, if the firms pursue a JD project, they jointly determine the rate of KD pursued in the second period of the game. The increase in the knowledge levels of firms due to KD occurs in a deterministic manner.

To formalize the above discussion into research models, consider a two-period Stackelberg game setting, where the leader is the more powerful firm that makes the initial decision and the follower firm reacts to the leader's decision (Samaddar and Kadiyala 2006). Moreover, we assume complete and perfect information. Under the CD agreement in the initial stage of period one, the leader determines the pricing strategy it will charge for the knowledge it is willing to transfer to its competitor. The follower reacts to the pricing strategy and determines the amount of knowledge it will purchase in the second stage of period one. In the second period for the CD mechanism, first the leader then the follower determines their individual amounts of KD.

In the first stage of the first period under the JD agreement, the leader sets the portion of the joint profits it will earn from the new product. Naturally, this decision also sets the portion of the joint profit allocated to firm 2. In the second (third) stage of period one, the leader (follower) determines the amount of knowledge it will share with its competitor. In the second period of JD, the firms make the joint KD decision. Thus, for the JD mechanism the second period consists of one stage.

4.2.2 Expected Profit

Consistent with the NPD literature, we assume that revenue from the new product is earned when development efforts are complete and it is released to the marketplace (at the end of the second period) (Kim 1998, Santiago and Vakili 2005). The KT/KS and development decisions that are made by each firm reflect the following key trade-off: a firm may enhance its own ability to generate expected revenue from proprietary knowledge, or it may generate revenue from selling or sharing a portion of its knowledge. For the CD mechanism, firm 2, who is the recipient of KT, also considers the increased probability of developing a successful new product due to new knowledge

received through KT. Of course due to the uncertainty regarding knowledge integration, the increase in revenue is also uncertain. We assume that each firm's predictions about the effectiveness of the KT or KS process, or the uncertainty associated with the marketplace is common knowledge.

While making the KT or KS and KD decisions the firms maximize expected profit over the two-period horizon. Expected profit consists of: (i) the expected net revenue earned from the new product; (ii) the cost of KD pursued in period two; and (iii) the revenue or cost incurred for KT or KS in period one. Each of these drivers of profit are described below.

First, we consider expected net revenue. At the end of the second period, the level of knowledge held separately by each firm (CD) or shared jointly by both firms (JD) determines the features, functionality and manufacturing efficiency of the new product introduced to the marketplace, and, thereby, drives the expected net revenue over the product's lifecycle. For the CD mechanism, the expected net revenue earned from the new product is expressed as a function of the probability that the new product will have the features and functionality making it successful in the marketplace, the customer's valuation of knowledge, the firm's own level of knowledge, and the firm's level of knowledge relative to its competitor. Therefore, the impact on firm 1's expected revenue due to the transfer of knowledge to firm 2 is captured by those customers who flock to the firm offering the new product with the most features (i.e., with more knowledge). For firm 2, the probability of developing a successful product depends on whether or not it engages in KT from firm 1. Pursuing KT increases the level of knowledge embodied by firm 2, resulting in a larger probability of developing a successful product at the end of the NPD project. For the JD case, the expected net revenue earned from the new product is expressed as a function of the probability that the new product will have the features and functionality making it successful in the marketplace, the customer's valuation of the knowledge that has been jointly embedded into the new product, and the joint level of knowledge embedded by both firms in the NPD project.

Second, we consider the costs incurred by firms to pursue knowledge development during period two. These costs reflect the salaries of employees who perform knowledge creating activities such as experimentation, simulation, and prototyping. Also, costs are incurred for consultants and trainers and the integration of new hires. KD costs are incurred for materials, the operation of laboratories, and equipment including information technology. KD costs include the monetary resources

committed to permit employees to attend conferences and workshops, as well as executive programs. Lastly, KD costs, such as overtime, are required to sustain team productivity levels during KD.

Third, consider the revenue and costs incurred directly for KS and KT. For the CD mechanism, the transfer of knowledge impacts the expected profit of the firms in the following manner: The leader that is the source gains revenue from sharing knowledge and the leader incurs a cost due to loss of proprietary knowledge. This loss can be viewed as an opportunity cost reflecting the loss in future revenue that would have been derived from the new product based on sole ownership of the knowledge. Meanwhile, the follower firm incurs a cost for the payment of the knowledge it receives from the source firm. The detrimental effect of sharing knowledge with a competitor also impacts the expected profit earned by each firm entering into the JD agreement. In particular, each firm incurs a cost due to its loss of proprietary knowledge. This loss is similar to the cost incurred by the source firm in the CD mechanism.

4.3 Literature Review

Past literature has addressed knowledge creation between competitors. Loebecke et al. (1999) examine the sharing of knowledge which may be a key source of competition in a two-player game theoretical setting. They consider the negative effects of sharing knowledge with a competitor. They suggest one of the most crucial elements to the firm's decision as to whether to share knowledge or not is the firm's ability to manage the process of KS. The analysis by Loebecke et al. suggests that, even in the best mechanism, firms are not sure whether to share knowledge or not. Nevertheless, firms overcome this uncertainty if they have developed an effective control strategy to manage the dynamics of the KS process.

The problem of bargaining over the sharing of NPD knowledge between two competitors is examined by D'Aspremont et al. (2000). In their model, one of the firms licenses knowledge to a buyer firm through general licensing, and the profit earned from licensing is a function of the knowledge shared. However, the firms are in a race to develop a new product first, unlike our model of general licensing where both can first develop the new product, but the profit will be a function of the knowledge they transfer.

Arora and Fosfuri (2003) analyze how the number of licenses sold is affected by competition from other technology holders, the strength of patent protection, and the nature of demand. They analytically show that firms license a technology when the

monetary gains from licensing exceed the loss in revenue due to increased competition in the marketplace. According to their results, if the licensor firm has a small market share, it is more likely to license since the loss of competitive advantage due to licensing is lower. In addition, they find that competition in the market for technology induces licensing of innovations, and firms may find it individually profitable to license even though their joint profits may be higher in the absence of any licensing. The authors also find that the number of licenses per patent holder decreases with the degree of product differentiation.

In his study of 107 chemical product firms, Fosfuri (2006) analyzes whether the existence of multiple technology holders triggers more aggressive licensing behavior. His findings indicate that licensing behavior displays an inverted U-shaped relationship with the number of potential suppliers and is negatively related to the licensor's market share and to the degree of product differentiation.

Kulatikala and Lin (2006) explore how cooperation (in terms of licensing) among firms pursuing development project can discourage competition in the end-product market. The authors develop a model in which a firm invests in a development project of an innovation and can license its knowledge to a potential competitor. The authors focus on cooperation through general licensing, and determine the impacts of financial constraints on the structure of the cooperation.

The competitive interaction between Intel and Microsoft, two producers of complementary products, is analyzed by Casadesus-Masanell and Yoffie (2007). They consider the trade-off between the firms' individual incentives to pursue development efforts for their own products, and the benefits of directing the joint investment into developing complementary products. The findings show that conflicts emerge between the firms, in terms of pricing and launch time decisions for the new products.

In his study focused on the KS decisions among competitors, Spiegel (2007) considers three firms that engage in a development projects who compete for market share in the end market. The findings show that the firm with the highest level of knowledge is better off licensing its knowledge to one or both of the other firms. The author considers the trade-off between the adverse effects of knowledge loss that provides competitive advantage, and the benefits from earning revenue due to the sale of knowledge.

We extend the existing literature on several dimensions. We build on the past literature about KT or KS between firms and aim to develop complete KM strategies for

firms that consider cooperating with other firms. While most of the previous studies aim to solely develop cooperation strategies, we aim to examine the decision of firms with respect to KT/KS *and* KD decisions of those firms developing new products. Our model captures the complex and dynamic relationships between KT/KS and KD. For example, for the CD case, the effectiveness of KT/KS is a function of the integration capability, which is dependent on the initial knowledge levels of the firms, and the existing knowledge level of the recipient firm, as well as the level of knowledge it bought. Similarly, the effectiveness of KS for the JD case is a function of the integration capability, which is driven by the initial knowledge levels of the firms engaged in KS, and the levels of knowledge dedicated to the JD project by each firm. Finally, the effectiveness of KD for firms is a function of both the efforts expended and the existing knowledge level of the firms receiving KD. We capture the diminishing returns due to knowledge creation through KT/KS and KD.

The past research that examines cooperation between firms analyzes the firms' decisions regarding KT or KS. Meanwhile, through considering KD, as well as KT/KS, as means of knowledge creation, we aim to develop complete KM strategies for firms considering cooperation with other firms that compete in the same market. We identify the conditions that lead firms to cooperate through CD or JD mechanisms. In addition, we aim to examine the impacts of market or firm related factors on firms' KM strategies. For example, we analyze the impact of expected customer valuation or the extent of loss or proprietary knowledge (due to cooperation) on firms' KT/KS and KD decisions. We capture the impact of firm related factors such as the absorptive capacity of the recipient firm, or the initial knowledge levels of the firms on the KM strategies.

4.4 The Model

In this section, we delve into the details of the two models. A summary of notation appears in Table C.1 of Appendix C.

4.4.1 Competitive Development

We explore the CD agreement which is one form of cooperative mechanism. Through a CD agreement, firm 1 (source) sells a portion of its knowledge to firm 2 (recipient) in exchange for revenue. Subsequently, both firms develop new products individually and compete in the same market.

4.4.1.1 Levels of Knowledge

Let K_{ij} denote the level of knowledge applied to the NPD project by firm i at time j , where $i \in \{1,2\}$ and $j \in \{0,1,2\}$. We denote the leader as firm 1 and the follower as firm 2. The initial time levels of NPD knowledge are known and given by K_{10} and K_{20} for firms 1 and 2, respectively. The initial levels of knowledge may be inferred based on the overall educational background of team members working on the NPD projects, years of work experience, and performance appraisals (Leonard-Barton et al. 1994, Epple et al. 1996, Carrillo and Gaimon 2004). In addition, each firm's initial level of knowledge can be measured by the number of patents and publications awarded to that firm (Liebeskind et al. 1996; Shane, 2000). In period one, each firm's level of knowledge changes due to the transfer of knowledge. In period two, the levels of knowledge increase through KD. Next, we describe how each firm's level of knowledge evolves.

In the first period of the NPD project, the question of KT arises. According to CD mechanism, firm 1 keeps the rights to continue using the knowledge it sells to firm 2 for its own NPD project. Let KT_i denote the period one change in the level of knowledge of firm i due to KT, $i=1,2$. Since firm 1 retains the rights to use the knowledge it sells to firm 2, its level of knowledge does not change during the first period ($KT_1=0$). Thus, the knowledge level of firm 1 at the end of the first period is given in Equation (4.1). However, the knowledge level of firm 2 increases due to the purchase of new knowledge ($KT_2 \geq 0$). The knowledge level of firm 2 at the end of the first period is given in Equation (4.2). Let Q (decision variable) denote the amount of knowledge firm 2 buys from firm 1 in period one. Naturally, firm 2 cannot buy more knowledge than that held by firm 1 at the beginning of period one ($Q \leq K_{10}$). Empirical results show that the effectiveness of KT is related to the resources allocated to the transfer activity, as well as the levels of knowledge of both firms participating in the transfer (Argote and Ingram 2000, Cummings and Teng 2003). We capture these relationships as follows.

$$K_{11} = K_{10} \tag{4.1}$$

$$K_{21} = K_{20} + KT_2 \tag{4.2}$$

Firm 2 benefits more from KT as its level of absorptive capacity increases. Absorptive capacity indicates the firm's ability to recognize the value of new external information, assimilate it, and apply it for competitive advantage (Cohen and Levinthal

1990). The absorptive capacity of the firm 2 is a function of two factors, the integration capability and the initial knowledge level of the firm that is the recipient of the knowledge. The level of absorptive capacity reflects the firm's initial level of knowledge since a firm with higher level of knowledge is better able to comprehend and deploy knowledge it receives from another firm. The level of firm 2's absorptive capacity is uncertain. At the initial time, the portion of knowledge firm 2 is able to integrate is unknown to both firms. Let $\beta^P[K_{10}, K_{20}]$ denote the expected portion of knowledge firm 2 is able to integrate (expected integration capability of firm 2) that satisfies the probability density function $\Phi(z)$ with mean \bar{z} and standard deviation σ (Naturally, $0 < \beta^P[K_{10}, K_{20}] < 1$).

Firm 2's expected integration capability is a function of the initial knowledge levels of the both firms (K_{10}, K_{20}). As the initial knowledge of firm 1 or the initial knowledge of firm 2 increases, the expected integration capability of firm 2 increases. The magnitude of increase in the expected integration capability exhibits diminishing returns to scale with respect to K_{10} and K_{20} . Mathematically, the mean of $\Phi(z)$ is a function of K_{10} and K_{20} satisfying the first and second order conditions $\partial \bar{z} / \partial K_{10} > 0$, $\partial \bar{z} / \partial K_{20} > 0$ and $\partial^2 \bar{z} / \partial K_{10}^2 < 0$, $\partial^2 \bar{z} / \partial K_{20}^2 < 0$. As either K_{10} or K_{20} increases, additional knowledge is deployed that reduces the extent of uncertainty in the expected integration capability of firm 2 (as measured by the standard deviation σ). Mathematically, the standard deviation of $\Phi(z)$ decreases at a non-increasing rate with respect to K_{10} and K_{20} , giving us $\partial \sigma / \partial K_{10} < 0$, $\partial \sigma / \partial K_{20} < 0$ and $\partial^2 \sigma / \partial K_{10}^2 > 0$, $\partial^2 \sigma / \partial K_{20}^2 > 0$. The impact of the initial levels of knowledge on the probability distribution of the expected integration capability is known to both firms.

The second component of absorptive capacity is the initial level of knowledge of firm 2. As firm 2's own level of knowledge increases (K_{20}), the level of knowledge gained by firm 2 increases at a decreasing rate. Also, a firm with a higher level of knowledge requires less KT efforts to obtain the same increase in knowledge as a firm with a lower level of knowledge. As the initial knowledge level of firm 2 increases, the level of knowledge gained by firm 2 increases at a decreasing rate. Similarly, as the extent of knowledge purchased from firm 1 increases (Q), the level of knowledge gained by firm 2 increases at a decreasing rate. This gives us $KT_2 = \beta^P[K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}$ where $0 \leq \theta_1, \theta_2 \leq 1$. Mathematically, the increase in the knowledge level of firm 2 in period one due to KT satisfies a simplified Cobb-Douglas function, where the inputs are the portion of knowledge firm 2 predicts it will be able to integrate, the knowledge level of firm 2 at the

beginning of period one, and the amount of knowledge purchased from firm 1. Equations (4.3) and (4.4) summarize the above discussion regarding how KT affects the period one levels of knowledge of firms 1 and 2.

$$K_{11} = K_{10} \quad (4.3)$$

$$K_{21} = K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2} \quad (4.4)$$

Whereas in the first period knowledge creation is embodied in the KT decision, in the second period each firm invests in KD. Let KD_i denote the period two change in the level of knowledge of firm i due to KD. Firm 1 (leader) makes the initial KD decision, followed by the firm 2's (follower) decision. Thus, the knowledge levels of the firms at the end of the second period are:

$$K_{i2} = K_{i1} + KD_i \quad (4.5)$$

Let γ_i (decision variable) denote the period two efforts undertaken by firm i for KD. Again, the increase in each firm's knowledge level from KD is a function of its absorptive capacity. First, each firm's ability to increase knowledge during period two is a function of its level of knowledge at the end of period one. A firm with a higher level of knowledge requires less KD efforts to obtain the same increase in knowledge as a firm with a lower level of knowledge (Carrillo and Gaimon 2004, Jacobs 2006, Hatch and Macher 2005). Moreover, the increase in firm knowledge due to KD exhibits diminishing returns (Carrillo and Franza 2006, Jacobs 2006). Thus, the increase in the level of knowledge of firm i in period two is given by $\gamma_i K_{i1}^{\mu_i}$, where μ_i represents the rate of diminishing returns ($0 \leq \mu_i \leq 1$). Firm 1 and 2's level of knowledge at the end of period two appears in Equations (4.6) and (4.7), respectively, and reflects the above discussion regarding the impact of KD.

$$K_{12} = K_{11} + K_{11}^{\mu_1} \gamma_1 = K_{10} + K_{10}^{\mu_1} KD_1 \quad (4.6)$$

$$\begin{aligned} K_{22} &= K_{21} + K_{21}^{\mu_2} \gamma_2 \\ &= K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2} + (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{\mu_2} \gamma_2 \end{aligned} \quad (4.7)$$

4.4.1.2 Expected Profit

Having completed the presentation of the dynamics of each firm's level of NPD knowledge, we turn our attention to the expected profit functions. As previously described, the knowledge level of each firm drives its ability to earn net revenue. Firm i 's expected net revenue is comprised of three components: the valuation of its level of knowledge by loyal customers, the extent that it gains or loses revenue due to switching customers who compare the levels of knowledge of both firms, and the probability that firm i is alone in the market at the end of period two, i.e., its competitor does not successfully develop a new product by the end of that period.

First, we consider the portion of the expected net revenue earned by each firm that is solely driven by its own level of knowledge at the end of period two. This component of revenue can be viewed as the revenue earned from firm i 's loyal customers who do not consider the knowledge embedded into the new product by firm i 's competitor. Three elements drive the expected net revenue from loyal customers. Let v_i denote the loyal customers' valuation of the knowledge embedded by firm i into the new product. Therefore, the net revenue from loyal customers is expressed, in part, by product of the customers' valuation of knowledge and the level of firm i 's knowledge, K_{i2} . In addition, the revenue firm i earns from its loyal customers is stochastic, as described below.

Let δ_i denote the probability that the new product developed by firm i will have the features and functionality making it successful in the marketplace. Under the CD mechanism, we assume that firm 1's probability of developing a new product (δ_1) does not change if it engages in KT with firm 2 since firm 1 retains the rights to use the knowledge it sells. Meanwhile, if firm 2 engages in KT, its knowledge level increases and the probability that it successfully develops a new product is larger. Mathematically, let δ_2 denote the probability firm 2 develops a successful product under KT, whereas let δ_2^N denote the probability if KT does not occur. Clearly, we have $\delta_2 \geq \delta_2^N$. Therefore, $\delta_i v_i K_{i2}$ denotes the expected revenue earned from loyal customers when the new product is released to the market at the end of period two.

The second portion of expected net revenue reflects consumers' who base their purchasing decision on the product which has embedded in it the higher level of knowledge. We refer to these as "switching customers." Firm i earns (loses) revenue based on the difference between its period two level of knowledge and that of its

competitor's. Mathematically, firm i 's revenue is a function of, $K_{i2}-K_{k2}$, where $i,k \in \{1,2\}$ and $i \neq k$ (Lichtenstein and Burton 1989, Ali and Seshari 1993). It is important to note that when customers switch from firm i to firm k , firm k earns additional revenue from the switching customers while firm i 's revenue declines. In addition, the revenue firm i earns (loses) from switching customers is stochastic, as described below.

Each firm faces uncertainty with respect to how its own level of knowledge relative to its competitor's impacts the customers' valuation in the marketplace. We assume that the distribution of the firms' customers' valuation of the knowledge is common knowledge for the firms, where the firm's expected valuation of knowledge in the marketplace is denoted as w_i^P . Naturally, if firm i 's knowledge exceeds firm k 's, then firm i realizes the gain in expected revenue whereas firm k realizes the loss and vice versa. The expected net revenue increase or loss due to switching customers is denoted by $\delta_i \delta_k w_i^P (K_{i2}-K_{k2})$, where $i,k \in \{1,2\}$ and $i \neq k$.

Finally, consider the situation where firm i enter the market alone at the end of period two. In this situation, firm i gains additional market share and revenue as the monopolist. Let z_i denote the customers' valuation of the knowledge embedded by firm i into the new product if firm i the only one to successfully develop a new product. Therefore, $\delta_i(1-\delta_k)z_i K_{i2}$ denotes the expected revenue earned by firm i due to the additional market share gained if firm k is not successful developing a new product.

It is important to note that, while each component of the expected net revenue earned from the new product is a linear function of firm i 's level of knowledge (the difference between the levels of knowledge of firms i and k) at the end of period two, the increase in the knowledge levels of the firms during the NPD project, whether from KT or KD, exhibit diminishing returns. Thus, we capture the increasing difficulty in generating revenue from embedding additional knowledge into the new product.

When firms cooperate through CD, each either earns revenue or incurs cost due to KT (Appleyard 1996, d'Aspremont 2000). Let $G[KT_i]$ denote the period one revenue earned or cost incurred due to KT between firms. In the first stage of period one, firm 1 (leader) sets the price (P) for the knowledge it sells to firm 2. Firm 1 determines the price that maximizes its expected profit. In the second stage of the first period, given the price, firm 2 determines the amount of knowledge to buy (Q) that maximizes its own profit. The revenue earned by firm 1 from the KT equals the cost incurred by firm 2 and is given in Equation (4.8):

$$G[KT_i] = PQ \quad (4.8)$$

Both firms incur a cost due to KD pursued in the second period, given by $c_i\gamma_i^2$. The cost of KD for firm i increases at an increasing rate in relation to the efforts expended for several reasons (Clark and Fujimoto 1991, Roemer et al. 2000, Krishnan and Zhu 2006). As more and more KD is undertaken, greater efforts are needed for coordination and supervision. A larger amount of KD may be associated with a larger amount of disruption to ongoing activities, especially if the knowledge is generated when employees attend training programs. In addition, as the extent of KD increases, firms resort to less and less efficient means (Kim 1998, Biskup and Simons 2004). Finally, as a consequence of KT in period one, firm 1 incurs a cost due to the loss of proprietary knowledge. By engaging in KT, firm 1 loses the sole ownership of a portion of its knowledge that is a source of competitive advantage. In other words, in period one, firm 1 incurs an opportunity cost reflecting the future loss in net revenue had it been alone in introducing a new product based on the knowledge sold to firm 2. Thus, m_1Q is the cost due to the loss of proprietary knowledge for firm 1, where m_1 is the associated marginal cost.

The two-period expected profit firm 1 maximizes while determining P in the first stage of period one is depicted in Equation (4.9).

$$E\{\pi_1\} = \delta_1 v_1 K_{12} + \delta_1 \delta_2 w_1^P (K_{12} - K_{22}) + \delta_1 (1 - \delta_2) z_1 K_{12} - c_1 \gamma_1^2 + PQ - m_1 Q \quad (4.9)$$

Given P , firm 2 determines the Q in the second stage of period one that maximizes its two-period expected profit, as shown in Equation (4.10).

$$E\{\pi_2\} = \delta_2 v_2 K_{22} + \delta_1 \delta_2 w_2^P (K_{22} - K_{12}) + \delta_2 (1 - \delta_1) z_2 K_{22} - c_2 \gamma_2^2 - PQ \quad (4.10)$$

Finally, to determine the optimal amounts of KD in period two, firms 1 and 2 also maximize expected profit functions in Equations (4.9) and (4.10), respectively.

Figure 4.1 illustrates the evolution of knowledge over the periods, the decisions made by each firm in periods one and two, and the expected profit earned at the launch time of the new product for the CD mechanism.

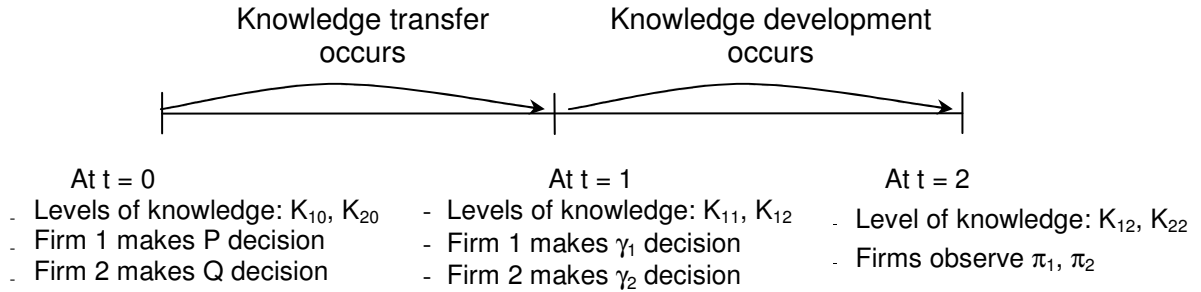


Figure 4.1 Sequence of events for the CD mechanism

4.4.2 Joint Development

Forming a JD is another possible mechanism of cooperation for firms developing new products for the same market. With the JD agreement, firms to cooperate in developing a new product and releasing it to the market. Subsequently, both firms share the expected revenue generated and the cost of knowledge development, which we refer to as expected net revenue (Fosfuri and Rønde 2004, Anand and Khanna 2000a).

4.4.2.1 Levels of Knowledge

We model the JD mechanism between two firms in a two-period model, similar to the CD model. In the first period, the question of KS arises. The first period is comprised of three stages. Firm 1, the leader, determines the portion of the total expected net revenue it will receive at the end of period 2 when the product is released to the market (stage one) as well as the amount of knowledge it will contribute to the JD project (stage two). Firm 2, the follower, determines the amount of knowledge it will contribute to the project given firm 1's prior decisions (stage three). Naturally, Firm 2 will earn the portion of expected net revenue that remains after firm 1 takes its share. In the second period, both firms make a joint decision regarding the extent of KD to pursue before releasing the product to the market. The portion of the cost of the KD incurred by each firm is the same as the distribution of expected net revenue. The objective for each firm is to maximize its own expected profit, which is expressed as a function the expected net revenue it earns when the product is released minus a term reflecting the loss in its expected revenue that results from sharing knowledge. The loss in expected revenue occurs because the firm forgoes the benefits it would have realized had it retained that knowledge as proprietary.

The knowledge levels of each firm at the start of the first period are known to both firms and are denoted by K_{10} and K_{20} . At the end of the first period, K_{JD1} denotes the joint level of knowledge dedicated to the JD project. K_{JD1} is expressed as a function of three elements: the amount of knowledge shared by firm 1, the amount of knowledge shared by firm 2, and the capability of the firms to integrate the shared knowledge. Let Q_i denote the amount of knowledge contributed by firm i to the JD project, where $i \in \{1,2\}$. Given the leader-follower setting, firm 1 determines Q_1 first, and, after observing Q_1 , firm 2 determines Q_2 . Naturally, the firms cannot share a larger level of knowledge than what is available at the beginning of period one ($Q_1 \leq K_{10}$, $Q_2 \leq K_{20}$).

The knowledge shared by both firms, as determined in the second and third stages of the first period, must be integrated. However, the ability of the firms to integrate the shared knowledge is stochastic. Let $\beta^P[K_{10}, K_{20}]$ denote the common expectation of the portion of knowledge both firms will be able to integrate in period 2 ($0 < \beta^P[K_{10}, K_{20}] < 1$). The expected value satisfies the probability density function $\Phi(z)$ with a mean \bar{z} and standard deviation σ . The mean and standard deviation of $\Phi(z)$ are functions of the initial knowledge levels of both firms. As the initial level of knowledge of firm 1 or 2 increases, the expected integration capability increases at a decreasing rate ($\partial \bar{z} / \partial K_{10} > 0$, $\partial \bar{z} / \partial K_{20} > 0$ and $\partial^2 \bar{z} / \partial K_{10}^2 < 0$, $\partial^2 \bar{z} / \partial K_{20}^2 < 0$). In addition, as the initial level of knowledge of firm 1 or 2 increases, more knowledge can be leveraged to reduce the uncertainty in the expected integration capability, but at a decreasing rate ($\partial \sigma / \partial K_{10} < 0$, $\partial \sigma / \partial K_{20} < 0$ and $\partial^2 \sigma / \partial K_{10}^2 > 0$, $\partial^2 \sigma / \partial K_{20}^2 > 0$). The above stochastic relationships are similar to those in Carrillo and Gaimon (2004).

The joint knowledge level dedicated to the JD project is given in Equation (4.11), where θ_1 and θ_2 ($0 \leq \theta_1, \theta_2 \leq 1$) reflect the diminishing returns as each firm contributes more and more knowledge to the JD.

$$K_{JD1} = \beta^P[K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} \quad (4.11)$$

In period two, the firms jointly undertake KD for the new product. Let γ_{JD} denote the extent of efforts to be jointly allocated to KD by the firms in period two. The increase in the knowledge realized from KD in period two increases at a decreasing rate as the joint level of knowledge dedicated to the JD project increases. Therefore, a more knowledgeable joint entity is better equipped to generate and absorb new knowledge,

but with diminishing returns, as denoted by μ_{JD} ($0 \leq \mu_{JD} \leq 1$). Thus, the increase in the joint level of knowledge in period two is given by $\gamma_{JD} K_{JD1}^{\mu_{JD}}$. Equation (4.12) depicts the level of joint knowledge at the launch time of the product (K_{JD2}).

$$K_{JD2} = K_{JD1} + \gamma_{JD} K_{JD1}^{\mu_{JD}} \quad (4.12)$$

4.4.2.2 Expected Profit

Having completed the presentation of the dynamics of the firms' level of NPD knowledge, we turn our attention to the expected profit functions. Similar to the CD mechanism, the joint knowledge level of the firms drives their ability to earn expected net revenue. The expected net revenue is comprised of three components: the net revenue earned from the launch of the jointly developed new product, minus the costs of KD and the costs of KS for each firm.

It is important to note that, at the first stage of period one of the JD agreement, firm 1 determines the portion of expected profit to be allocated to firms 1 and 2. Let, λ and $1-\lambda$ denote the portions of expected net revenue earned at the end of period two, by firm 1 and firm 2, respectively ($0 \leq \lambda \leq 1$). Subsequently, we assume that each firm incurs the same portion of the KD costs. In addition, each firm incurs a cost due to the loss of proprietary knowledge that occurs from KS.

The expected net revenue earned by firm i from the new product released by the JD project is a function of the joint knowledge level at the end of period two. We capture the uncertainty associated with the revenue earned from the new product in two dimensions. First, the firms face uncertainty in their ability to jointly develop a product that successfully meets the feature and functionality requirements of the customers. Let δ_{JD} denote the probability that the new product developed jointly by the firms will have the features and functionality making it successful in the marketplace. Second, firm i 's profit is a function of customers' valuation of the knowledge, which is uncertain. We assume that the distribution of the firms' customers' valuation of the knowledge is common knowledge for the firms, where the firm's expected valuation of knowledge in the marketplace is denoted as v_{JD}^P . This gives us the expected net revenue from the new product released at the end of period two as $\delta_{JD} v_{JD}^P K_{JD2}$. Since firm 1 (firm 2) earns λ ($1-\lambda$) portion of the expected net revenue, the expected net revenue earned by firm 1

(firm 2) from the new product generated by the JD project is denoted by $\lambda\delta_{JD}v_{JD}^PK_{JD2}$ ($((1-\lambda)\delta_{JD}v_{JD}^PK_{JD2})$).

The expected profit is also a function of the costs associated with KD pursued jointly by the firms in the second period, denoted by $c_{JD}\gamma_{JD}^2$. Similar to the CD mechanism, we assume that the cost of KD is a quadratic function of the KD efforts pursued by the firms. In addition to reflecting how net revenue will be shared in the JD agreement, λ and $1-\lambda$ denote the portion of KD costs shared by firms 1 and 2. Thus, the cost of KD incurred is $\lambda c_{JD}\gamma_{JD}^2$ and $(1-\lambda)c_{JD}\gamma_{JD}^2$ for firms 1 and 2, respectively.

Finally, as a consequence of KS in period one, each firm incurs a cost due to the loss of proprietary knowledge. When the firms enter into JD, they lose the competitive advantage they had due to sole ownership of their portion of the knowledge. In other words, in period one, firm i incurs an opportunity cost reflecting the future loss in net revenue from new product it would have released based on knowledge it shared. Let m_i denote the marginal cost incurred by firm i for sharing knowledge. Thus, m_1Q_1 and m_2Q_2 are the costs due to loss of proprietary knowledge for firms 1 and 2, respectively.

Equations (4.13) and (4.14) mathematically capture the expected profit to be maximized by firms 1 and 2, respectively, when determining the period one KS decisions. Therefore, in period one, each firm maximizes its own expected profit.

$$\begin{aligned} E\{\pi_1\} &= \lambda\{v_{JD}^PK_{JD2} - c_{JD}\gamma_{JD}^2\} - m_1Q_1 \\ &= \lambda\{\delta_{JD}v_{JD}^P(\beta^P[K_{10},K_{20}]Q_1^{01}Q_2^{02} + (\beta^P[K_{10},K_{20}]Q_1^{01}Q_2^{02})^{\mu_{JD}}\gamma_{JD}) - c_{JD}\gamma_{JD}^2\} \\ &\quad - m_1Q_1 \end{aligned} \quad (4.13)$$

$$\begin{aligned} E\{\pi_2\} &= (1-\lambda)v_{JD}^PK_{JD2} - c_{JD}\gamma_{JD}^2 - m_2Q_2 \\ &= (1-\lambda)\{\delta_{JD}v_{JD}^P(\beta^P[K_{10},K_{20}]Q_1^{01}Q_2^{02} + (\beta^P[K_{10},K_{20}]Q_1^{01}Q_2^{02})^{\mu_{JD}}\gamma_{JD}) \\ &\quad - c_{JD}\gamma_{JD}^2\} - m_2Q_2 \end{aligned} \quad (4.14)$$

However, since firms make the KD decision (γ_{JD}) jointly in period two, they maximize the expected net revenue function in Equation (4.15).

$$E\{\pi_{JD}\} = v_{JD}^PK_{JD2} - c_{JD}\gamma_{JD}^2 \quad (4.15)$$

Figure 4.2 illustrates the evolution of knowledge, the decisions made by each firm in period one and made jointly by the firms in period two, and the profit earned at the launch time for the JD mechanism.

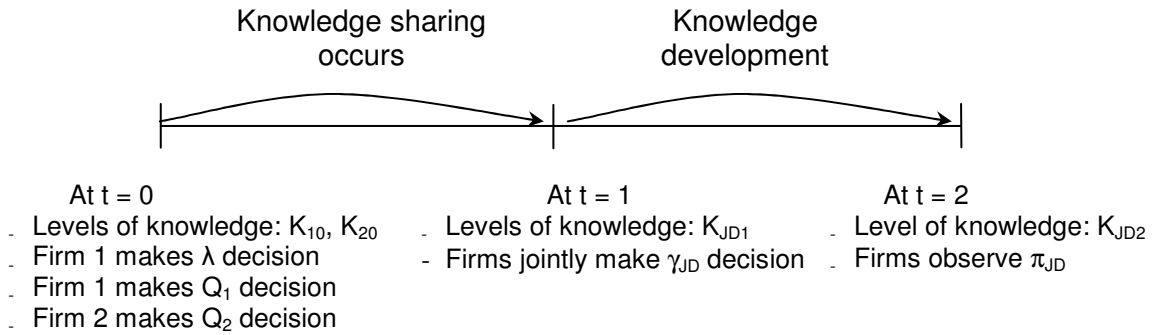


Figure 4.2 Sequence of events for the JD mechanism

4.5 Analytical and Numerical Analysis

We solve the models introduced in sections 4.4.1 and 4.4.2 using backward induction. Sections 4.5.1 and 4.5.2 provide the analysis for the models capturing the CD and JD mechanisms, respectively. For each cooperation mechanism, we give the optimal solutions and explore the impact of various parameters on the firms' KM strategies through analytical and numerical analysis. In addition we illustrate the impact of uncertainty associated with both market and firm characteristics on the each firm's knowledge creation decisions. The proofs of propositions are included in the Appendix C.

4.5.1 Competitive Development

4.5.1.1 Optimal Solution and Analytic Sensitivity Analysis

Propositions 1 to 4 depict the optimal KM strategies for the leader and follower firms under CD mechanisms. Equation (4.16) gives the optimal amount of KD pursued by firms 1 and 2 in period two that maximizes the profit functions (4.13) and (4.14), respectively. Note that the KD pursued in period two by firms 1 and 2 are symmetrical. In addition, we see that the KD pursued by each firm is a function of its knowledge level at the end of period one, as well as drivers of expected revenue and the costs of KD.

PROPOSITION 1. *The optimal amount of KD pursued by firm 1 in the second period satisfies Equation (4.16). In addition, the optimal amount of KD pursued by firm 2 in the second period satisfies Equation (4.17):*

$$Y_1^* = \frac{\delta_1\{v_1 + \delta_2 w_1^P + (1 - \delta_2)z_1\}K_{11}^{\mu_1}}{2c_1} \quad (4.16)$$

$$Y_2^* = \frac{\delta_2\{v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2\}K_{21}^{\mu_2}}{2c_2} \quad (4.17)$$

From Equations (4.16) and (4.17), the optimal amount of KD for firm i is larger (smaller) if: (i) firm i 's probability of developing a successful new product is large (small); (ii) firm i 's customers' valuation of the knowledge embedded by firm i into the new product (v_i) is large (small); (iii) firm i 's expected valuation by the customers for exceeding/falling short of the competitor's knowledge (w_i) is large (small); (iv) firm i 's customer's valuation of knowledge if firm i is the only firm developing the new product (z_i) is large (small); (v) the knowledge level of firm i at the end of period one (K_{i1}) is large (small); and (vi) the marginal cost of KD for firm i (c_i) is small (large).

From (v) we obtain an interesting insight: there is a complementary relationship between firm 2's pursuit of KT in the first period and KD in the second period. We obtain this result because any investment by firm 2 in KD has greater impact when the increase in the level of knowledge of the firm in the first period is large. Clearly, this result shows that to the extent possible, firm 2 should undertake efforts that increase the effectiveness of KT.

In Proposition 2, below, we describe the optimal amount of knowledge bought by firm 2 in period one, which is a function of the price set by firm 1.

PROPOSITION 2. *The optimal amount of knowledge firm 2 buys in period one after observing the price charged by firm 1 satisfies Equation (4.18):*

$$2c_2 + \{\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)\}\mu_2(K_{20} + \beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2 - 1} \\ = \frac{2c_2 P}{\{\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)\}\beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} Q^{\theta_2 - 1}} \quad (4.18)$$

From Equation (4.18), we observe the impact of several firm and market characteristics on the interaction between the KT decisions of firms 1 (P) and 2 (Q). A

high price set by firm 1 in the first period (P) drives firm 2 to purchase a small (large) amount of knowledge (Q) if: (i) the valuation of knowledge by firm 2's loyal customers (v_2) is large (small); (ii) firm 2 is the only firm to successfully enter the market and the customers' valuation of firm 2 knowledge (z_2) is large (small); (iii) firm 2's prediction of the valuation by its switching customers (w_2^P) is large (small); (iv) the prediction of the portion of KT that firm 2 will be able to integrate $\beta^P[K_{10}, K_{20}]$ is large (small); (v) the level of knowledge of either firm 1 or 2 at the beginning of the first period (K_{10} or K_{20}) is large (small); (vi) the rate of returns to KT of firm 2's initial knowledge level (θ_1) is large (small); and (vii) the marginal cost of KD pursued by firm 2 (c_2) is small (large).

According to these results, if the valuation of knowledge by firm 2's customers is large (conditions (i), (ii), (iii)), firm 2 is driven to purchase more knowledge from firm 1 if the price set by firm 2 per unit knowledge is small. Meanwhile, if the valuation of loyal or switching customer's of firm 2 is below a threshold value, large (small) price set by firm 1 drives firm to purchase large (small) amount of knowledge. For example, due to small customer valuation, the value of embedding knowledge into the new product is small for firm 2, and firm 1 sets a smaller price to encourage firm 1 to purchase larger amount of knowledge at a smaller cost. However, since the benefits firm 2 realizes from developing a superior product, firm 2 refrains from purchasing large amount of knowledge from firm 1. As a result, although the price set by firm 1 is smaller; firm 2 purchases a smaller amount of knowledge from firm 1.

In addition, firm 2 is driven to purchase a large amount of knowledge when firm 1 sets a smaller price if firm 1's probability of successfully developing the new product or the effectiveness of transferring knowledge from firm 1 is large (conditions (iv), (v), (vi)). Meanwhile, if the cost of KD is large (condition (vii)), firm 2 focuses on increasing its level of knowledge by purchasing a large amount of knowledge from firm 1, despite the high price set by firm 1.

The conditions given in Equation (4.19) and (4.20) must be satisfied for firms 1 and 2 to cooperate thorough CD mechanism. These conditions mathematically depict the rational decision making of firms 1 and 2: Each firm is willing to cooperate with the other firm if the expected profit under the condition that it cooperates exceeds the expected profit under the condition that it develops the new product individually. Thus, for the firms to engage in CD mechanism, both firms expected profit if they cooperate should be larger than their expected profits if they don't cooperate.

PROPOSITION 3. Firm 1 will cooperate with firm 2 if the inequality in Equation (4.19) is satisfied. Firm 2 will cooperate with firm 1 if the inequality in Equation (4.20) is satisfied.

$$\begin{aligned}
(P - m_1)Q \geq & (X^N - X)K_{10} + \frac{\{(X^N)^2 - X^2\}K_{10}^{2\mu_1}}{4c_1} + \delta_1 w_1^P (\delta_2 - \delta_2^N) K_{20} \\
& + \delta_1 \delta_2 w_1^P \left(\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2} + \frac{Y(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2}}{2c_2} \right) \\
& - \delta_1 \delta_2^N w_1^P \left(\frac{Y^N K_{20}^{2\mu_2}}{2c_2} \right)
\end{aligned} \tag{4.19}$$

$$\begin{aligned}
PQ \geq & Y^N K_{20} + \frac{Y^N K_{20}^{2\mu_2}}{4c_2} - \delta_1 \delta_2^N w_2^P \left(K_{10} + \frac{X^N K_{10}^{2\mu_1}}{2c_1} \right) \\
& - Y(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}) + \frac{Y^2 (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2}}{4c_2} \\
& - \delta_1 \delta_2 w_2^P \left(K_{10} + \frac{X K_{10}^{2\mu_1}}{2c_1} \right)
\end{aligned} \tag{4.20}$$

where

$$\begin{aligned}
X &= \delta_1 (v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1) \\
Y &= \delta_2 (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2) \\
X^N &= \delta_1 (v_1 + \delta_2^N w_1^P + (1 - \delta_2^N) z_1) \\
Y^N &= \delta_2^N (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2).
\end{aligned}$$

Equation (4.18) does not yield a closed form solution for firm 2's KT decision (Q), which is expressed as a function of firm 1's KT decision (P). However, if we assume that the returns to firm i's KD in relation to its level of knowledge at the end of period one equals one-half ($\mu_i=1/2$, $i=1,2$), then the optimal solutions for firm 1 and 2 are dramatically simplified. (This assumption is similar to the assumption in Pacheco-de-Almeida and Zemsky, 2007). The results obtained with $\mu_i=1/2$ are depicted in Proposition 4 (Equations (4.21) - (4.24)).

PROPOSITION 4. Suppose $\mu_1=\mu_2=1/2$. The optimal equilibrium price charged by firm 1 for knowledge sold to firm 2 in the first period satisfies Equation (4.21). In addition, the optimal equilibrium amount of knowledge firm 2 will buy in the first period after observing the price charged by firm 1 satisfies Equation (4.22). Finally, the optimal equilibrium amount of KD pursued by firms 1 and 2 satisfy Equations (4.23) and (4.24), respectively.

$$P^* = \frac{m_1 Y(4c_2 + Y)}{\theta_2 Y(4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y)} \quad (4.21)$$

$$Q^* = \left[\frac{4c_2 m_1}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \theta_2 \{ \theta_2 Y(4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y) \}} \right]^{\frac{1}{\theta_2 - 1}} \quad (4.22)$$

$$\gamma_1^* = \frac{X K_{10}^{1/2}}{2c_1} \quad (4.23)$$

$$\gamma_2^* = \frac{Y \left[K_{20} + \left\{ \frac{1}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \left(\frac{4c_2 m_1}{\theta_2 Y(4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y)} \right)^{\theta_2} \right\}^{\frac{1}{\theta_2 - 1}} \right]^{1/2}}{2c_2} \quad (4.24)$$

$$\begin{aligned} \text{where } X &= \delta_1 (v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1) \\ Y &= \delta_2 (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2) \end{aligned}$$

Since we are able to obtain closed form solutions for the firms KM decision through the simplifying assumption, we are also able to isolate the impact of several parameters on the knowledge creation strategies of firms. In Propositions 5 - 8, we present results of analytic sensitivity analysis that provide important insights on the KM strategies pursued by firms 1 and 2. The results follow from Equations (4.21) to (4.24). Proposition 5 shows how firm and market-related parameters impact the KT decision of firm 1 (P). Proposition 6 depicts how firm and market related parameters impact firm 2's KT decision (Q). Propositions 7 and 8 show the impact of these parameters on the firms' period two KD decisions (γ_1 and γ_2), respectively.

PROPOSITION 5. *Firm 1 optimally pursues a larger (smaller) price for KT to firm 2 in the first period (P) if any of the following conditions hold:*

- (i) *The reduction in revenue from the loss in of proprietary knowledge firm 1 incurs when it sells knowledge to firm 2 (m_1) is large (small);*
- (ii) *The prediction by firm 1 of the valuation by switching customers in relation to the difference in the levels of knowledge of both firms (w_1^P) is large (small);*
- (iii) *The effectiveness of KT on increasing the level of knowledge of firm 2 (θ_2) is small (large).*

PROPOSITION 6. Firm 2 optimally buys a larger (smaller) amount of knowledge in the first period (Q) after observing the price set by firm 1 if any of the following conditions hold:

- (i) The reduction in revenue from the loss in of proprietary knowledge firm 1 incurs when it transfers knowledge to firm 2 (m_1) is small (large);
- (ii) The prediction by firm 1 of the valuation by switching customers in relation to the difference in the levels of knowledge of both firms (w_1^P) is small (large);
- (iii) The effectiveness of KT on increasing the level of knowledge of firm 2 (θ_2) is large (small);
- (iv) Both firms' prediction of the portion of KT that firm 2 will be able to integrate $\beta^P[K_{10}, K_{20}]$ is large (small);
- (v) The initial level of knowledge of firm 1 or 2 (K_{10} or K_{20}) is large (small).

PROPOSITION 7. Firm 1 optimally pursues a larger (smaller) amount of KD in the second period (γ_1) if any of the following conditions hold:

- (i) The valuation of firm 1 knowledge by loyal customers (v_1) is large (small);
- (ii) The prediction by firm 1 of the valuation by switching customers in relation to the difference in the levels of knowledge of both firms (w_1^P) is large (small);
- (iii) Firm 1 is the only firm to successfully enter the market and the customers' valuation of firm 1 knowledge (z_1) is large (small);
- (iv) Marginal cost of KD pursued by firm 1 in the second period (c_1) is small (large);
- (v) The probability that the new product developed by firm 1 will have the features and functionality that make it successful in the marketplace (δ_1) is large (small).

PROPOSITION 8. Firm 2 optimally pursues a larger (smaller) amount of KD in the second period (γ_2) if any of the following conditions hold:

- (i) The reduction in revenue from the loss in of proprietary knowledge firm 1 incurs when it transfers knowledge to firm 2 (m_1) is small (large);

- (ii) *The prediction by firm 1 of the valuation by switching customers in relation to the difference in the levels of knowledge of both firms (w_1^P) is small (large);*
- (iii) *The effectiveness of KT on increasing the level of knowledge of firm 2 (θ_2) is large (small);*
- (iv) *Both firms' prediction of the portion of KT that firm 2 will be able to integrate $\beta^P[K_{10}, K_{20}]$ is large (small);*
- (v) *The initial level of knowledge of firm 1 or 2 (K_{10} or K_{20}) is large (small).*

From Propositions 5 through 8, we obtain important insights about firm 1 and firm 2's KM strategies. First, suppose the reduction in revenue from the loss in of proprietary knowledge firm 1 incurs when it transfers knowledge to firm 2 (m_1) is large. Under this condition, firm 1 sets a larger price in period one for the knowledge sold to firm 2 (P). This result occurs since firm 1 aims to compensate for the cost of loss of sole ownership of knowledge, either by reducing the level of knowledge bought by firm 2 or by increasing the expected revenue directly earned from the transfer of knowledge. A large price set by firm 1 for selling the knowledge results in a small amount of knowledge (Q) purchased by firm 1. While a large reduction in firm 1's revenue due to the loss in proprietary knowledge does not impact firm 1's pursuit of KD (γ_1), it does drive firm 2 to pursue a smaller amount of KD (γ_2). Essentially, firm 2 starts period two with less knowledge and is therefore less able to exploit the benefits from KD. Thus, because of the large loss in revenue due to the loss in proprietary knowledge by firm 1, firm 2 develops an inferior product. Meanwhile, firm 1 is able to develop a product of the same quality as under the condition where the cost of loss of proprietary knowledge is small.

Another interesting insight is related to the impact of several parameters on the effectiveness of KT to firm 2. As expected, if the firms' prediction of the portion of KT that firm 2 will be able to integrate $\beta^P[K_{10}, K_{20}]$ is large, firm 2 purchases a larger amount of knowledge from firm 1 in the first period. With the larger level of knowledge at the end of the first period, knowledge creation in period two is more effective so that firm 2 pursues a higher amount of KD.

In a result that is not obvious, we find that the firms' prediction of the portion of KT that firm 2 will be able to integrate does not impact firm 1's decisions on the period one price or the period two amount of KD. Although the price set by firm 1 is not impacted by the integration capability of firm 2, the amount of knowledge purchased by

firm 2 is larger and the expected revenue earned by firm 1 from the KT is larger. Therefore, if firm 2's integration capability is large, it embeds more knowledge into its new product and the expected revenue earned by firm 2 in the marketplace is larger. Meanwhile, the level of knowledge embedded by firm 1 is does not change, and thus, the expected profit for firm 1 is not necessarily lower: Although the expected revenue earned (cost incurred) by firm 1 due to exceeding (falling short of) the level of knowledge of firm 2 is smaller (larger), and the reduction in revenue due to the loss of proprietary knowledge is larger, firm 1 also earns more expected revenue due to the larger amount of KT. It interesting to note that the above shifts in the KM strategies of firms and 2 are also obtained if the effectiveness of KT on increasing the level of knowledge of firm 2 (θ_2), 1 is large, or the initial level of knowledge of firm 1 or 2 (K_{10} or K_{20}).

Results that are not obvious emerge when we consider the scenarios where each of the following parameters is large: (i) loyal customers' valuation of firm 1's level of knowledge (v_1); and (ii) firm 1 is the only firm to successfully enter the market and the customers' valuation of firm 1 knowledge (z_1). Under this condition, the period one decisions of firms 1 and 2, and the amount of KD pursued by firm 2 in the second period is not impacted by this condition. This result occurs since firm 1, who is the leader, makes the price decision based on the valuation of knowledge embedded by firm 2, rather than its own predictions. Since firm 2 is the follower, firm 2's knowledge creation decisions are also driven by the same parameters. Meanwhile, firm 1 optimally pursues a larger amount of KD, in order to develop a superior earn larger revenue from its loyal customers, as well as from all the customers if firm 2 is not able to successfully develop the new product. Thus, firm 1 is able to integrate the customers' valuation level of knowledge of firm 1 into the decisions constituting its KM strategy.

Next, suppose that the firm 1's prediction of the valuation by its switching customers (w_1^P) is large. Under this condition, firm 1 optimally sets a higher price in the first period and the amount of knowledge purchased by firm 1 is smaller. In the second period, firm 1 pursues a larger amount of KD, while firm 2 pursues KD at a smaller amount. Through setting a large price in period one, firm 1 reduces the knowledge purchased by firm 2, and firm 2 develops an inferior product. Meanwhile, since the amount of the KD pursued by firm 1 is larger, firm 1 develops a more superior product than it would have with small prediction of customers' valuation. Thus, the expected revenue earned (cost incurred) by firm 1 due to exceeding (falling short of) the knowledge embedded into the new product by firm 2 is larger (smaller).

Finally, suppose that the rate of returns to KT of knowledge purchased by firm 2 (θ_2) is large. Under this condition, firm 1 sets a smaller price and the amount of knowledge purchased by firm 2 is larger, resulting in greater expected net revenue from KT for firm 1. Since the knowledge level of firm 2 at the end of period one is larger and the value of increasing the knowledge level of firm 2 is larger, the amount of KD pursued by firm 2 in the second period is larger. Meanwhile, the amount of KD pursued by firm 1 is not impacted by the parameter relating to the effectiveness of KT to firm 2. Thus, the knowledge level of firm 1 remains unchanged, while firm 2 embeds a larger level of knowledge into the new product. In this scenario, firm 1's period one decision results in a higher expected revenue earned directly from KT, rather than the revenue earned from the product in the marketplace.

4.5.1.2 Numerical Analysis

In this section, we introduce results based on numerical sensitivity analysis. We present one base example, Example 1, to reflect the decision-making environments of the CD mechanism. In addition, we present six variations of Example 1. The purpose of the numerical examples is to illustrate some key analytical results and to extend analytical results by providing insights on the impact of several parameters on the firms' KM decisions and on the profit earned by the firms.

The particular functions and input parameters we employ are inspired by the KM literature, interviews with managers from the automotive industry, and articles from academic and practitioner publications. Table C.2 contains a detailed account of all functional forms and input parameter values. Table C.3 summarizes the results of Example 1. For the variations of the base example, due to different input values for z_2 , c_2 , v_2 , w_2^P , δ_1 , and δ_2 , we obtain dramatically different solutions for the KT and KD decisions of firms 1 and 2. In addition, we show the impact of firm and market-related characteristics on each firm's expected profit. Figures 4.3 to 4.6 illustrate key managerial insights.

The situation reflected in Example 1 is based on the following parameter settings. Although both firms 1 and 2 have a solid foundation of knowledge at the outset of the NPD project, the initial knowledge level of firm 1 exceeds the initial knowledge level of firm 2 ($K_{10}=100$, $K_{10}=80$). The parameters of effectiveness of KT from firm 1 to firm 2 ($\beta^P[K_{10},K_{20}]$, θ_1 , θ_2) are moderately large. In addition, the probability of successfully developing the new product (δ_1) is 0.5 for firm 1, and is 0.5 for firm 2 if it engages in KT

(δ_2) and 0.4 if it doesn't (δ_2^N). The customers' (expected) valuation of the knowledge embedded into the product under various market conditions (v_i, w_i^P, z_i) have the same input values for firms 1 and 2.

Example 1a is identically defined as Example 1 except that we vary the input value for the probability that firm 1 successfully develops the new product (δ_1) between 0 and 1. As illustrated in Figures 4.3a to 4.3e, for the scenario driven by input values given in Example 1, as the probability of successfully developing new product increases for firm 1, the price set by firm 1 in the first period (P) increases. The more firm 1 expects to earn larger expected net revenue from the new product, the less firm 1 is inclined to sell its competitive knowledge to firm 2. However, as the price set by firm 1 in the first period increases with firm 1's probability of successfully developing a new product, the amount of knowledge purchased by firm 2 (Q) decreases. In addition, from Figure 4.3c, we observe that the KD pursued by firm 1 (γ_1) increases as the probability of firm 1 successfully developing the new product increases, while the KD pursued by firm 2 (γ_2) remains the same. As a result, as firm 1's probability of successfully developing new product increases, the expected profit for firm 1 increases ($E\{\pi_1\}$), while the expected profit for firm 2 ($E\{\pi_2\}$) decreases (whether the firms cooperate or not) (Figures 4.3d and 4.3e).

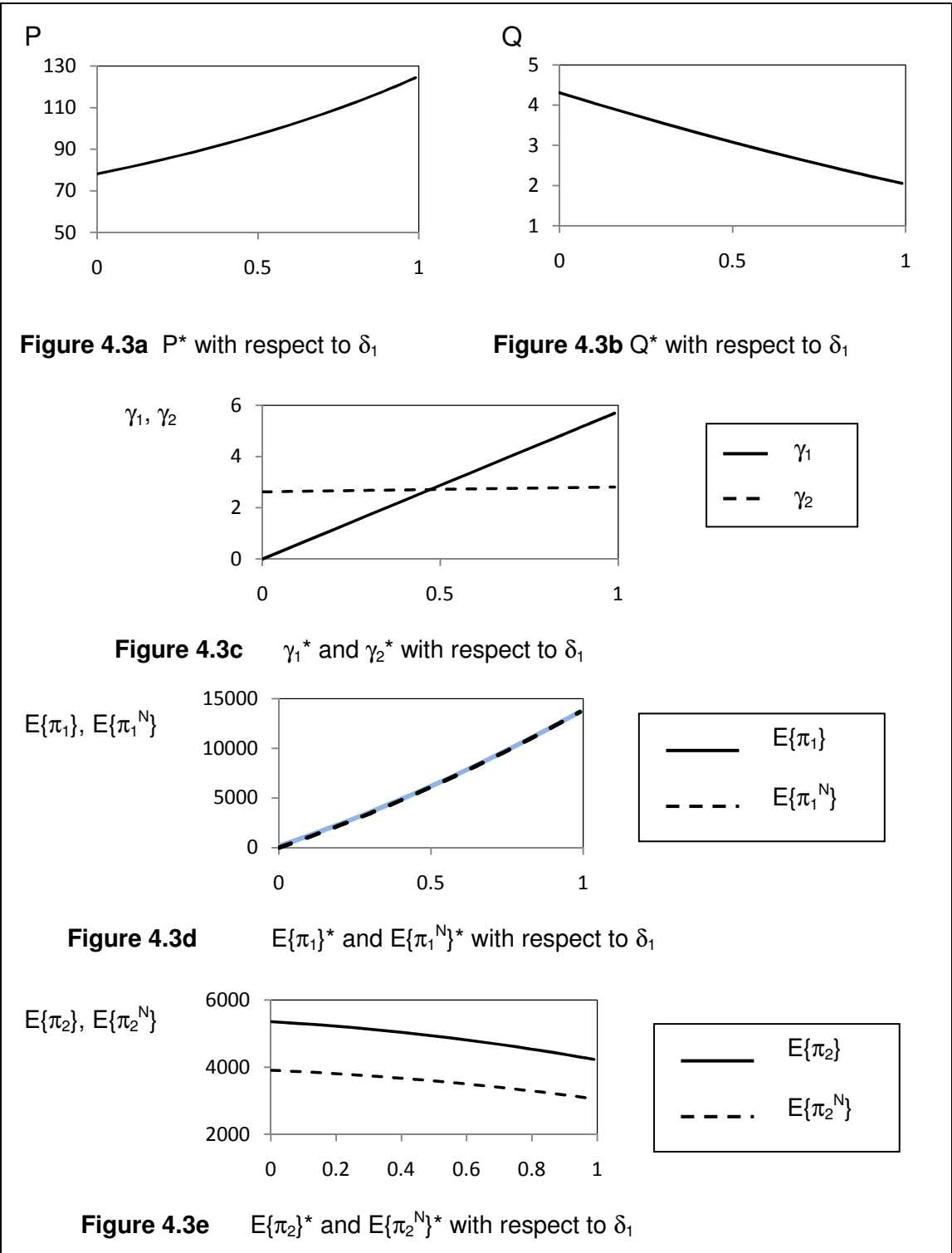


Figure 4.3 KT and KD decisions and the expected profits of firms 1 and 2 with respect to δ_1

In Example 1b, we vary the input value for the probability that firm 1 successfully develops the new product if it cooperates with firm 1 (δ_2) between 0.41 and 1. From this, we obtain substantially different results for the firms' KM decisions and expected profit functions. Note that since the probability that firm 1 successfully develops the new product if it cooperates (δ_2) is larger than the probability that firm 1 successfully develops the new product if doesn't cooperate (δ_2^N). Therefore, for Example 1 and its variations, we define $\delta_2 > 0.4$. As illustrated in Figures 4.4d and 4.4e, for values of δ_2 smaller than 0.55, firm 2 does not engage in KT with firm 1. For values of δ_2 larger than 0.79, firm 1 does not engage in KT with firm 2. This result occurs for two reasons. First, for small values of δ_2 , the cost incurred for KT outweighs the benefits from increased probability and knowledge level due to KT. Second, for large values of δ_2 , the cost firm 1 incurs due to KT (loss of expected revenue from the new product and the loss of proprietary knowledge) outweighs the revenue earned from selling knowledge. If $0.54 < \delta_2 < 0.79$, as the probability that firm 2 successfully develops the new product if it cooperates increases, the price set by firm 1 per unit knowledge sold to firm 2 decreases, as the knowledge purchased by firm 2 increases. This result occurs since firm 1 aims to increase its earnings due to KT through increasing the amount of knowledge purchased by firm 2. The amount of KD pursued by firm 1 does not change as firm 2's probability of successfully developing the new product (if it cooperates) increases. Meanwhile, the amount of KD pursued by firm 2 increases as δ_2 increases, since the value of increasing knowledge in the second period is more prominent due to a greater level of knowledge for firm 2 at the end of the first period. As a result, the expected profit for firm 1 decreases while the expected profit for firm 2 increases and as the probability of successfully developing the new product if firm 2 cooperates increases.

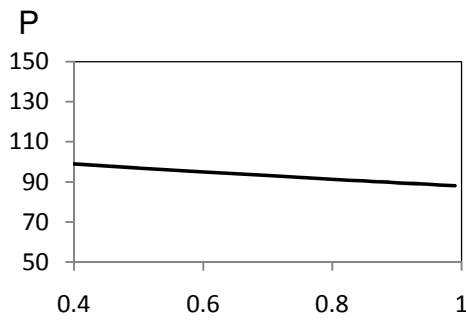


Figure 4.4a P^* with respect to δ_2

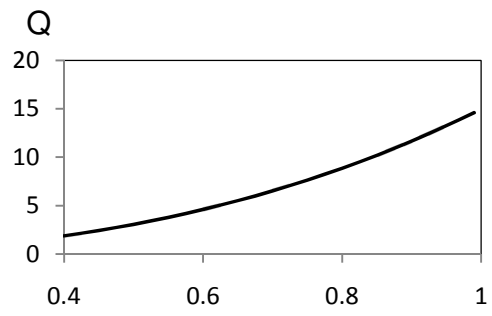


Figure 4.4b Q^* with respect to δ_2

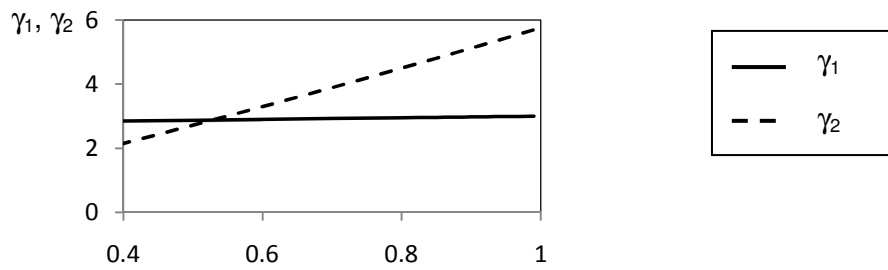


Figure 4.4c γ_1^* and γ_2^* with respect to δ_2

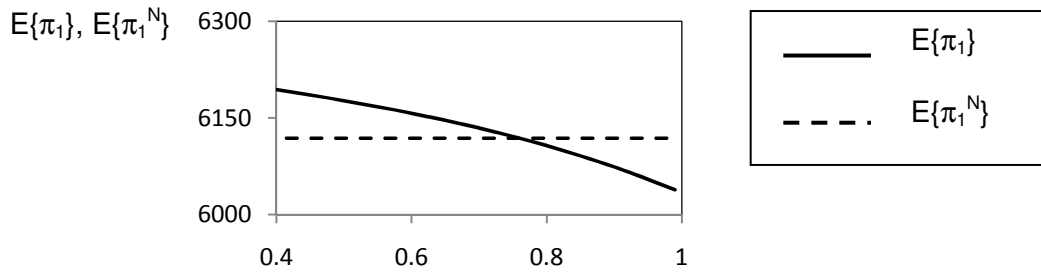


Figure 4.4d $E\{\pi_1\}^*$ and $E\{\pi_1^N\}^*$ with respect to δ_2

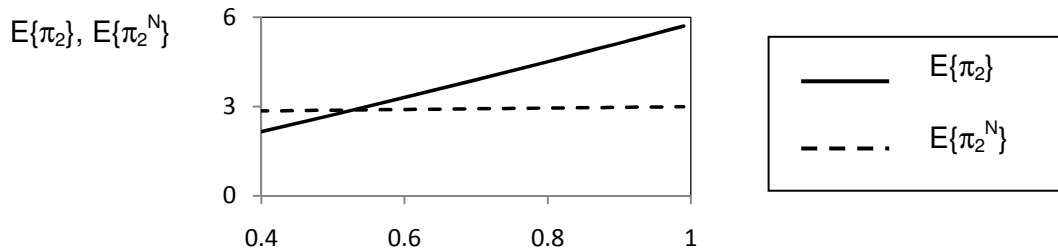


Figure 4.4e $E\{\pi_2\}^*$ and $E\{\pi_2^N\}^*$ with respect to δ_2

Figure 4.4 KT and KD decisions and the expected profits of firms 1 and 2 with respect to δ_2

The impact of customer's valuation of level of knowledge embedded by firm 2, regardless of knowledge embedded by firm 1 (v_2), is examined in Example 1c. As illustrated in Figures 4.5a to 4.5c, as customer valuation increases, firm 1 sets a smaller price per unit knowledge sold. Firm 1 sets a smaller price to increase the amount of knowledge purchased by firm 2, and focuses on the expected revenue earned from the transfer of knowledge in the first period. Firm 2 then purchases larger amount of knowledge and pursues a greater amount of KD, while the amount of KD pursued by firm 1 does not change. As firm 2's customer's valuations increase, firm 2 is more inclined to embed a larger level of knowledge into the new product. In the second period, firm 2 increases its level of knowledge through KD to develop a superior product. Meanwhile, firm 1 does not focus on KD since the value of increasing knowledge in the second period is small. However, as illustrated in Figures 4.5d and 4.5e, the expected profit for both firm 1 and firm 2 increases if they engage in KT. Firm 1's expected profit increases from the expected revenue earned from KT, while firm 2's expected profit increases from the expected revenue from the new product in the marketplace. Finally, as the customer's valuation of level of knowledge of firm 2 increases, the expected revenue for firm 2 increases if it does not cooperate, while the expected revenue for firm 1 decreases if it does cooperate. In Example 1d we vary the input value for the customer's valuation for knowledge embedded by firm 2 compared to knowledge embedded by firm 1 (w_2^P). Similarly, for Example 1e, we vary the customer's valuation for knowledge embedded by firm 2 if firm 1 fails to successfully develop the new product (z_2). The KM decisions of firms under CD mechanism and the expected profits of firms 1 and 2 (whether they cooperate or do not cooperate) for Examples 1d and 1e, as illustrated in Figures C.1 and C.2, is similar to the solutions obtained for Example 1c.

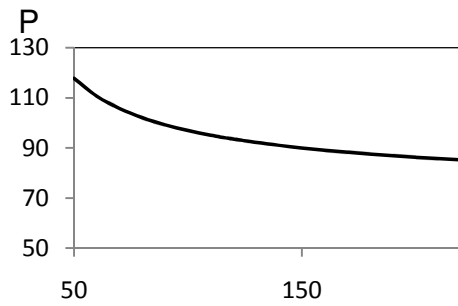


Figure 4.5a P^* with respect to v_2

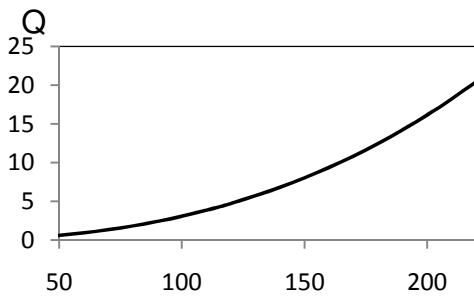


Figure 4.5b Q^* with respect to v_2

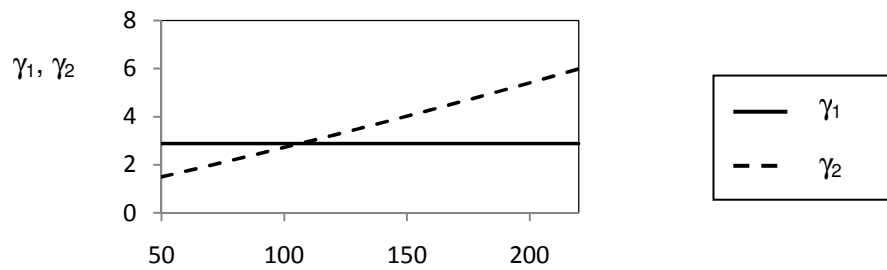


Figure 4.5c γ_1^* and γ_2^* with respect to v_2

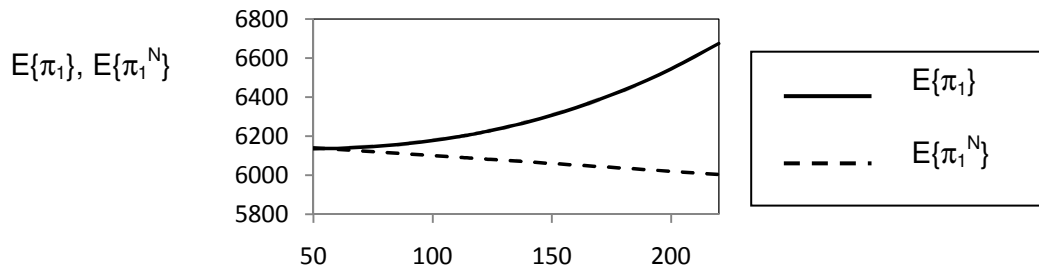


Figure 4.5d $E\{\pi_1\}^*$ and $E\{\pi_1^{N_1}\}^*$ with respect to v_2

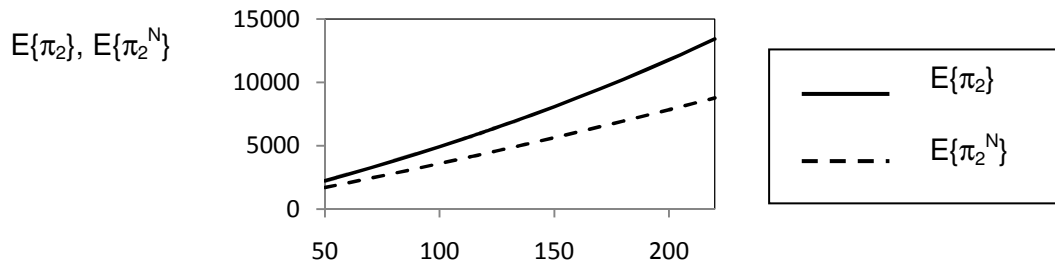


Figure 4.5e $E\{\pi_2\}^*$ and $E\{\pi_2^{N_1}\}^*$ with respect to v_2

Figure 4.5 KT and KD decisions and the expected profits of firms 1 and 2 with respect to v_2

Finally, the impact of cost of KD for firm 2 (c_2) is examined in Example 1f, illustrated in Figures 4.6a-4.6e. From these figures, we obtain interesting insights. As the cost of KD for firm 2 increases, the price set by firm 1 decreases. As KD cost increases, firm 2's ability to increase knowledge in the second period becomes more limited, and firm 2 does not find it useful to buy a high amount of knowledge from firm 1. Meanwhile, firm 1, who knows that firm 2's ability to develop knowledge is limited, finds firm 2 less of a threat in the new product market, and decreases the price it sets per unit knowledge. As expected, the amount of KD pursued by firm 2 in the second period decreases, while the amount of KD pursued by firm 1 does not change. As a result, the expected profit for firm 1 increases, while the expected profit for firm 2 decreases as its cost of KD increases.

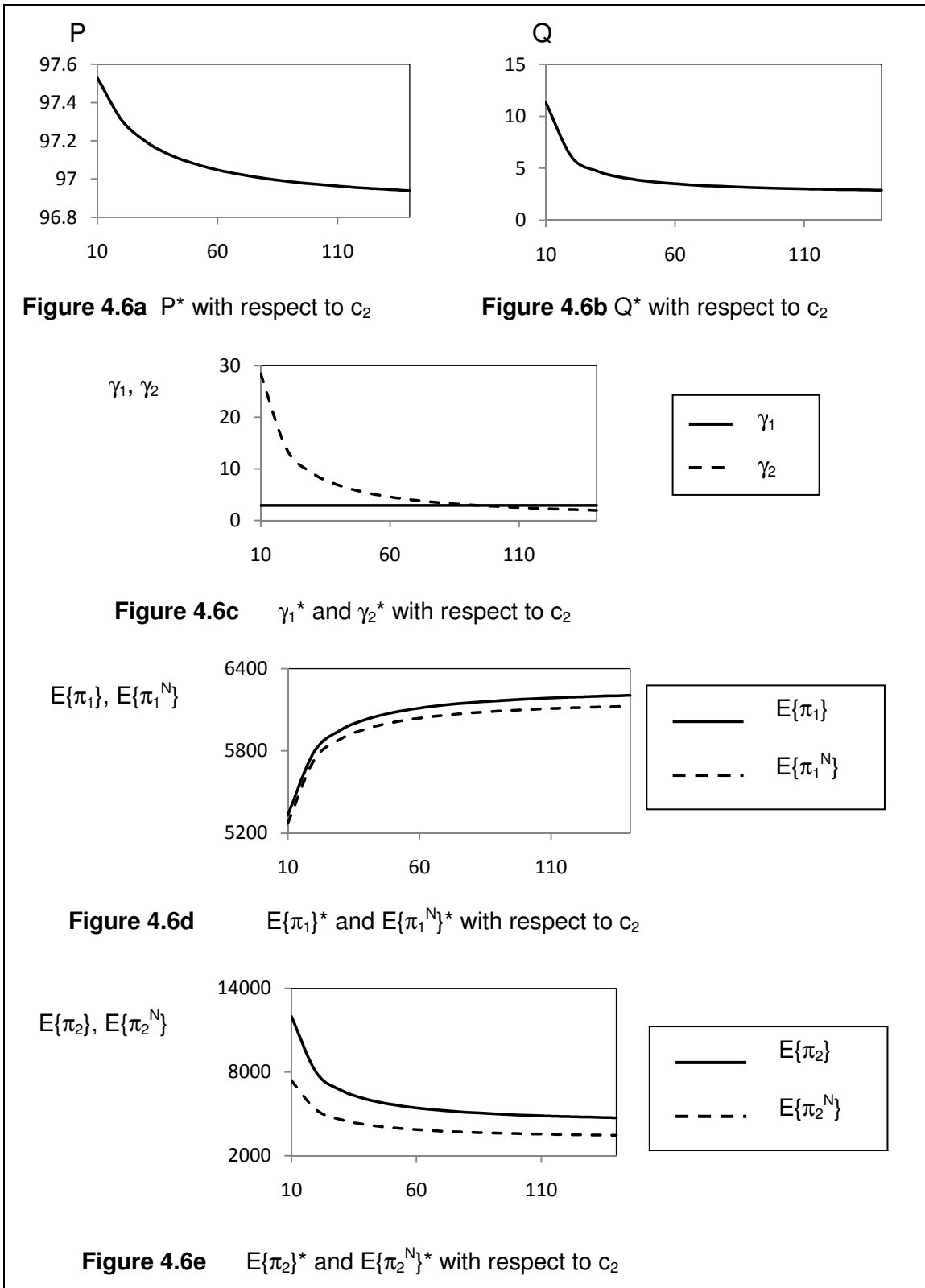


Figure 4.6 KT and KD decisions and the expected profits of firms 1 and 2 with respect to c_2

4.5.1.3 Experimental Analysis of Impact of Uncertainty

In this section, an exploration of the impact of the external (exogenous) environment and integration capabilities of the firms on the firm's decisions and competitive positions is analyzed. An experimental design approach, similar to the one developed in Gaimon and Ho (1994), is used to examine the effect of various exogenous conditions on a firm's optimal KT and KD decisions, and on their profits. Results are presented which characterize the effect on the optimal solutions due to the following conditions: (i) different expected valuation of firm 1 and firm 2's customer's for exceeding or falling short of the level of knowledge embedded by the competitor into the new product (ii) different expected integration capability of firm 2 of the knowledge purchased from firm 1 in the first period. Similar to the input values in section 4.5.1.2, the particular functions and input parameters we employ are inspired by the KM literature, interviews with managers from the automotive industry, and articles from academic and practitioner publications.

In order to isolate the effect of uncertainty on the firm's decisions, we controlled the other exogenous conditions so that any differences attributed to the different experimental factor settings. As the starting point of the experimental design, we consider Example 1, which is the base example introduced in section 4.5.1.2. In the stochastic numerical analysis, customer's valuation of knowledge embedded into the new product by a firm compared to its competitor (w_i^P), and the integration capability of firm 2 ($\beta^P[K_{10}, K_{20}]$) is a random variable satisfying a triangular distribution and defined at two levels: high and low uncertainty. It is assumed that a low level of uncertainty associated with each of these variables is characterized by a small standard deviation, whereas a relatively large standard deviation is used to represent a high level of uncertainty. The means of the exogenous demand distributions are assumed identical so that the results obtained are solely attributed to different levels of uncertainty.

Corresponding to each cell in the experimental design, values are randomly drawn from the assumed distributions and the model is solved for firms 1 and 2 for CD mechanism. One hundred replications are generated to guarantee stability of the results. The firm's decisions regarding knowledge creation, and their expected profits for the cases they cooperate and they do not cooperate are computed. These values are then

analyzed to obtain insights concerning the effects associated with the different levels of uncertainty in customer valuation and integration capability.

In order to examine the impact of the stochastic valuation of customers of firm 1 (w_1^P), two experiments are presented. For the first experiment, symmetric triangular distribution used is used for exogenous customer valuation. For the second experiment, a skewed triangular distribution is assumed (the mean is to the right of the mode) so that there is a greater chance of experiencing exogenous customer valuation in excess of the mode. The means of each distribution, however, are equal. The three parameters used to define the triangular distributions for the random variable w_1^P are given by: lower value, upper value and mode. These values and other relevant data are given in Table C.4. Skewed distributions used to represent customer's valuation have realistic interpretations. While a firm may be uncertain as to the exact customer valuation it will experience, it knows the lower bound (at least zero). However, the difference between the upper bound of the demand distribution and the mean may be much greater than the difference between the lower bound and the mean. This situation may be particularly realistic for new product introduction. Table C.5 compares the means obtained over all factor combinations.

The primary insights offered by the stochastic experiments involve the impact of uncertainty on the firm's first and second period decisions. From Table C.5, a high degree of uncertainty for firm 1's customers valuation of the knowledge level of firm 1 compared to the knowledge level of firm 2 is associated with a higher price set by firm 1 in period one and lower KD pursued by firm 1 in the second period. The amount of knowledge purchased by firm 2 and the amount of KD firm 2 pursues in the second period is not impacted by higher uncertainty. In terms of expected profit, if the uncertainty regarding customer valuation is larger, the expected profit for firm 1 if it cooperates with firm 2 through CD mechanism is smaller while the expected profit for firm 2 if it cooperates with firm 1 is larger. Moreover, if the distribution of customer valuation of firm 1 is skewed, the impact of uncertainty on firm 1's decisions is more pronounced. Meanwhile, skewed distribution drives firm 1 to pursue knowledge creation at a smaller amount, and results in a smaller expected profit for 2 if it engages in cooperation through CD mechanism.

The impact of firm 2's prediction of switching customer's valuation of level of knowledge is similar to that of w_1^P . However, as uncertainty increases, the expected profit of firm 1 if it cooperates decreases while, the expected profit of firm 2 if it

cooperates increases. Skewed distribution amplifies the results regarding expected profit. These results indicate that firms' own predictions for customers' valuation of competition results in larger expected profit for that firm under CD mechanism.

The impact of uncertainty regarding integration capability of firm 2 on the firm's KM decision and expected profits are examined through a similar approach. The input values for the three parameters used and other relevant data regarding the triangular distribution for $\beta^P[K_{10}, K_{20}]$ are given in Table C.6. When we analyze the results regarding impact of uncertainty associated with the integration capability of firm 2, given in Table C.7, we see that the KT and KD decision of firm 1 is not impacted by uncertainty associated with knowledge integration. The uncertainty drives firm 2 to purchase large amount of knowledge from firm 1 in period one and pursue larger amount of KD in period two. In addition, the expected profit of *both* firms is larger if the uncertainty associated with integration capability of firm 2 is larger. Meanwhile, skewed distribution reduces the impact of uncertainty.

4.5.2 Joint Development

4.5.2.1 Optimal Solution and Analysis

The JD model described in Section 4.4.2 is solved using backward induction. Proposition 9, below, illustrates the optimal KD pursued jointly by firms 1 and 2 in period two. From Proposition 9, we see that the KD pursued by the firms is a function of their joint knowledge level at the end of period one, as well as the expected customer valuation of the knowledge jointly embedded into the new product and the costs of KD.

***PROPOSITION 9.** The optimal amount of KD jointly pursued by the firms in the second period satisfies Equation (4.25):*

$$\gamma_{JD}^* = \frac{\delta_{JD} v_{JD}^P K_{JD1}^{\mu_{JD}}}{2c_{JD}} \quad (4.25)$$

From Equation (4.25), the optimal amount of joint KD for the firms is large (small) if: (i) the firm's probability of jointly developing a successful new product (δ_{JD}) is large (small); (ii) customers' expected valuation of the knowledge embedded jointly by the firms into the new product (v_{JD}) is large (small); (iii) the level of knowledge jointly dedicated to the JD project at the end of period one (K_{JD1}) is large (small); (iv) the

effectiveness of KD in increasing the joint knowledge level in period two (μ_{JD}) is large (small); and (v) the marginal cost of joint KD (c_{JD}) is small (large).

According to these results, the optimal amount of joint KD increases as the firms' capability to integrate shared knowledge ($\beta^P[K_{10}, K_{20}]$) increases, or the amount of returns on the knowledge shared by each firm on the joint knowledge level at the end of period one (θ_1, θ_2) increases. Thus, we observe a complementary relationship between the two means of knowledge creation, and observe that more-effective knowledge-sharing drives firms to pursue joint KD at a greater amount.

In Proposition 10, below, we describe the optimal amount of knowledge dedicated by firm 2 into the JD project in period one which is a function of the amount of knowledge dedicated by firm 1.

PROPOSITION 10. *The optimal amount of knowledge firm 2 dedicates to the JD project in the first period after observing the amount of knowledge dedicated by firm 1 satisfies Equation (4.26):*

$$1 + \frac{\mu_{JD} \delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^2 \mu_{JD}^{-1}}{2c_{JD}} = \frac{m_2}{(1-\lambda) \delta_{JD} v_{JD}^P \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2 Q_2^{\theta_2 - 1}} \quad (4.26)$$

We obtain interesting insights from Equation (4.26). A large (small) amount of knowledge dedicated by firm 1 into the JD project (Q_1) drives firm 2 to dedicate a large (small) amount of knowledge into the JD project (Q_2) if: (i) probability that the product jointly developed by the firms will have the features and functionally making it successful in the marketplace (δ_{JD}) is large (small); (ii) customer's valuation of joint knowledge (v_{JD}) is large (small); (iii) firms' common expectation of portion of knowledge that will be integrated into the JD project ($\beta^P [K_{10}, K_{20}]$) is large (small); (iv) portion of expected profit allocated to firm 1 (λ) is small (large); (v) marginal cost of loss of proprietary knowledge for firm 2 (m_2) is small (large); and (vi) the rate of returns to KS of knowledge dedicated by firm 2 (θ_2) is large (small).

Suppose conditions (i) or (ii) holds. Since large level of joint knowledge results in higher expected net revenue, the larger amount of knowledge shared by firm 1 drives firm 2 to dedicate a larger portion of its knowledge into the JD project. Similarly, the higher effectiveness of KS, given in condition (iii), results in a larger amount of

knowledge dedicated by firm 2 in period one if firm 1 shares a larger amount of knowledge. In addition, if the portion of expected profit allocated to firm 2 is large (condition (iv)), or sharing knowledge is less costly for firm 2 (condition (v)), firm 2 has less incentive to keep knowledge proprietary and shares a larger amount of knowledge per unit knowledge shared by firm 1. Meanwhile, if the increase in the level of joint knowledge at the end of period one, due to knowledge shared by firm 2, is small (as depicted in condition (vi)), firm 2 refrains from sharing a larger amount of knowledge with firm 1 and keeps a greater share of its knowledge proprietary.

The conditions given in Equation (4.27) and (4.28) must be satisfied for firms 1 and 2 to cooperate through the JD mechanism. These conditions mathematically depict the rational decision making of firms 1 and 2: Each firm is willing to cooperate with the other firm if the expected profit under the condition that it cooperates exceeds the expected profit under the condition that it develops the new product individually. Thus, for the firms to engage in JD mechanism, both firms expected profit if they cooperate should be larger than their expected profits if they don't cooperate.

PROPOSITION 11. *Firm 1 will cooperate with firm 2 through JD mechanism if the inequality in Equation (4.27) is satisfied. Firm 2 will cooperate with firm 1 through JD mechanism if the inequality in Equation (4.28) is satisfied.*

$$\begin{aligned} & \lambda \{ \delta_{JD} v_{JD}^P \left[\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} + \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{4c_{JD}} \right] - m_1 Q_1 \\ & \geq X^N K_{10} + \frac{(X^N)^2 K_{10}^{2\mu_1}}{4c_1} - \delta_1 \delta_2^N w_1^P \left(K_{20} + \frac{Y^N K_{20}^{2\mu_2}}{2c_2} \right) \end{aligned} \quad (4.27)$$

$$\begin{aligned} & (1 - \lambda) \{ \delta_{JD} v_{JD}^P \left[\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} + \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{4c_{JD}} \right] - m_2 Q_2 \\ & \geq Y^N K_{20} + \frac{(Y^N)^2 K_{20}^{2\mu_2}}{4c_2} - \delta_1 \delta_2^N w_2^P \left(K_{10} + \frac{X^N K_{10}^{2\mu_1}}{2c_1} \right) \end{aligned} \quad (4.28)$$

Equation (4.26) does not yield a closed-form solution for firm 2's KT decision (Q_2) which is expressed as a function of firm 1's KT decision (Q_1). However, if we assume that the returns to firms' KD in relation to their joint level of knowledge at the end of period one equals one half ($\mu_i=1/2$, $i \in \{1,2\}$), then the optimal solutions for firm 1 and

firm2 are dramatically simplified. The results obtained with $\mu_1=1/2$ are depicted in Proposition 12 (Equations (4.21)-(4.24)).

PROPOSITION 12. *Suppose $\mu_1=\mu_2=1/2$. The optimal portion of expected net revenue allocated by firm 1 to firm 1 is given in Equation (4.29). The optimal equilibrium amount of knowledge firm 2 will dedicate to the JD project in the first period after observing the amount of knowledge dedicated by firm 1 satisfies Equation (4.30). In addition, the optimal equilibrium amount of knowledge firm 1 will dedicate to the joint KD efforts in the first period satisfies Equations (4.31). Finally, amount of knowledge firm 1 will dedicate to the joint KD efforts in the first period satisfies Equation (4.32), respectively.*

$$\lambda = \frac{2\theta_2-1}{1-\theta_2}, \quad 0.52 < \theta_2 < 0.66 \quad (4.29)$$

$$Q_1^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD} (1-\theta_2)^{2-\theta_2}} \left(\frac{(2\theta_2-1)\theta_1}{m_1} \right)^{1-\theta_2} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1-\theta_1-\theta_2}} \quad (4.30)$$

$$Q_2^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD} (1-\theta_2)^{\theta_1+1}} \left(\frac{(2\theta_2-1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{1-\theta_1} \right]^{\frac{1}{1-\theta_1-\theta_2}} \quad (4.31)$$

$$\gamma_{JD}^* = \left[\left(\frac{\delta_{JD} v_{JD}^P}{c_{JD}} \right)^{2-\theta_1-\theta_2} \frac{\beta^P [K_{10}, K_{20}] (4c_{JD} + \delta_{JD} v_{JD}^P)^{\theta_1+\theta_2}}{4(1-\theta_2)^{2\theta_1+\theta_2}} \left(\frac{(2\theta_2-1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{2(1-\theta_1-\theta_2)}} \quad (4.32)$$

From Equations (4.29) to (4.32), we obtain important insights about firm 1 and firm 2's KM decisions in the first and second periods. In Propositions 13 and 14, we present results of analytic sensitivity analysis that provide important insights into the KM strategies pursued by the firms. Proposition 13 relates the drivers of effectiveness of KS with firm 1's decision on profit allocation (λ). Proposition 14 depicts the impact of several firm and market characteristics on the firm's individual knowledge-sharing decisions (Q_1 and Q_2), and joint KD decision (γ_{JD}).

PROPOSITION 13. Firm 1 optimally allocates a large (small) portion of the expected net revenue to itself (λ) if the rate of returns to KS of the amount of knowledge shared by firm 2 (θ_2) is large (small).

PROPOSITION 14. Suppose any of the following conditions hold:

- (i) The probability that the new product developed jointly by the firms will have the features and functionality that make it successful in the marketplace (δ_{JD}) is large (small);
- (ii) The expected valuation of customers of the knowledge embedded jointly by the firms into the new product (v_{JD}^P) is large (small);
- (iii) Both firms' prediction of the extent that knowledge resources shared by one firm can be integrated with the knowledge resources shared by the other firm ($\beta^P[K_{10}, K_{20}]$) is large (small);
- (iv) The initial level of firm 1 or 2 (K_{10} or K_{20}) is large (small);
- (v) The reduction in revenue from the loss of proprietary knowledge firm 1 or firm 2 incurs when it shares its knowledge with the other firm (m_1 or m_2) is small (large).

Then:

- (a) The amount of knowledge shared by firm 1 in the first period to be dedicated to the JD project (Q_1) is larger (smaller);
- (b) The amount of knowledge shared by firm 2 in the first period to be dedicated to the JD project (Q_2) is larger (smaller);
- (c) The amount of KD pursued jointly by the firms in the second period (γ_{JD}) is larger (smaller).

Proposition 13 reveals a key result: The portion of expected net revenue optimally allocated by firm 1 (λ) is driven only by the effectiveness of the knowledge amount shared by firm 2 on the knowledge jointly dedicated to the NPD project at the end of period one (θ_2). If the KS is effective, due to large rate of returns to KS of the amount of knowledge shared by firm 2, then firm 1 allocates a large portion of profit to itself. This result occurs due to firm 1's incentive to take advantage of an effective KS process early on, through allocating a larger portion of the expected net revenue to itself.

From Proposition 14, we obtain important insights about the firms' decisions regarding their KM strategies. First, suppose that the probability that the new product developed jointly by the firms will have the features and functionality to be successful in the marketplace (δ_{JD}) is large. This condition drives firm 1 (leader) to allocate a large amount of knowledge to the JD project (Q_1), which leads firm 2 to also share a large amount of knowledge (Q_2). With the large level of knowledge dedicated to the JD project at the end of the first period, the value of joint KD in the second period (γ_{JD}) is enhanced and occurs at a greater amount. Thus, the firms jointly embed a large level of knowledge into the new product. The firms pursue the same strategy if the expected customers' valuation of the knowledge embedded into the new product (v_{JD}^P) is large. This result occurs because developing a superior product drives larger expected net revenue in the marketplace and larger expected net revenue.

Next, suppose that the initial knowledge levels of either firm are large at the beginning of the first period. Then, the firms are driven to dedicate large amounts of knowledge to the joint NPD project and they jointly pursue a greater amount of KD. This result occurs since large initial level of knowledge of either firm drives large integration capability for firms ($\beta^P[K_{10}, K_{20}]$). Effective KS drives large knowledge levels that are jointly dedicated to the NPD project at the end of the first period. In addition, a large amount of KD pursued jointly in the second period drives firms to embed more knowledge into the new product, which leads to greater expected profits for both firms.

Another interesting insight is obtained when we analyze the impact of the cost incurred by firms due to loss of proprietary knowledge (m_1 or m_2). First, suppose firm 1 incurs a large marginal cost due to loss of sole ownership of knowledge. Under this condition, firm 1, who is the initial decision-maker in the first period, dedicates a small amount of knowledge to the JD project, in order to reduce the cost of loss of proprietary knowledge. In addition, firm 2 also shares a small amount of knowledge with firm 1 in period one. Since a smaller level of knowledge is dedicated to the JD project at the end of the first period, the value of KD is smaller, and firms jointly pursue KD at a smaller amount. Thus, the firms embed lower levels of knowledge to the new jointly developed product. As a result, the expected net revenue earned from the new product is smaller. The impact of the cost incurred by firm 2 due to loss of proprietary knowledge is similar. This result shows that the large cost incurred by one firm due to sharing knowledge with a competitor discourages both firms from dedicating knowledge to the JD project or pursuing a high amount of KD.

4.5.2.2 Numerical Analysis

In this section, we introduce results based on numerical sensitivity analysis. We present one base example, Example 2, to reflect the decision-making environment of JD mechanism. In addition, we present three variations of Example 2. The purpose of the numerical examples is to illustrate some key analytical results and to extend the analytical results by providing insights on the impact of several parameters on the firms' KM decisions and on the profit earned by the firms.

The particular functions and input parameters we employ are inspired by the KM literature, interviews with managers from the automotive industry, and articles from academic and practitioner publications. Table C.8 contains a detailed account of all functional forms and input parameter values. For the numerical example illustrating the JD mechanism, due to different input values for θ_2 , c_{JD} and θ_1 , we obtain different solutions for firm 1's decision regarding the allocation of expected net revenue, the firms' period one knowledge-sharing decisions and period two joint KD decision, as well as the solutions regarding joint and individual expected profit solutions. Table C.9 summarizes the results of Example 2. Figures 4.7 to 4.9 illustrate key managerial insights.

The situation reflected in Example 2 is based on the following parameter settings. Similar to the firms introduced in Example 1, both firms 1 and 2 have a solid foundation of knowledge at the outset of the NPD project, and firm 1's initial knowledge level exceeds the initial knowledge level of firm 2 ($K_{10}=100$, $K_{20}=80$). The integration capability of the firms for KS ($\beta^P[K_{10},K_{20}]$) is moderately large. However, we assume that the rate of returns to KS of knowledge shared by firm 2 (θ_2) is significantly larger than the rate of returns to KS of knowledge dedicated by firm 1 (θ_1). In addition, since the firms jointly develop the product and do not compete with each other in the end product market, the customers' valuation of knowledge embedded jointly by the firms (v_{JD}) is significant.

Example 2a is identical to Example 2, except that we vary the rate of returns to KS of knowledge shared by firm 2 (θ_2) between 0.52 and 0.66 (since from Equation (4.29), we know that $0.52 < \theta_2 < 0.66$). Firm 1 engages in KS for values of θ_2 between 0.56 and 0.65, and firm 2 engages in KS for values of θ_2 between 0.52 and 0.64, as illustrated in Figures 4.7d and 4.7e, respectively. Thus, for values of θ_2 smaller than 0.56 and larger than 0.64, firms develop the new product individually, without engaging in cooperation with the other firm. From Figure 4.7a, we see that the portion of expected net revenue allocated to firm 1 in the first period (λ) increases as the rate of returns to

KS of knowledge shared by firm 2 increases. Thus, firm 1 claims a larger portion of the profit in advance, in order to increase the gains from the possibility of being able to embed a high level of knowledge into the new product. Meanwhile, for smaller values of θ_2 , the knowledge amount dedicated by each firm to the JD project increases as θ_2 increases; for larger values of θ_2 , the knowledge amount dedicated by each firm to the JD project decreases as θ_2 increases. Specifically, firm 1 dedicates the largest amount of knowledge when $\theta_2=0.62$, and firm 2 dedicates the largest amount of knowledge when $\theta_2=0.61$. Similarly, the amount of KD pursued jointly by the firms in the second period increases as θ_2 increases for $0.52<\theta_2<0.61$ and decreases as θ_2 increases for $0.61<\theta_2<0.66$. This result occurs because of two reasons. First, for smaller values of θ_2 , the firms substitute for the small effectiveness of knowledge creation by sharing larger amount of knowledge and pursuing a higher amount of KD. For larger values of θ_2 , due to the increased effectiveness of KS (and thus KD), the firms focus less on knowledge creation. Second, as θ_2 increases beyond 0.61, the portion of expected net revenue allocated to firm 1 increases; thus, firm 1 earns the same expected profit by dedicating a lower amount of knowledge to the JD project. As a result, firm 2 earns a smaller portion of the expected net revenue, and is less willing to share knowledge with firm 1. A smaller level of knowledge at the end of period one drives the firms to pursue a smaller amount of KD in the second period. It is important to note that, for smaller values of rate of returns to KS of knowledge shared by firm 2, the amount of knowledge dedicated by firm 1 into the JD project exceeds the amount of knowledge dedicated by firm 2; for larger values of θ_2 , the amount of knowledge dedicated by firm 2 exceeds the one dedicated by firm 1. As illustrated in Figures 4.7d and 4.7e, these KM strategies are reflected in the expected profits earned by firms 1 and 2, which also follow a “first increase then decrease” pattern.

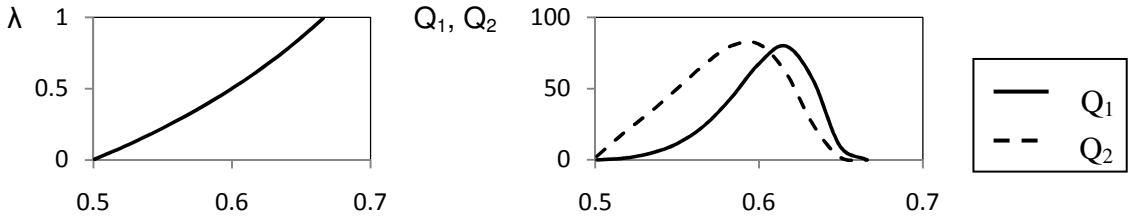


Figure 4.7a λ^* with respect to θ_2 **Figure 4.7b** Q_1^* and Q_2^* with respect to θ_2

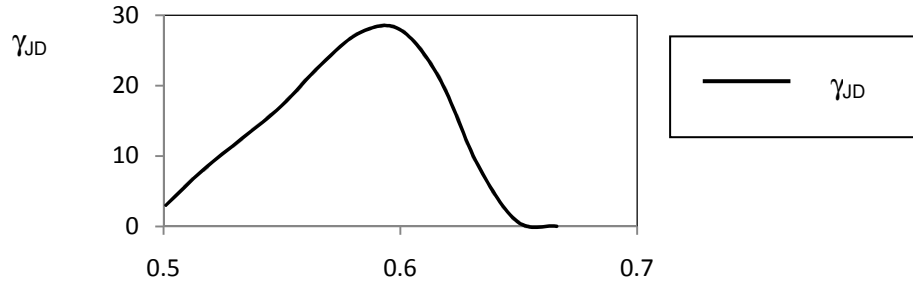


Figure 4.7c γ_{JD}^* with respect to θ_2

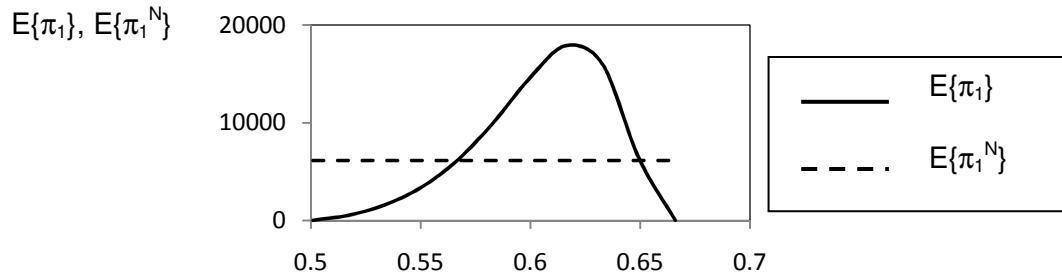


Figure 4.7d $E\{\pi_1\}^*$ and $E\{\pi_1^N\}^*$ with respect to θ_2

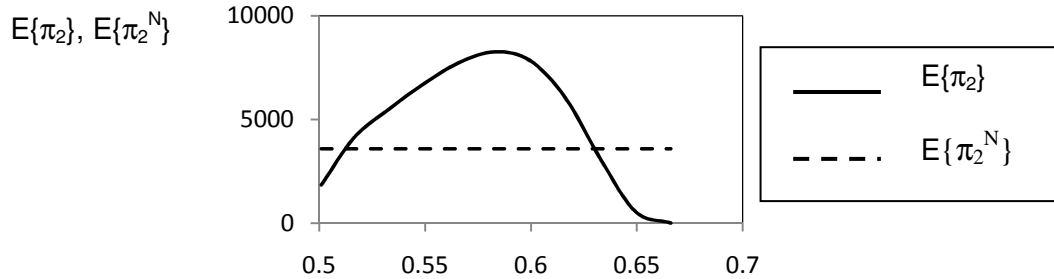


Figure 4.7e $E\{\pi_2\}^*$ and $E\{\pi_2^N\}^*$ with respect to θ_2

Figure 4.7 KS and KD decisions and the expected profits of firms 1 and 2 with respect to θ_2

The inputs for Example 2a are the same as Example 2, except that we vary the value of the rate of returns to KS of knowledge shared by firm 1 (θ_1) between 0 and 0.38 (since, for Example 2, we set $\theta_2=0.62$, we have $\theta_1<0.38$). The portion of the expected net revenue allocated to firm 1 (λ) is 0.63 and does not change as θ_1 changes, since λ is a function of θ_2 only (Figure 4.8a). However, as θ_1 , the amount of knowledge dedicated to the JD project by each firm (Q_1, Q_2) increases (Figure 4.8b). Since KS is more effective, the firms share a higher amount of knowledge, which increases the value of knowledge creation in the second period. Thus, for larger values θ_1 the amount of KD pursued jointly by the firms (γ_{JD}) is larger (Figure 4.8c). As a result, the knowledge embedded jointly into the new product is larger, resulting in higher expected profits for each firm (Figures 4.8d and 4.8e).

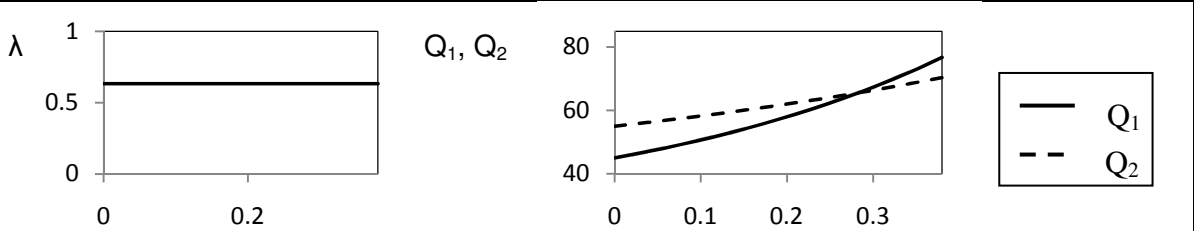


Figure 4.8a λ^* with respect to θ_1 **Figure 4.8b** Q_1^* and Q_2^* with respect to θ_1

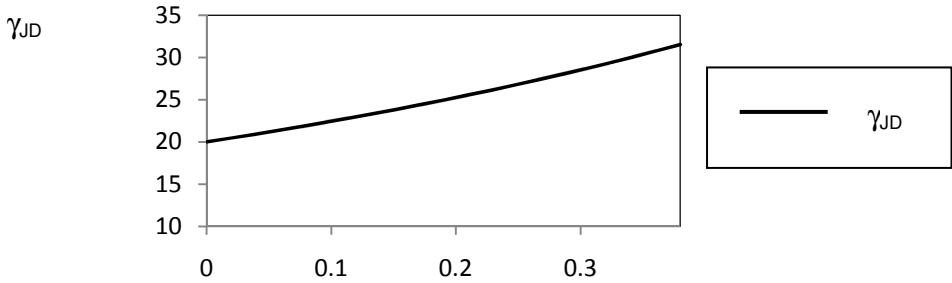


Figure 4.8c γ_{JD}^* with respect to θ_1

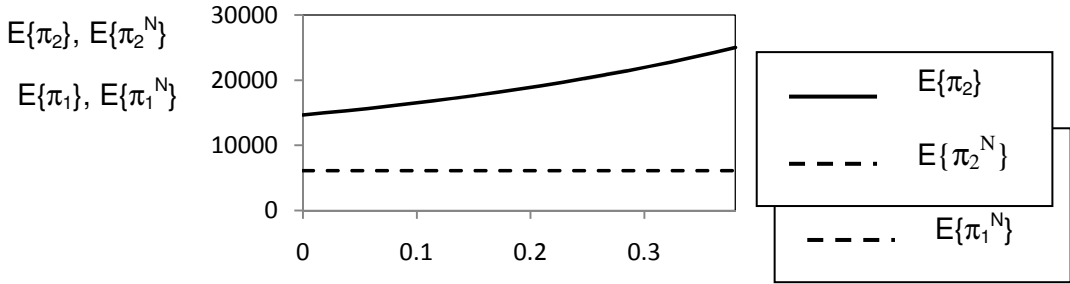


Figure 4.8d $E\{\pi_1\}^*$ and $E\{\pi_1^N\}^*$ with respect to θ_1

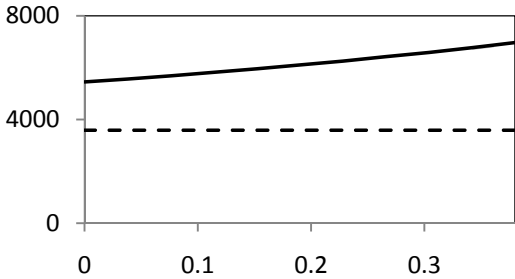


Figure 4.8e $E\{\pi_2\}^*$ and $E\{\pi_2^N\}^*$ with respect to θ_1

Figure 4.8 KS and KD decisions and the expected profits of firms 1 and 2 with respect to θ_1

For the third variation of Example 2, Example 2c, the same inputs are used, except that the value of cost of joint KD (c_{JD}) is varied between 20 and 220. From Figures 4.9d and 4.9e, we can see that for $20 \leq c_{JD} \leq 220$, firms 1 and 2 find it optimal to cooperate through JD mechanism rather than pursuing the NPD projects without cooperation. However, it is important to note that the additional profits earned by cooperating through the JD mechanism decreases as c_{JD} increases. Further, if the cost of joint KD exceeds a threshold value, it is optimal for firms to pursue NPD projects individually. Although the portion of expected profit allocated to firm 1 (λ) does not divert from 0.63 as c_{JD} increases, the amount of knowledge shared by the firms (Q_1 and Q_2) and the rate of joint KD pursued in period two decreases (Figures 4.9a to 4.9c). Since the value of KD in the second period is small, the firms refrain from dedicating high amount of knowledge in the first period. Thus, as the joint KD becomes more costly, the expected profit for each firm decreases (Figures 4.9d and 4.9e).

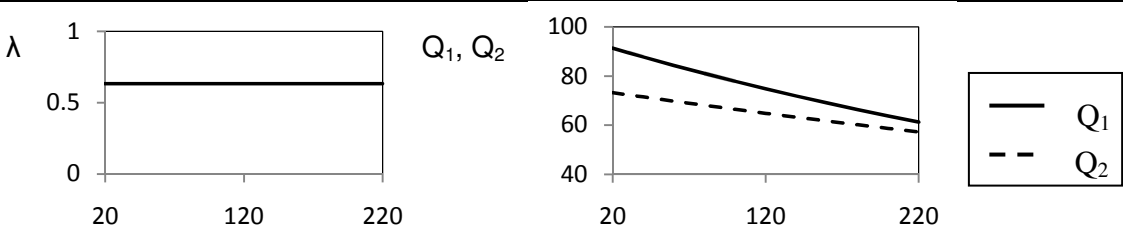


Figure 4.9a λ^* with respect to c_{JD} **Figure 4.9b** Q_1^* and Q_2^* with respect to c_{JD}

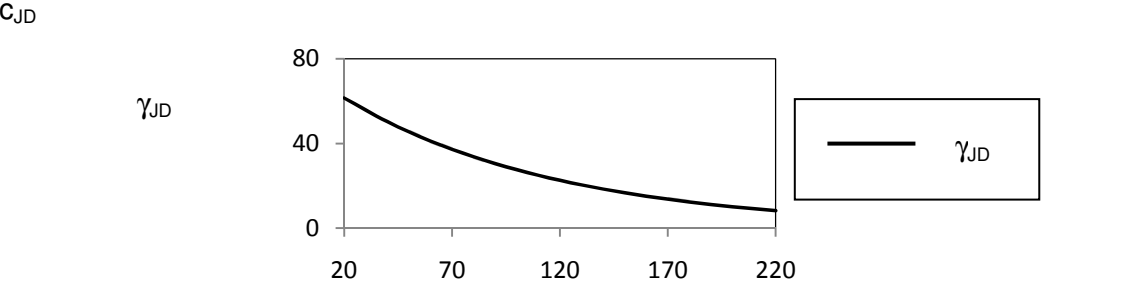


Figure 4.9c γ_{JD}^* with respect to c_{JD}

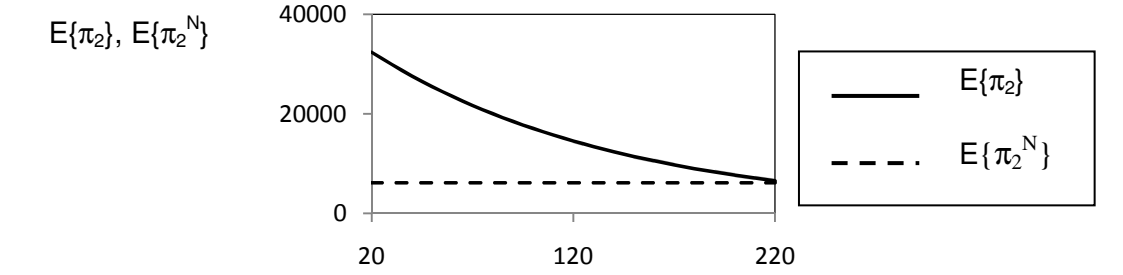


Figure 4.9d $E\{\pi_1\}^*$ and $E\{\pi_1^{N_1}\}^*$ with respect to c_{JD}

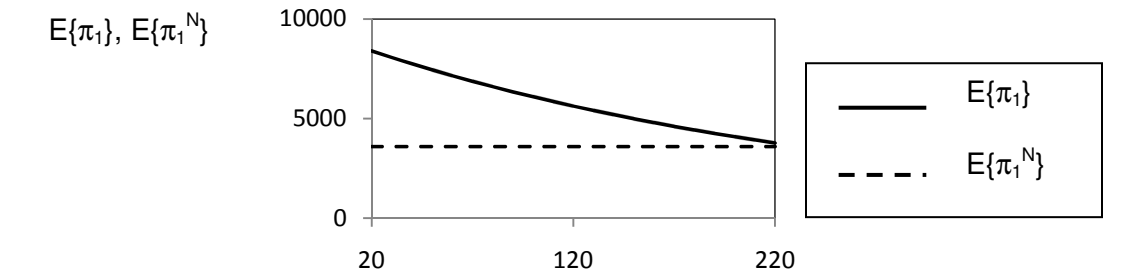


Figure 4.9e $E\{\pi_2\}^*$ and $E\{\pi_2^{N_1}\}^*$ with respect to c_{JD}

Figure 4.9 KS and KD decisions and the expected profits of firms 1 and 2 with respect to c_{JD}

4.5.2.3 Experimental Analysis of Impact of Uncertainty

In this section, an exploration of the impact of the external (exogenous) environment and integration capabilities of the firms on the firm's decisions and competitive positions is provided. Similar to the experimental analysis for the CD mechanism given in section 4.5.1.3, the effect of various exogenous conditions on a firm's optimal KS and joint KD decisions, and on their profits are examined. Results are presented which characterize the effect on the optimal solutions due to the following conditions: (i) different expected customer valuation of the knowledge jointly embedded by the firms into the new product, and (ii) different expected integration capability of firm 2 of the knowledge purchased from firm 1 in the first period.

As the starting point of the experimental design, we consider Example 2, which is the base example introduced in section 4.5.2.2. In the stochastic numerical analysis, customer's valuation of knowledge jointly embedded into the new product (v_{JD}^P), and the integration capability of the firms ($\beta^P[K_{10}, K_{20}]$) is a random variable satisfying a triangular distribution and defined at two levels: high and low uncertainty. It is assumed that a low level of uncertainty associated with these variables is characterized by a small standard deviation, whereas a relatively large standard deviation is used to represent a high level of uncertainty. The means of the exogenous demand distributions are assumed identical so that the results obtained are solely attributed to different levels of uncertainty.

In order to examine the impact of the stochastic valuation of customers of firm 1 (v_{JD}^P), two experiments are presented. First, the triangular distribution used for exogenous customer valuation is symmetric. Second, a skewed triangular distribution is assumed (the mean is to the right of the mode) so that there is a greater chance of experiencing exogenous customer valuation in excess of the mode. The means of each distribution, however, are equal. The three parameters used to define the triangular distributions for the random variable v_{JD}^P are given in Table C.10.

From Table C.11, the initial decision of the leader, the portion of expected profit allocated to firm 1 is not impacted by the uncertainty of customer valuation. According to the results, larger uncertainty regarding the customers' valuation of knowledge jointly embedded by the firms is associated with larger amount of knowledge dedicated by the firms into the JD project in period one, and larger amount of joint KD pursued in period two. However, the expected profit under the JD agreement is lower for both firms if uncertainty regarding customer valuation is large. This result indicates that uncertainty

drives the firms to jointly embed larger level of knowledge into the new product by pursuing knowledge creation at a large amount, while the gains in the marketplace from developing a superior product is outweighed by costs of knowledge creation. It is important to note that skewed distribution for high uncertainty experiment amplifies the results regarding the firms KS and KD decisions, while curtailing the reduction effect of uncertainty on the expected profit.

The impact of uncertainty regarding integration capability of the firms on the KM decision and expected profits are examined through a similar approach. The input values for the three parameters used and other relevant data regarding the triangular distribution for $\beta^P[K_{10}, K_{20}]$ are given in Table C.12. When we analyze the results regarding impact of uncertainty associated with the integration capability of firm 2, given in Table C.13, we see that the impact is similar to that of expected customer valuation: larger uncertainty of the integration capability of the firms is associated with larger amount of knowledge dedicated by the firms into the JD project, and larger amount of joint KD. Conversely, the expected profit for the firms if they cooperate through JD mechanism is smaller. Moreover, skewed distribution amplifies the effects regarding KS and KD, while mediates the reduction in the expected profits of the firms due to uncertainty.

4.5.2.4 Simultaneous Decision Making

In the model introduced in Section 4.5.2, whose analytical solutions and numerical and experimental analysis are provided in Sections 4.5.2.1, 4.5.2.2, and 4.5.2.3, we assume that firms make knowledge-sharing decisions sequentially. Firm 1, who is the leader, makes the profit allocation decision, followed by the initial decision regarding the amount of knowledge to dedicate to the JD project. Then, firm 2 responds by making its knowledge-sharing decision. In the second period, firms jointly set the amount of KD to be pursued. In this section, we approach the JD mechanism from a different angle, and we assume that after firm 1 makes the profit allocation decision, the firms make knowledge-sharing decisions simultaneously. Similar to the model introduced in the previous section, we assume firms jointly make the second period decision.

When we set the impact of the firms' joint knowledge level at the end of the first period (K_{JD1}) on the effectiveness of KD to power $\frac{1}{2}$ ($\mu_i=1/2$), we get the solutions for the decisions for firms 1 and 2, depicted in Proposition 15.

PROPOSITION 15. Suppose $\mu_1=\mu_2=1/2$ and firms 1 and 2 make KS decisions simultaneously. The optimal portion of expected net revenue allocated by firm 1 to firm 1 is given in Equation (4.33). The optimal equilibrium amount of knowledge firm 2 will dedicate to the JD after observing the amount of knowledge dedicated by firm 1 in the first period satisfies Equation (4.34). In addition, the optimal equilibrium amount of knowledge firm 1 will dedicate to the joint KD effort in the first period satisfies Equations (4.35). Finally, amount of knowledge firm 1 will dedicate to the joint KD effort in the first period satisfies Equation (4.36), respectively.

$$\lambda = \frac{2\theta_2-1}{1-\theta_2}, \quad 0.52 < \theta_2 < 0.66 \quad (4.33)$$

$$Q_1^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD}(1-\theta_2)} \left(\frac{(2\theta_2-1)\theta_1}{m_1} \right)^{1-\theta_2} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1-\theta_1-\theta_2}} \quad (4.34)$$

$$Q_2^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD}(1-\theta_2)} \left(\frac{(2\theta_2-1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{1-\theta_1} \right]^{\frac{1}{1-\theta_1-\theta_2}} \quad (4.35)$$

$$\gamma_{JD}^* = \left[\left(\frac{\delta_{JD} v_{JD}^P}{c_{JD}} \right)^{2-\theta_1-\theta_2} \frac{\beta^P [K_{10}, K_{20}]}{4} \left(\frac{4c_{JD} + \delta_{JD} v_{JD}^P}{1-\theta_2} \right)^{\theta_1+\theta_2} \left(\frac{(2\theta_2-1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{2(1-\theta_1-\theta_2)}} \quad (4.36)$$

Firm 1's profit allocation decision, given in Equation (4.33), is the same solution in Equation (4.29). From Equations (4.34) to (4.36), most of the results regarding the impact of firm and market characteristics on the firms' KM decisions are the same as the results given in Section 4.5.2.1 and 4.5.2.2. The only parameter whose impact of firms' KS and KD decision differs from the sequential model is the rate of returns to KS of knowledge shared by firm 2 (θ_2).

The results regarding the impact of θ_2 on the firms' KM decisions are obtained through a numerical analysis. Specifically, we consider the base Example 2 introduced in Section 4.5.2.2 and generate different input values for θ_2 . Figure 4.10 illustrates the impact of various values of θ_2 on firm 1's profit allocation decision, the firms' decisions

regarding KS and KD, and the expected profit for firms 1 and 2. From Figure 4.10a, the portion of expected net revenue allocated to firm 1 increases as the rate of returns to KS of knowledge shared by firm 2. The amount of knowledge shared by firm 1 increases as the rate of returns to KS of knowledge shared by firm 2 increases for values of θ_2 smaller than 0.59 and decreases as the rate of returns increases for values of θ_2 larger than 0.59. Similarly, the amount of knowledge shared by firm 1 increases as the rate of returns to KS of knowledge shared by firm 2 increases for values of θ_2 smaller than 0.61 and decreases as the rate of returns to KS of knowledge shared by firm 2 increases for values of θ_2 larger than 0.61. Thus, the relationship between the amount of knowledge shared by the firms and the effectiveness of KS follows a similar pattern to the one in Example 2a, where the decision making was sequential. However, the amount of knowledge shared for each value of θ_2 smaller if the decision making is simultaneous, compared to the sequential game. As the rate of returns to KS of knowledge shared by firm 2 increases, the amount of KD jointly pursued by the firms, and the expected profit earned by each firm also initially increases then decreases from the Figures 4.10c, 4.10d and 4.10e, respectively. It is important to note that although the amount of joint KD is relatively similar in value to the sequential game, the expected profit for each firm is smaller in value for each θ_2 , since the amount of knowledge shared by firm 2 is smaller. Thus, the range of θ_2 for which firms engage in cooperation through JD is smaller (Figures 4.10d and 4.10e).

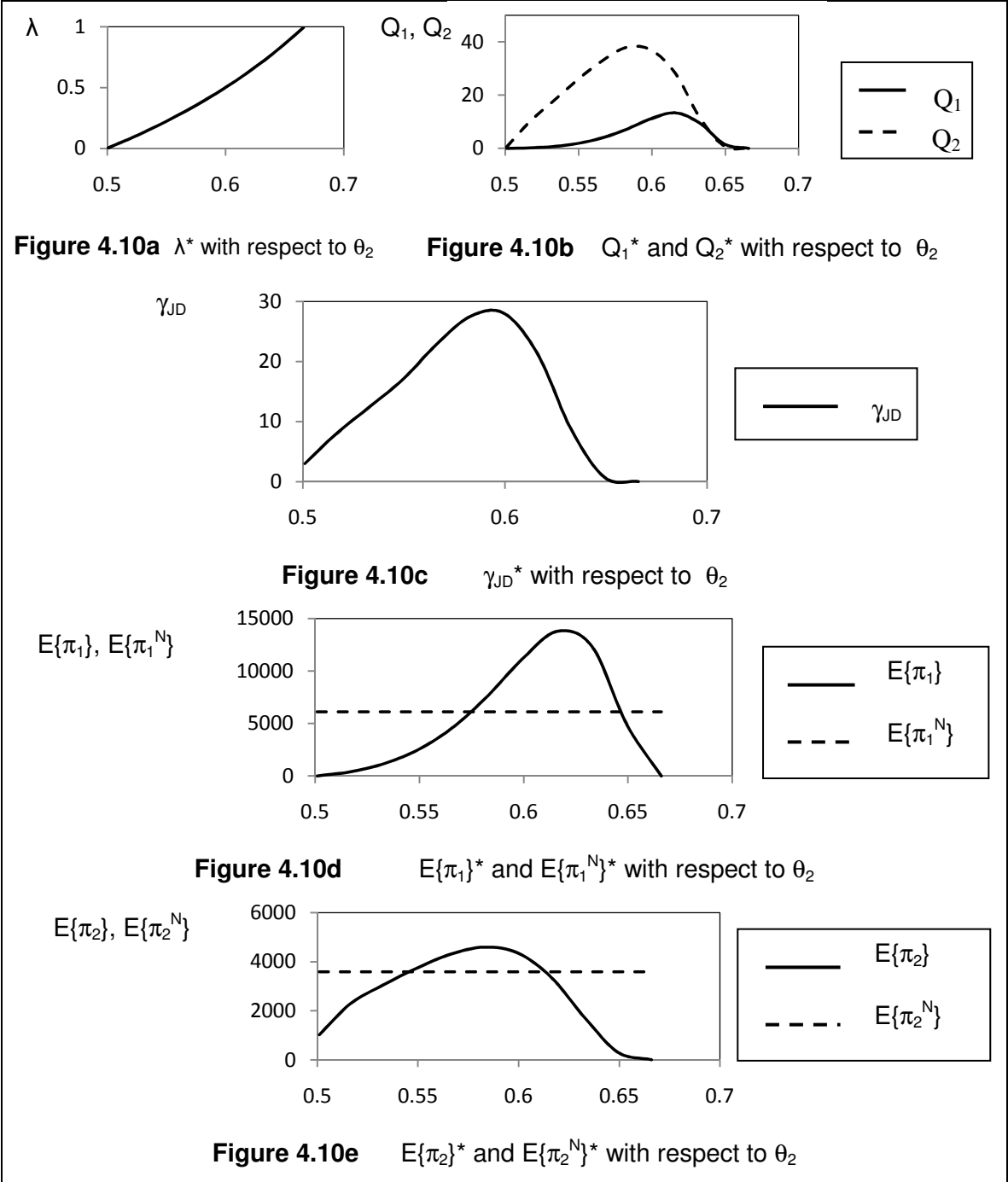


Figure 4.10 KS and KD decisions and the expected profits of firms 1 and 2 with respect to θ_2 in simultaneous decision making setting

4.6 Conclusions and Future Research

In this chapter, we provide a framework for analyzing the knowledge flow between two competing firms engaged in cooperative agreements. We introduce two two-period game theoretical models that explore KM strategies that drive NPD for two profit-maximizing firms. Knowledge management strategies include the KT or KS between firms and the KD pursued either by each firm independent of its competitor, or jointly. Furthermore, we examine two mechanisms of cooperation between the competitors: CD and JD agreements. We develop analytical models that examine the KM strategies for two firms that cooperate through the CD or JD mechanism. We extend the results of analytical analysis by developing numerical examples. Our results provide insights to the factors that drive each firm's KM decisions including the effects of firm and market-specific characteristics.

4.6.1 Competitive Development

Key analytical insights are obtained demonstrating the interactions between each firm's period one KT decisions. In a surprising result, we find that if firm 1 charges a lower price for its knowledge, firm 2 may purchase either a larger or smaller amount of knowledge. If the valuation of knowledge by firm 2's customers is large, a lower price set by firm 1 drives firm 2 to purchase a larger amount of knowledge. Meanwhile if the valuation of knowledge by firm 2's customers is small, a lower price set by firm 1 drives firm 2 to purchase a smaller amount of knowledge. According to this result, if the level of knowledge of firm 2 is not valued highly by the customers in the marketplace, firm 2 may refrain from focusing on KT although the price set by firm 1 may be lower.

We also find that firm 2 purchases less knowledge if firm 1 charges a low price and firm 1's probability of successfully developing the new product is small or the effectiveness of transferring knowledge from firm 1 is small. Similar to the impact of direct competition mentioned above, if firm 2 is not likely to develop a successful product, or does not have high gains due to KT, small price charged by firm 1 may drive firm 2 away from engaging in KT, since expected value of transferring knowledge is small. Furthermore, if the cost of KD in period two is larger, firm 2 focuses on transferring a larger (small) amount of knowledge from firm 1 in period one, despite a high (small) price set by firm. According to this result, large cost of KD for firm 2 either drives firm 2 to focus on KT as opposed to KD as a means of knowledge creation, or to

pursue knowledge creation at a smaller rate and develop an inferior product to reduce costs.

Additional analytic results are obtained under the modest simplifying assumption that the rate of diminishing returns to KD associated with each firm's level of knowledge equals one-half. We find that if the expected capability of firm 2 to integrate knowledge transferred from firm 1 is large, then firm 2 purchases a larger amount of knowledge in period 1 and pursues more KD in period 2. This result highlights the complementary relationship between the two means of knowledge creation for firm 2. However we also find that the knowledge integration capability of firm 2 does not impact the price set by firm 1 in the first period or the amount of KD pursued by firm 1 in the second period. Thus, the expected net revenue of firm 1 on the competitive dimension is smaller while the expected net revenue earned due to selling knowledge to firm 1 is larger, despite the same price set by firm 1. The expected profit earned by firm 1 is larger although the KT cost is larger. The impact of the rate of returns to KT of firm 2's initial knowledge level is similar to the results for expected integration capability.

We obtain insights on the impact of direct competition between firms 1 and 2 by exploring the customers' valuation of the difference between the knowledge each firm embeds into their product (switching customers). If the switching customers' valuation of firm 2 knowledge is high, then the price set by firm 1 in period one is smaller and firm 2 pursues more KT in period one and more KD in period 2. Meanwhile, the amount of firm 1's KD is not impacted. Thus, if the level of direct competition is high, firm 1's strategy is to increase its expected revenue by driving firm 2 to purchase a larger amount of knowledge; whereas firm 2 focuses on increasing expected net revenue by embedding more knowledge into the product offered in the marketplace. This result occurs since gains due to developing a superior product is outweighed by the gains through KT, firm 1 focuses on earning revenue from knowledge sold to firm 2. Similarly, we show that if the cost of the loss of proprietary knowledge suffered by firm 1 is small, the firms are driven to follow the same strategy. Since the gains due to selling knowledge to firm 2 outweighs the cost of loss of sole ownership of knowledge for firm 1, firm one focuses on earning revenue from KT. Meanwhile, since cost of KT is smaller for firm 2, firm 2 focuses on embedding knowledge into the new product, and on earning large expected revenue in the marketplace.

Beyond the analytic results reported above, numerical results are obtained on the effect of the probability that firm 1 successfully develops the new product. One might

expect that with a high probability, firm 1 has the confidence to transfer more knowledge to firm 2, and thereby charges a lower price. This is not the case. If the probability is high, firm 1 pursues a large amount of KD in period 2 and sets a higher price for knowledge transfer in the first period. The higher price reduces the amount purchased by firm 2, while the amount of KD pursued by firm 2 does not change. Therefore, as the probability of firm 1 succeeding in its NPD project increases, firm 1 pursues a more aggressive KD strategy in period 2 and firm 2 is driven to an inferior competitive position overall. As a result, the expected profit for firm 1 is smaller while the expected profit for firm 2 is smaller. Meanwhile, if the probability that firm 2 successfully develops the new product is large, firm 2 sets a smaller price in period one, driving firm 2 to purchase more knowledge. In addition, firm 2 pursues more KD in the second period, and thus, is driven to focus on developing a superior product. Firm 1, whose KD is not impacted by the probability that firm 2 successfully develops the new product focuses on earning larger revenue from KT. However, through numerical analysis we show that the expected profit of firm 1 is smaller while the expected profit of firm 2 is larger.

Numerical results are obtained that illustrate the impact of the cost of KD pursued by firm 2. We find that if the cost is high, firm 2 offers an inferior product to the marketplace at the end of period 2; firm 1's product features do not change. Specifically, since firm 2 pursues less KD in the second period, there are less overall benefits from KT in period one. The lesser pursuit of KD in period 2 makes firm 2 less of a competitive threat to firm 1. To raise its revenue and with less fear of direct competition, firm 1 seeks to entice firm 2 to undertake KT in period 1 and charges a lower price. The lower price, however, only serves to lessen the reduction in KT pursued by firm 2. Thus, whereas firm 2's cost reducing strategy leads it to deliver an inferior product to the marketplace, the level of knowledge embedded into firm 1's product does not change. Although the revenue generated from the lower amount of KT reduces firm 1's profit, firm 1's expected net revenue due to switching customers increases. As a result, the expected profit of firm 1 is larger while the expected profit of firm 2 is smaller.

It is important to note two results regarding the impact of the cost of KD for firm 2. First, if the cost of KD for firm 2 is significantly large, firm 2 does not enter into cooperation with firm 2 through CD mechanism. Through focusing its resources in developing the product without cooperation, firm 2 is able to avoid the cost of KT, and earn larger expected profit. Meanwhile, since large cost of KD for firm 2 drives firm 2 to not engage in KT, firm 2's expected profit is smaller if the firms do not cooperate. Thus,

large cost of KD for firm 2 drives firm 2 to not cooperate with firm 1, while firm 1 would have been better off engaging into CD with firm 1. Second, the KM strategies of the firms are more sensitive to the cost of KD for firm 2 compared to the cost of KD for firm 1.

Based on extensive numerical experimentation, we explore the impact of uncertainty associated with the valuation of knowledge by firm 1's switching customers. Assuming the distribution for uncertainty is symmetric around the mean, with a high degree of uncertainty; firm 1 charges a high price for KT in period one and undertakes less KD in period two. In contrast, the high uncertainty has no effect on firm 2's KT or KD decisions. As a result, firm 1 develops an inferior product, while the quality of the product introduced by firm 2 is not impacted. Although the revenue earned by firm 1 due to KT is larger, since the expected net revenue earned from the product in the marketplace, the expected profit of firm 1 is smaller. As a result, the expected profit for firm 2 is larger despite large cost of KT. According to this result, uncertainty regarding switching customers' valuation of firm 1 drives firm 1 to focus on earning revenue from KT, however, loss in expected net revenue outweighs the gains of selling knowledge to firm 2. Meanwhile, due to the inferior product developed by firm 1, the expected net revenue earned by firm 2 due to direct competition is larger. Moreover, if the distribution of customer valuation of firm 1 is skewed so that there is a greater chance of experiencing large valuation by switching customers of firm 1, the detrimental impact of uncertainty on firm 1's decisions is more pronounced. This result highlights that significantly large uncertainty regarding switching customers' valuation of firm 1 knowledge drives firm 2 to be more willing to cooperate while firm 1 refrains from competition.

The impact of the uncertainty associated with the switching customers' valuation of firm 2 knowledge is similar to the results for uncertainty associated with the switching customers' valuation of firm 2 knowledge in terms of firms KM strategies. However, while larger uncertainty associated regarding firm 2 knowledge results in smaller expected profit for firm 1, firm 2's expected profit is larger. If uncertainty is represented by a skewed distribution so that there is a greater chance of experiencing large valuation by switching customers of firm 2, these results are amplified. Therefore, as uncertainty regarding the effect of direct competition increases, the expected profit of firm 1 decreases, while the expected profit of firm 2 may increase or decrease.

Similarly, we obtain insights on the effect of uncertainty regarding the integration capability of firm 2 using numerical methods. We find that the price and KD decisions of firm 1 are not impacted by the level of uncertainty associated with firm 2's ability to

integrate KT. However, if uncertainty is symmetric around the mean, then more uncertainty drives firm 2 to purchase a larger amount of knowledge from firm 1 in period one and pursue a larger amount of KD in period two, which leads to better quality products for the marketplace. The expected profit of *both* firms is larger if the uncertainty associated with integration capability of firm 2 is larger. For firm 1, the expected revenue is smaller in competition dimension; however, the revenue due to KT is larger, thus firm 1 gains larger expected revenue, despite setting the same price and pursuing same amount of KD. For firm 2, the expected revenue earned from the marketplace outweighs the cost incurred for KT. Meanwhile, skewed distribution reduces the impact of uncertainty on firm 2's KT and KD decisions, and on expected profits of both firms. These results highlight an important insight: Uncertainty in customer valuation drives a different effect on firm 1 and 2 solutions than uncertainty in integration. Thus, to the extent possible, the firms should carefully assess the source of uncertainty.

The above insights show that there are many parameters that impact the KM strategies of firms that are in the same market and have the opportunity to cooperate through a CD agreement. Our results extend the literature in multiple dimensions. First, while past literature, such as D'Aspremont et al (2000), Arora and Fosfuri (2003) have identified that competition in the marketplace plays an important role in firms KM strategies, our results reveal that different market characteristics may drive significantly different KM strategies for the firms. While past literature have focused on firms that race to develop a new product first to reap benefits in the marketplace, we show that the features and functionality of the product and the valuation of the quality of the product in the marketplace drive firms to pursue unique KT and KD strategies. In particular, the impact of the valuation of loyal customers and the valuation of customers if one firm is the sole developer of the new product on the firms KM strategies and expected profits differ significantly from the impact of direct competition.

Second, while past literature (Kutikala and Lin 2006, Fosfuri 2006) have focused on KT decisions of firms, particularly in terms of decisions regarding licensing, we have complex relationships we capture on the evolution of knowledge in NPD projects. Specifically, we recognize the two means of knowledge creation, KT and KD pursued by the firms to increase their knowledge levels. We develop analytical and numerical insights on the impact of market and firm characteristics on each firm's KT and KD strategies.

Third, our analysis captures the impact of the absorptive capacity of the firm that is the recipient of knowledge on the firms' decisions regarding knowledge creation, and expected profits. Unlike past literature that have considered the beneficial impact of tapping into an outside source for knowledge, we capture the impact of the expected absorptive capacity and the expected integration capability of the recipient firm on *both* firms KM strategies and decisions. Our results show that the components of expected absorptive capacity, such as the initial relevant knowledge of the firms, expected integration capability, and the amount of knowledge transferred have significant impact of firms knowledge creation decisions. In addition, the uncertainty regarding the integration capability should be carefully assessed by the firms, since the expected profits of the firms can be significantly affected by this factor.

4.6.2 Joint Development

Our analytical results reveal important insights regarding the interaction effects between the firms' period one KS decisions. According to these results, if firm 1 dedicates a large amount of knowledge to the JD project, firm 2 may dedicate a larger or smaller amount of knowledge. If the probability of jointly developing a successful product or the customer's valuation of joint knowledge or higher effectiveness of KS is small, then larger (smaller) amount of knowledge shared by firm 1 drives firm 2 to dedicate a smaller (larger) portion of its knowledge into the JD project. For example, while firm 1 may aim to reap benefits from the new product by sharing large level of knowledge, firm 2 refrains from dedicating large level of knowledge to the new since the expected net revenue earned from the product in the marketplace is small.

In addition, if sharing knowledge is less costly for firm 2, or the portion of expected profit allocated to firm 2 is large, or the increase in the level of joint knowledge at the end of period one, due to knowledge shared by firm 2 is small, firm 2 has less incentive to keep knowledge proprietary and shares a larger amount of knowledge per unit knowledge shared by firm 1. Thus, if the drivers of expected profit for one firm are small, the firms pursue a "compensation strategy," where smaller level of knowledge dedicated by one firm is compensated by the larger level of knowledge dedicated by the other firm.

Additional analytic results are obtained under the modest simplifying assumption that the rate of diminishing returns to KD associated with joint level of knowledge equals one-half. We find that the initial decision in period one, the portion of expected profit

allocated to firm 1 (and, therefore, firm 2), is dependent only on the rate of returns to KS of the knowledge dedicated by firm 2. As the effectiveness of knowledge shared by firm 2 increases, the portion of expected profit allocated to firm 1 also increases. By following this strategy, firm 1 aims to increase its gains from the knowledge shared by firm 2.

Meanwhile, according to the numerical analysis, large rate of return to KS of the knowledge dedicated by firm 2 may drive firm 2 to dedicate either a larger or smaller amount of knowledge. For smaller values of the rate of returns of knowledge dedicated by firm 2, the amount of knowledge shared by the firms, and the joint amount of KD, as well as expected profit for the firms, increases as the effectiveness of knowledge shared by firm 2 increases. However, for larger values of the returns of knowledge dedicated by firm 2, the amount of KS and KD pursued by the firms *decreases* as the effectiveness of knowledge shared by firm 2 increases. This result occurs since firm 1, who is leader, claims a larger portion of the expected profit for larger values of the returns of KS by firm 2. This drives firm 2 to refrain from dedicating high amount of knowledge to the JD project. Since the value of increasing the knowledge embedded in the JD project in the second period is small, the KD is also pursued at a smaller amount. Similarly, for smaller values of rate of returns of knowledge shared by firm 2, the expected profit of firms 1 and 2 increase as rate of returns increase, while for larger values of rate of returns, the expected profits of the firms decrease as rate of returns increase. In addition, firm 1 (2) prefers to develop the new product individually if the rate of returns of knowledge shared by firm 2 is small (large). Thus, for the firms there is a range of values for rate of returns of knowledge shared by firm 2 where firms cooperate through JD. This result occurs since for the firms there is a tradeoff between the increase/decrease in the portion of expected net revenue they earn versus decrease/increase in the level of knowledge dedicated by the other firm into the JD project.

As expected, if the parameters that drive the effectiveness of KS to firm 2 are large, the firms are driven to dedicate larger amount of knowledge to the JD project. In addition, the firms share more knowledge with their competitor if the cost of loss of sole ownership is small. Due to the complementary relationship between the knowledge creation pursued in periods one and two, firms are also driven to pursue a greater amount of KD, if the effectiveness of KS is large or if the cost of sharing knowledge is small. Thus, larger effectiveness of KS and smaller cost of loss of proprietary knowledge drives larger expected profit for firms if they cooperate, and drives firms engage in cooperation through JD.

Furthermore, if the initial knowledge level of either firm, the firms' joint probability of successfully developing the new product, or the customer's valuation of knowledge embedded in the new product is large, the firms are driven to dedicate a high amount of knowledge to the JD project in period one, and pursue a higher amount of KD in period two. This result occurs since the firms' expected gains from embedding large levels of knowledge into the new product outweigh the cost of knowledge creation. The expected net revenue *and* the individual expected profits earned by the firms are also larger under these conditions. The numerical analysis reveals that a small cost of joint KD also drives the firms to pursue the above KM strategy. Thus, as the drivers of expected net revenue are large of joint KD efforts are less costly for firms, the firms are driven to engage in KS and develop the new product jointly.

Based on extensive numerical experimentation, we explore the impact of uncertainty associated with the firms' customer's valuation of joint knowledge. Assuming the distribution for uncertainty is symmetric around the mean, with a high degree of uncertainty; the firms dedicate larger amounts of knowledge in the first period, and pursue larger amount of KD in the second period. However, the expected profit under the JD agreement is lower for both firms if uncertainty regarding customer valuation is large. This result indicates that uncertainty drives the firms to develop a superior product by pursuing knowledge creation at a large amount, while the gains in the marketplace from developing a superior product is outweighed by costs of knowledge creation. Moreover, if the distribution of customer valuation of firm 1 is skewed so that there is a greater chance of experiencing large customer valuation, the increasing impact of uncertainty on the firms' decisions is more pronounced, while the reduction effect of uncertainty on the expected profit is diminished.

The impact of the uncertainty associated with the integration capability of the firms is similar to the results for uncertainty associated with the customers' valuation of joint knowledge in terms of firms KM strategies. However, the expected profit for the firms if they cooperate through JD mechanism is smaller. Moreover, skewed distribution amplifies the effects regarding KS and KD, while it lessens the reduction in the expected profits of the firms due to uncertainty.

The insights regarding the KM strategies and expected profits of firms enhances the current understanding of cooperation through JD mechanism. First, many market and firm characteristics impact the KS and KD decisions of the firms. While the effectiveness of KS overall is critical for the firms, it is important for the firms to assess

the individual drivers of effectiveness of KS. Past literature, including Samaddar and Kadiyala (2006), have identified the initial relevant NPD knowledge of the firms as an important component of effectiveness of KS. However, we identify that the rate of returns to KS of knowledge shared by each firm, and the expected integration capability of the firms, each impact the KS and KD strategies of the firms differently. In addition, the market characteristics, such as the customers' valuation of knowledge significantly impact the firms KM strategies, and the expected gains of each firm at the end of the JD project.

Second, engaging in JD projects create value for the firms if the firms can develop viable KS and KD strategies. Many studies, such as Anand and Khanna (2000a), Cassiman and Veugeler (2006) have examined the KS among firms through empirical analysis, and considerable research exists on the normative analysis of cooperation through JD mechanism (Appleyard (1996), Atallah (2005)). However, through viewing cooperation via JD mechanism as games between firms that operate in the same market, we provide a viable theoretical lens to understand the decision making process regarding KM strategies of the firms. Moreover, this study contributes to the literature in terms of adding insights regarding uncertainty associated with the customers valuation of knowledge (market) and the firms' capability to integrate the knowledge dedicated to the JD project.

Third, we build on the past literature in examining the dynamic relationship between two forms of knowledge creation, namely KS and KD, for JD mechanism. Our findings reveal that there exists a complementary relationship between the joint knowledge dedicated by the firms to the JD project, and the KD efforts. Meanwhile, we show that the amount of knowledge dedicated by each firm may constitute complements or substitutes for each other, and this relationship is driven by various firm and market characteristics.

Finally, the insights depicted in this chapter provide a framework on the drivers of firms' decisions regarding whether or not to enter JD agreements. For example, our results regarding the range of values for rate of returns to KS of knowledge shared by the follower firm illustrate that firms may not choose to cooperate if the effectiveness of KS is significantly large or significantly small. Hence, the ability of firms to identify, absorb, and improve on knowledge shared by another firm does not necessarily imply that these firms are well positioned to profit from NPD projects that are built on the KS process. It is crucial for firms to identify the drivers of effectiveness of KS process.

4.6.3 Future Research

We believe this study is an important step in understanding firms' cooperation strategies in a competitive market. Based on our analysis, we outline a number of fruitful avenues for future research.

First, the model introduced for the CD mechanism can be enriched by including the price competition in the marketplace. In this chapter, we assume that customers' (expected) valuations of knowledge embedded by the firms drive the firms' expected revenue from the new products in the marketplace. However, in a more realistic setting, the firms' decisions would include the price set for the products developed. Specifically, since each firm may embed different levels of knowledge into the new product they develop, the products may vary in quality. The firms may maximize their expected profit by setting an optimal price for the product in the marketplace, considering the quality of the product (in comparison to the product developed by the competitor). Such an extension of the model using a Bertrand-game setting in the marketplace would provide important insights on the impact of price competition on the firms' decision regarding KT and KD.

Second, the model introduced in Section 4.4.1 captures the impact of KM strategies on the firms' probability of developing a successful product in a simplified manner. Specifically, we assume the probability of developing a successful product is independent of the knowledge level embedded by each firm into the new product. This assumption can be relaxed by defining the probability of developing a successful product as a function of the level of knowledge of the firms at the end of first or second periods. This extension allows us to capture the complex interactions regarding the uncertainty of NPD process.

Third, for the JD mechanism, we assume that the portion of expected profit allocated to each firm is determined by firm 1 at the beginning of the first period. However, depending on the structure of the firms and the agreement between firms, the allocation of expected profit between the firms may take various forms. For example, an extension of the model introduced in Section 4.4.2, which allocates the expected profit to each firm in proportion to the amount of knowledge dedicated to the JD project (i.e. $\lambda = Q_1 / (Q_1 + Q_2)$), where λ is the portion of the profit allocated to firm 1, would provide interesting insights on the impact of profit allocation on firms' KM strategies.

Finally, consideration of other cooperation mechanisms between firms that compete in the market will provide insightful analysis of the KM in NPD problem at the

firm level. One such mechanism is a two-directional transfer of knowledge between firms that compete in the same market. Cross-licensing of knowledge, in terms of patents, components or modules between firms, which is a common mechanism of cooperation between firms in certain industries (i.e. semiconductor and electronics industries), is an example of a two-directional KT. We believe that extending the analysis provided in this chapter by delving into other mechanisms of cooperation will yield a fruitful avenue of research.

CHAPTER 5

CONCLUSIONS AND OPEN RESEARCH QUESTIONS

Management of knowledge involved in the new product development (NPD) projects is critical to the success of firms competing in environments that require rapid innovation. Although there is agreement of its importance, there is a lack of general understanding and recommendations regarding KM strategies for successful NPD. The fundamental contribution of this thesis is a rich and multifaceted understanding of how KM strategies drive successful NPD outcomes. The research addresses the integration of KM and NPD at different decision making levels of the firm. First I consider the KM strategies of a manager responsible for a single NPD project. This research integrates key factors from the largely separate literatures of KM and NPD. Second, I consider KM at strategic level where a firm establishes strategies to transfer or share knowledge resources with a competitor. This research on NPD also reflects themes in the literature on strategic management. From this research, we are better able to understand the unique nature of KM in the context of NPD. In this final chapter, we draw conclusions from the three studies that comprise this thesis. We then identify a number of open research questions with respect to management of knowledge for NPD.

5.1 Knowledge Management Strategies for Product and Process Design Teams

In Chapter 2, a normative model is developed to aid the manager of an NPD project determine her KM strategy for the product and process design teams. The timing and extent of knowledge embedded by each team during the development project determine the features, functionality, and manufacturing efficiency of the product and process. Thus, the manager's KM strategy drives the net revenue earned when the product is launched. The manager impacts the knowledge levels of the product and process design teams through knowledge creation. The manager determines the optimal rates of KA for each team and the rates of KT between teams. Also, the manager may determine the optimal product launch time, which reflects the tradeoff between early market benefits versus the development of superior product and process features.

5.1.1 The Delay or Front-Loading Strategies

Two possible strategies that the NPD manager may follow when pursuing KA for each team or KT between teams are introduced. First, in the *front-loading strategy* the manager pursues KA or KT at an initially high rate that decreases throughout the remainder of the NPD project. In particular, the front-loading strategy occurs when the effectiveness of KA or KT is high at the outset of the NPD project. This situation may arise if the levels of knowledge of the product or process design teams are relatively large at the initial time, if there is limited technical or market uncertainty early in the development project, or if the returns to KA or KT are considerable. The rate of KA or KT decreases over time for several reasons. First, further additions to the level of product or process design team knowledge are more difficult to realize as a result of diminishing returns. Second, as time passes, less time remains in the NPD project to accrue the benefits from an increase in the level of product design team knowledge. Third, since the level of knowledge of the product or process team increases over time, the manager's ability to leverage LBD increases.

Second, the *delay strategy* occurs when the effectiveness of KA or KT is small early in the development project. A low level of effectiveness may occur if the initial level of product and process design team knowledge is small, if there is considerable technical or market uncertainty early in the NPD project, or if the returns to KA or KT are small. Due to the limited effectiveness, the manager pursues KA or KT at a relatively small but increasing rate early in the development project. The rate increases for two reasons. First, over time, the levels of product and process design team knowledge increase through LBD and knowledge creation. Second, technical and market uncertainty are resolved over time. As a result, the effectiveness of KA or KT increases early in the development project. Eventually, the rate of KA or KT reaches a peak and declines thereafter. The decline occurs for several reasons. First, the level of product or process team knowledge reaches a point where additional gains are difficult to achieve (diminishing returns). Second, over time less of the NPD project remains to accrue the benefits KA or KT. Third, over time the manager is better able to increase knowledge by leveraging LBD which is free. Basically, in the delay strategy, the manager optimally delays her peak investment in KA or KT until a later time when the investment is more effective.

The above analytic results are extended numerically (details not given here) to observe how the delay versus front loading strategy impact the optimal product launch

time and profit. If the initial levels of knowledge of both teams are small, the manager optimally pursues the delay strategy for KT or KA. As the initial levels of knowledge increase, the peak rate of KT or KA occurs earlier. Eventually, when the initial levels of knowledge are sufficiently large, the manager optimally switches and pursues the front-loading strategy for KT or KA. Moreover, we find that as the initial levels of product and process team knowledge increase, the manager launches a superior product earlier and earns higher profit. In addition, the rates of return on KA or KT also drive the levels of effectiveness. Lastly, the effectiveness of knowledge creation is impacted by the rates of technical and market uncertainty. Analogous results are obtained for the other drivers of effectiveness of KA or KT.

The above insights are particularly important since the manager has some control over the effectiveness of knowledge creation and on the technical and market uncertainty. Specific actions that may be pursued by the manager to increase the effectiveness of KA and KT and reduce the impact of uncertainty are depicted in Chapter 2.

5.1.2 Complementary Relationships

Another important insight from the model is that the manager should consider key complementary relationships among the KA and KT strategies and the impact of these strategies on the optimal product launch time. If KT in *either* direction or KA for *either* team is higher, the manager pursues higher rates of knowledge creation for *both* teams. The higher rates of KA and KT enable the design teams to embed more knowledge into the development project over time. Thus, the manager optimally launches the product earlier. A larger rate of KA or KT optimally occurs if the effectiveness is larger or the cost is smaller.

Analytically, we show that if the rate of LBD for *either* team is larger, then the manager optimally pursues more KA for *both* teams and more KT in *both* directions. Numerically we show that if the rate of LBD of either team is larger, then the manager earns higher profit by releasing a superior product at an earlier time. Therefore, a high rate of LBD reduces the tradeoff between time-to-market benefits and developing a superior product and process. Clearly, we show that LBD is a key source of competitive advantage.

5.1.3 Uncertainty Resolution

We analyze the effect of uncertainty resolution that occurs during the development project. The rate of technical and market uncertainty is exogenous reflecting external market conditions and technology change. Analytic results are obtained demonstrating that if uncertainty is relatively small early in the development project or if uncertainty is resolved quickly over time then the manager pursues higher rates of KA and KT for both teams. As a result, higher levels of design team knowledge are embedded in the development project over time and an earlier product launch occurs resulting in a higher profit. Alternatively, suppose the extent of uncertainty is large early in the development project or decreases slowly. As a result, KA and KT are less effective and are pursued at lesser rates. However, we also find that by undertaking more KA and KT, and thereby increasing the levels of product and process design knowledge, the manager may *endogenously* reduce the *impact* of technical and market uncertainty. Therefore, the extent to which the manager reduces her pursuit of KA or KT is moderated by the ability of the product and process design teams to apply their knowledge to reduce uncertainty.

5.1.4 Synergy or Conflict

We analyze the impact of costs due to conflict or benefits from synergy when KT between the product and process design teams occurs simultaneously. Our results reveal that the benefits related to synergy lead to higher rates of KT in both directions. Due to the complementary relationships, this gives us higher rates of KA for both teams. With higher levels of product and process design knowledge embedded in the development project, the manager realizes an earlier launch of the product, although the product may not always be superior. Beyond these analytic results, numerical results show that synergy leads to higher profit.

In contrast, there are two possible outcomes if additional costs occur due to conflict when the transfer of knowledge for both teams occurs simultaneously. First, the conflict may cause the manager to pursue less KT in both directions, which leads to less KA over time. Moreover, product and process design knowledge are embedded in the development project at a slower rate and the product launch time is delayed. Second, the manager may undertake a higher rate of KT in one direction and a lower rate in the other. In this case, the levels of knowledge embedded by the design teams may be larger or smaller so we do not know whether the product launch is earlier or delayed.

Beyond these analytic results, numerically we find that conflict always leads to lower profit.

5.2 Stochastic Analysis of the Management of Knowledge for Product and Process Design Teams

In Chapter 3, we develop a stochastic model to aid the manager of an NPD project determine her KM strategy for the product and process design teams. The timing and extent of knowledge embedded by each team during the development project determine the features, functionality, and manufacturing efficiency of the product and process. The manager determines the optimal rate and timing of knowledge creation, which includes KD for the design team and KT between the product and process design teams. The optimal dynamic rates of knowledge creation are obtained to maximize the expected profit, which consists of the expected net revenue when the product is released less the costs for knowledge creation during development.

5.2.1 The Delay or Front-Loading Strategies

Similar to the results of the model introduced in Chapter 2, the results we obtain for the stochastic model introduced in Chapter 3 reveals that front-loading and delay strategies are the two possible strategies the manager may pursue for knowledge creation. However, in chapter 3 we identify drivers of front-loading or delays strategies for KD and KT that are different from the ones we have obtained in Chapter 2. For example, the effectiveness of KD is high if the initial level of product design knowledge is large, or if the extent of errors detected while pursuing KD is small. Also, KD is front-loaded if the manager estimates that the cumulative level of useful product design knowledge substantially enhances the probability of a successful product launch. Moreover, what is not obvious is that KD is front-loaded when the cumulative level of useful process design knowledge is not a key driver of net revenue. In this situation, the manager focuses on developing product design knowledge as a means of maximizing expected net revenue.

Similarly, KT to the product (process) design team is front-loaded if the initial level of process (product) team knowledge is large, or if the rate of errors detected by KT to the product (process) design team is small. In addition, if the ability of process design knowledge to drive net revenue is large (small) early in the NPD project, the manager follows front-loading strategy for KT to the product (process) design team. Lastly, in a

result that is not so apparent, the manager front-loads KT to the product design team if the cumulative product design knowledge is not a key driver of the probability of successful launch of the new product early in the NPD project. Under this condition, the manager accelerates the increase in the product design knowledge to increase the probability of developing a successful product.

The manager pursues delay strategy for KD or KT if the effectiveness of KD or KT is small at the initial time. The conditions that drive the delay strategy are the opposite from those that lead to the front-loading strategy.

We discuss two of the six combinations of KM solutions that can occur. First, suppose the initial knowledge level of the product design team is large, the initial knowledge level of the process design team is small, and the effectiveness of KT to the product design team is larger than the effectiveness of KT in the other direction. Under these conditions the manager is driven to pursue a product oriented development strategy whereby the KD for the product design team and the KT to the process design team is front-loaded and the KT to the product design team is delayed. Second, suppose the above conditions are reversed. Here, the manager is driven to pursue a process oriented development strategy, in which the manager is driven to front-load KT to the product design team and delay KD for the product design team and the KT to the process design team. Third, suppose that initial levels of knowledge of both product and process design teams are large. This condition drives the manager to purpose a *front-loaded development* strategy, where all the knowledge creation efforts follow a front-loading strategy.

The KM strategies that are given above are driven by the initial knowledge levels of the product and process design teams. Suppose the initial levels of the product and process design teams are small. The manager's strategy for under these conditions is driven by two other factors: (i) the extent of errors uncovered by KD for the product design team and KT between the teams and (ii) the drivers of expected net revenue.

5.2.2 The Impact of Errors Detected during Knowledge Creation

We analyze the impact of errors that are detected by KD or KT activities on the KM strategy of the manager. We show that if the extent of design changes triggered by KD for the product design team, then the manager pursues KD at a smaller rate throughout the development project. Analogous results hold for the pursuit of KT in either direction.

In addition, our results reveal three key insights with respect to the impact of errors uncovered on the timing of KD and KT. First, if the extent of errors uncovered by KD for the product design team is large, then the manager is driven to pursue product oriented development strategy (strategy depicted at the first quadrant of Figure 3.4). Second, the manager is driven to pursue process oriented development strategy if the extent of errors uncovered by KT to the product design team is large. Finally, if KT to the process design team uncovered large extent of errors, then the manager is driven to pursue *front-loaded product development* strategy. According to this strategy, the manager front-loads the KD and KT to the product design team and delays KT to the process design team. Thus, the manager accelerates the increase in the knowledge level of the product design team and transfers knowledge related to the attributes and features of the product later in the project. Thus, more effective KT to the process design team mediates the impact of the errors uncovered by KT from the product design team.

The extent of errors uncovered by KD and KT during the project is may be related to the complexity of the NPD project. In addition, the types of processes and activities undertaken by the manager for KD or KT also drive the extent of errors uncovered by knowledge creation. The actions that may be taken by the manager to reduce the impact of errors uncovered by the knowledge creation are given in Chapter 3.

5.2.3 The Impact of Drivers of expected net revenue

We analyze the impact of drivers of expected net revenue on the manager's KD and KT strategies. We find that if the product design knowledge substantially increases the probability of releasing a successful product early in the development project, then the manager pursues larger rates of KD for the product design team *and* larger rates of KT to both the product and process design teams. Similarly, the rates of knowledge creation for both teams are pursued at a larger rate if the process design knowledge substantially increases the net revenue generated by the new product early in the project, or the impact of time-based-competition in the market is large. Therefore, with respect to these drivers of expected net revenue, we observe a complementary relationship between the KD and KT.

Our results also reveal that the drivers of expected revenue impact the timing of the knowledge creation for the product and the process design teams. Specifically, we show that if the product design knowledge significantly increases the probability of developing a successful product, or the time-based competition in the marketplace is

large, then the manager is driven to pursue product oriented development strategy. Meanwhile the manager is driven to pursue process oriented development strategy if the ability of the process design knowledge to enhance net revenue is large. These results demonstrate that the manager should carefully assess the drivers of expected net revenue due to their impact on the manager's KM strategy, and take actions to influence them to the extent possible.

5.3 Knowledge Management Strategies for New Product Development: Competition versus Joint Development

In this Chapter 4, we provide a framework for analyzing the knowledge flow between two competing firms engaged in cooperative agreements. We introduce two two-period game theoretical models that explore KM strategies that drive NPD for two profit-maximizing firms. Knowledge management strategies include the KT or KS between firms and the KD pursued either by each firm independent of its competitor, or jointly. Furthermore, we examine two mechanisms of cooperation between the competitors: CD and JD agreements. We develop analytical models that examine the KM strategies for two firms that cooperate through the CD or JD mechanism. We extend the results of analytical analysis by developing numerical examples. Our results provide insights to the factors that drive each firm's KM decisions including the effects of firm and market-specific characteristics.

5.3.1 Competitive Development

Key analytical insights are obtained demonstrating the interactions between each firm's period one KT decisions. In a surprising result, we find that if firm 1 charges a lower price for its knowledge, firm 2 may purchase either a larger or smaller amount of knowledge. For example, if the valuation of knowledge by firm 2's customers is small, a lower price set by firm 1 drives firm 2 to purchase a smaller amount of knowledge, driving firm 2 to refrain from focusing on KT although the price set by firm 1 may be lower.

Additional analytic results are obtained under the modest simplifying assumption that the rate of diminishing returns to KD associated with each firm's level of knowledge equals one-half. We find that if the expected capability of firm 2 to integrate knowledge transferred from firm 1 is large, then firm 2 purchases a larger amount of knowledge in

period 1 and pursues more KD in period 2. This result highlights the complementary relationship between the two means of knowledge creation for firm 2.

We obtain insights on the impact of direct competition between firms 1 and 2 by exploring the customers' valuation of the difference between the knowledge each firm embeds into their product (switching customers). Thus, if the level of direct competition is high, firm 1's strategy is to increase its expected revenue by driving firm 2 to purchase a larger amount of knowledge; whereas firm 2 focuses on increasing expected net revenue by embedding more knowledge into the product offered in the marketplace. This result occurs since gains due to developing a superior product is outweighed by the gains through KT, firm 1 focuses on earning revenue from knowledge sold to firm 2.

Beyond the analytic results reported above, numerical results are obtained on the effect of the probability that firm 1 successfully develops the new product. As the probability of firm 1 succeeding in its NPD project increases, firm 1 pursues a more aggressive KD strategy in period 2 and firm 2 is driven to an inferior competitive position overall. Meanwhile, if the probability that firm 2 successfully develops the new product is large, firm 2 sets a smaller price in period one, driving firm 2 to purchase more knowledge. In addition, firm 2 pursues more KD in the second period, and thus, is driven to focus on developing a superior product.

Numerical results are obtained that illustrate the impact of the cost of KD pursued by firm 2. We find that if the cost is high, firm 2 offers an inferior product to the marketplace at the end of period 2; firm 1's product features do not change. Although the revenue generated from the lower amount of KT reduces firm 1's profit, firm 1's expected net revenue due to switching customers increases. As a result, the expected profit of firm 1 is larger while the expected profit of firm 2 is smaller.

Based on extensive numerical experimentation, we explore the impact of uncertainty associated with the valuation of knowledge by firm 1's switching customers. Assuming the distribution for uncertainty is symmetric around the mean, with a high degree of uncertainty; uncertainty regarding switching customers' valuation of firm 1 drives firm 1 to focus on earning revenue from KT, however, loss in expected net revenue outweighs the gains of selling knowledge to firm 2. Meanwhile, due to the inferior product developed by firm 1, the expected net revenue earned by firm 2 due to direct competition is larger. The impact of the uncertainty associated with the switching customers' valuation of firm 2 knowledge is similar to the results for uncertainty

associated with the switching customers' valuation of firm 2 knowledge in terms of firms KM strategies.

Similarly, we obtain insights on the effect of uncertainty regarding the integration capability of firm 2 using numerical methods. If uncertainty is symmetric around the mean, then more uncertainty drives firm 2 to purchase a larger amount of knowledge from firm 1 in period one and pursue a larger amount of KD in period two, which leads to better quality products for the marketplace. The expected profit of *both* firms is larger if the uncertainty associated with integration capability of firm 2 is larger.

The above insights show that there are many parameters that impact the KM strategies of firms that are in the same market and have the opportunity to cooperate through a CD agreement. Our results extend the literature in multiple dimensions. First, while past literature, such as D'Aspremont et al (2000), Arora and Fosfuri (2003) have identified that competition in the marketplace plays an important role in firms KM strategies, our results reveal that different market characteristics may drive significantly different KM strategies for the firms. While past literature have focused on firms that race to develop a new product first to reap benefits in the marketplace, we show that the features and functionality of the product and the valuation of the quality of the product in the marketplace drive firms to pursue unique KT and KD strategies. In particular, the impact of the valuation of loyal customers and the valuation of customers if one firm is the sole developer of the new product on the firms KM strategies and expected profits differ significantly from the impact of direct competition.

Second, while past literature (Kutikala and Lin 2006, Fosfuri 2006) have focused on KT decisions of firms, particularly in terms of decisions regarding licensing, we have complex relationships we capture on the evolution of knowledge in NPD projects. Specifically, we recognize the two means of knowledge creation, KT and KD pursued by the firms to increase their knowledge levels. We develop analytical and numerical insights on the impact of market and firm characteristics on each firm's KT and KD strategies.

Third, our analysis captures the impact of the absorptive capacity of the firm that is the recipient of knowledge on the firms' decisions regarding knowledge creation, and expected profits. Unlike past literature that have considered the beneficial impact of tapping into an outside source for knowledge, we capture the impact of the expected absorptive capacity and the expected integration capability of the recipient firm on *both* firms KM strategies and decisions. Our results show that the components of expected

absorptive capacity, such as the initial relevant knowledge of the firms, expected integration capability, and the amount of knowledge transferred have significant impact on firms' knowledge creation decisions. In addition, the uncertainty regarding the integration capability should be carefully assessed by the firms, since the expected profits of the firms can be significantly affected by this factor.

5.3.2 Joint Development

Our analytical results reveal important insights regarding the interaction effects between the firms' period one KS decisions. According to these results, if firm 1 dedicates a large amount of knowledge to the JD project, firm 2 may dedicate larger or smaller amount of knowledge. If the probability of jointly developing a successful product or the customer's valuation of joint knowledge or higher effectiveness of KS is small, then larger (smaller) amount of knowledge shared by firm 1 drives firm 2 to dedicate a smaller (larger) portion of its knowledge into the JD project. In addition, if the drivers of expected profit for one firm are small, the firms pursue a "compensation strategy," where smaller level of knowledge dedicated by one firm is compensated by the larger level of knowledge dedicated by the other firm.

Additional analytic results are obtained under the modest simplifying assumption that the rate of diminishing returns to KD associated with joint level of knowledge equals one-half. We find that the initial decision in period one, the portion of expected profit allocated to firm 1 (and, therefore, firm 2), is dependent only on the rate of returns to KS of the knowledge dedicated by firm 2. As the effectiveness of knowledge shared by firm 2 increases, the portion of expected profit allocated to firm 1 also increases. By following this strategy, firm 1 aims to increase its gains from the knowledge shared by firm 2.

Meanwhile, according to the numerical analysis, large rate of return to KS of the knowledge dedicated by firm 2 may drive firm 2 to dedicate either a larger or smaller amount of knowledge. For smaller values of the rate of returns of knowledge dedicated by firm 2, the amount of knowledge shared by the firms, and the joint amount of KD, as well as expected profit for the firms, increases as the effectiveness of knowledge shared by firm 2 increases. However, for larger values of the returns of knowledge dedicated by firm 2, the amount of KS and KD pursued by the firms *decreases* as the effectiveness of knowledge shared by firm 2 increases. This result occurs since firm 1, who is leader, claims a larger portion of the expected profit for larger values of the returns of KS by firm 2. Similarly, for smaller values of rate of returns of knowledge shared by firm 2, the

expected profit of firms 1 and 2 increase as rate of returns increase, while for larger values of rate of returns, the expected profits of the firms decrease as rate of returns increase. In addition, firm 1 (2) prefers to develop the new product individually if the rate of returns of knowledge shared by firm 2 is small (large). Thus, for the firms there is a range of values for rate of returns of knowledge shared by firm 2 where firms cooperate through JD.

Based on extensive numerical experimentation, we explore the impact of uncertainty associated with the firms' customer's valuation of joint knowledge. Assuming the distribution for uncertainty is symmetric around the mean, with a high degree of uncertainty; the firms dedicate larger amounts of knowledge in the first period, and pursue larger amount of KD in the second period. However, the expected profit under the JD agreement is lower for both firms if uncertainty regarding customer valuation is large. This result indicates that uncertainty drives the firms to develop a superior product by pursuing knowledge creation at a large amount, while the gains in the marketplace from developing a superior product is outweighed by costs of knowledge creation. The impact of the uncertainty associated with the integration capability of the firms is similar to the results for uncertainty associated with the customers' valuation of joint knowledge in terms of firms KM strategies. However, the expected profit for the firms if they cooperate through JD mechanism is smaller.

The insights regarding the KM strategies and expected profits of firms enhances the current understanding of cooperation through JD mechanism. First, many market and firm characteristics impact the KS and KD decisions of the firms. While the effectiveness of KS overall is critical for the firms, it is important for the firms to assess the individual drivers of effectiveness of KS. Past literature, including Samaddar and Kadiyala (2006), have identified the initial relevant NPD knowledge of the firms as an important component of effectiveness of KS. However, we identify that the rate of returns to KS of knowledge shared by each firm, and the expected integration capability of the firms, each impact the KS and KD strategies of the firms differently. In addition, the market characteristics, such as the customers' valuation of knowledge significantly impact the firms KM strategies, and the expected gains of each firm at the end of the JD project.

Second, engaging in JD projects create value for the firms if the firms can develop viable KS and KD strategies. Many studies, such as Anand and Khanna (2000a), Cassiman and Veugeler (2006) have examined the KS among firms through

empirical analysis, and considerable research exists on the normative analysis of cooperation through JD mechanism (Appleyard (1996), Atallah (2005)). However, through viewing cooperation via JD mechanism as games between firms that operate in the same market, we provide a viable theoretical lens to understand the decision making process regarding KM strategies of the firms. Moreover, this study contributes to the literature in terms of adding insights regarding uncertainty associated with the customers valuation of knowledge (market) and the firms' capability to integrate the knowledge dedicated to the JD project.

Third, we build on the past literature in examining the dynamic relationship between two forms of knowledge creation, namely KS and KD, for JD mechanism. Our findings reveal that there exists a complementary relationship between the joint knowledge dedicated by the firms to the JD project, and the KD efforts. Meanwhile, we show that the amount of knowledge dedicated by each firm may constitute complements or substitutes for each other, and this relationship is driven by various firm and market characteristics.

Finally, the insights depicted in this chapter provide a framework on the drivers of firms' decisions regarding whether or not to enter JD agreements. For example, our results regarding the range of values for rate of returns to KS of knowledge shared by the follower firm illustrate that firms may not choose to cooperate if the effectiveness of KS is significantly large or significantly small. Hence, the ability of firms to identify, absorb, and improve on knowledge shared by another firm does not necessarily imply that these firms are well positioned to profit from NPD projects that are built on the KS process. It is crucial for firms to identify the drivers of effectiveness of the KS process.

5.4 Open Research Questions

We believe this thesis is an important step in understanding the KM strategies in the NPD domain at different decision making levels of the firm. Based on our analysis, we outline a number of fruitful avenues for future research.

The research that focuses on the KM strategies for NPD projects should extend the analysis to understand the incentive and motivation structure associated with decision making. In particular, decision makers at different levels of organizational hierarchy may have different incentives regarding the success, failure, and progress of the development of a new product. For example, in Chapters 2 and 3, the manager of the product and process design teams that work on the development of a new product

and the associated new process, is the decision maker, and directs the KM activities of the teams. However, product and process design teams that have individual incentives to develop superior product or process designs, may follow different KD and especially different KT strategies if they had a motivation to keep their respective knowledge proprietary. Thus, capturing the impact of motivation and incentives on the strategies of the decision makers would increase our understanding of the KM in NPD projects.

Research opportunities are plentiful with respect to the analysis of knowledge flow between the NPD projects within a firm. For example, in this thesis, we examine the KM strategies for NPD projects for the development of a single product. However, it is common that there are KT and KS among projects that work on the development of multiple products, which may be substitutable in the marketplace. Thus, research that analyzes the knowledge flow among development projects has the potential to derive interesting insights.

Finally, modeling the effect of uncertainty on the KM decisions at different decision making levels is a promising area of research. Although some of the drivers of uncertainty and risk with respect to evolution of knowledge and NPD projects are captured in this thesis, the uncertainty regarding the successful develop of a product, the launch time of a new product, the value earned from the product, and the effectiveness of efforts pursued for KM are multi dimensional. Research that examines the multiple drivers of uncertainty, the interaction effects among uncertainty regarding KM and NPD, and the managerial perspectives on risks and benefits associated with KM for NPD projects has the potential to make a valuable contribution to the field.

APPENDIX A

Section A.1 provides the Hamiltonian to be maximized for the model presented in Chapter 2. Sections A.2 and A.3 includes the proofs for the Theorems and Corollaries presented in Chapter 2. The details of the numerical examples from Chapter 3 are provided in Section A.4.

Table A.1 Model notation

Notation	Definition
T	Time; $t \in [0, T]$; T is time the product is launched to the market.
D(t), (M(t))	Level of knowledge embedded in the product (process) design at time t; $D(0)=D_0 \geq 0$, $(M(0)=M_0 \geq 0)$; (state variable).
α, (a)	Measure of the rate of LBD associated with the level of product (process) design knowledge at time t, $\alpha \geq 0$ ($a \geq 0$); (exogenous).
$\beta(t)$, (b(t))	Rate of KT at time t from the process (product) to the product (process) design team, $\beta(t) \geq 0$, ($b(t) \geq 0$); (control variable).
$\gamma(t)$, (g(t))	Rate of KA for the product (process) design team at time t, $\gamma(t) \geq 0$, ($g(t) \geq 0$); (control variable).
$\delta_1(t)$, ($\delta_2(t)$)	Extent of technical or market uncertainty resolution associated with product (process) development efforts at time t, respectively, $0 \leq \delta_1(t)$, $\delta_2(t) \leq 1$; (exogenous).
X(t), (Y(t))	Cumulative level of <i>useful</i> knowledge embedded in the product (process) design at time t of the NPD project; (state variable).
V[X(T), Y(T), T]	Net revenue expressed as a function of the product launch time and the cumulative useful levels of product and process knowledge deployed during the NPD project.
C₁[$\beta(t)$], (C₂[b(t)])	Cost of efforts to increase the product (process) design team knowledge through KT from the process (product) design at time t, $C_1[\beta(t)] \geq 0$, ($C_2[b(t)] \geq 0$).
C₃[$\beta(t)$, b(t)]	Addition (reduction) in the cost of KT due to conflict (synergy) when KT occurs simultaneously in both directions, $C_3[\beta(t), b(t)] > 0$, ($C_3[\beta(t), b(t)] < 0$).

$C_4[\gamma(t)],$ $(C_5[g(t)])$	Cost of pursuing KA to increase the level of product (process) design team knowledge at time t, $C_4[\gamma(t)] \geq 0, (C_5[g(t)] \geq 0)$.
$\lambda_1(t), (\lambda_2(t))$	Marginal value of an additional unit of product (process) design team knowledge at time t; (adjoint variable).
$\lambda_3(t), (\lambda_4(t))$	Marginal value of an additional unit of cumulative useful product (process) design knowledge at time t; (adjoint variable).

A.1 The Hamiltonian

The Hamiltonian to be maximized appears below.

$$H = - C_1[\beta] - C_2[b] - C_3[\beta, b] - C_4[\gamma] - C_5[g] + \lambda_1\{\alpha D^{\rho_1} + d_1\beta M^{\rho_2} D^{\rho_3} + d_2\gamma D^{\rho_4}\} + \lambda_2\{aM^{r_1} + m_1bD^{r_2}M^{r_3} + m_2gM^{r_4}\} + \lambda_3\delta_1D + \lambda_4\delta_2M \quad (A.1)$$

The proofs of the theorems and corollaries that follow are based on the first order conditions for optimality of the control, state, and adjoint variables. Also, we know the objective is concave in the control and state variables and the right sides of the state variable equations are concave with respect to the state variables and linear with respect to the control variables. Therefore, sufficiency is satisfied.

A.2 Proofs of Theorems and Corollaries

Proof of Theorem 1

The proof of Theorem 1 follows from the optimality conditions of the adjoint variables given below.

$$\lambda_{1t}^* = -\lambda_1\{\alpha\rho_1D^{\rho_1-1} + d_1\beta\rho_3M^{\rho_2}D^{\rho_3-1} + d_2\gamma\rho_4D^{\rho_4-1}\} - m_1\lambda_2br_2D^{r_2-1}M^{r_3} - \lambda_3\delta_1, \lambda_1(T) = 0. \quad (A.2)$$

$$\lambda_{2t}^* = -\lambda_2\{ar_1M^{r_1-1} + m_1br_3D^{r_2}M^{r_3-1} + m_2gr_3M^{r_4-1}\} - d_1\lambda_1\beta\lambda_2M^{\rho_2-1}D^{\rho_3} - \lambda_4\delta_2, \lambda_2(T) = 0. \quad (A.3)$$

$$\lambda_{3t}^* = 0 \text{ and } \lambda_3(T) = V_{X(T)} \quad (A.4)$$

$$\lambda_{4t}^* = 0 \text{ and } \lambda_4(T) = V_{Y(T)} \quad (\text{A.5})$$

Recall that $\alpha, D, d_1, \beta, M, d_2, \gamma, m_1, b, \delta_1$, and $V_{X(T)} \geq 0$ and $0 \leq \rho_1, \rho_2, \rho_3, \rho_4, r_1, r_2, r_3 \leq 1$. Then, from the optimality conditions given in Equations (A.2)-(A.5), $\lambda_{1t}^* \leq 0$ for $t \in [0, T]$. The proof is analogous for $\lambda_{2t}^* \leq 0$ for $t \in [0, T]$. Therefore, given the terminal time conditions, we know that the marginal values of product and process design knowledge are non-negative over the entire NPD project ($\lambda_1 \geq 0, \lambda_2 \geq 0$ for $t \in [0, T]$). Lastly, the solutions for $\lambda_3^*(t)$ and $\lambda_4^*(t)$ follow directly from (A.4) and (A.5). *Q.e.d.*

Proof of Theorem 2

This proof follows directly from Equations (2.6)-(2.9) in Section 2.4. *Q.e.d.*

Proof of Corollary 1

We know $0 < r_2, \rho_2, r_3, \rho_3 < 1$; $M_t, M, D_t, D, \lambda_1, \lambda_2 \geq 0$; and $\lambda_{1t}, \lambda_{2t} \leq 0$. From Equations (2.10) and (2.11), we have

$$b_t^* = \frac{d_1 \lambda_1 M^{\rho_2} D^{\rho_3} \left(\frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \right) - C_{1\beta\beta}(\beta_t^*)}{C_{3\beta b}} \quad (\text{A.6})$$

$$b_t^* = \frac{m_1 \lambda_2 D^{r_2} M^{r_3} \left(\frac{\lambda_{2t}}{\lambda_2} + r_2 \frac{D_t}{D} + r_3 \frac{M_t}{M} \right) - C_{3\beta b}(\beta_t^*)}{C_{2bb}} \quad (\text{A.7})$$

If we equate the rights hand sides of Equations (A.6) and (A.7), we derive:

$$\beta_t^* = \frac{C_{2bb} \left[d_1 \lambda_1 M^{\rho_2} D^{\rho_3} \left(\frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \right) \right] - C_{3\beta b} \left[m_1 \lambda_2 D^{r_2} M^{r_3} \left(\frac{\lambda_{2t}}{\lambda_2} + r_2 \frac{D_t}{D} + r_3 \frac{M_t}{M} \right) \right]}{C_{1\beta\beta} C_{2bb} - C_{3\beta b}^2}$$

To simplify, we introduce:

$$\phi := \frac{1}{C_{1\beta\beta}C_{2bb} - C_{3\beta b}^2} \quad \text{and}$$

$$\psi := C_{2bb} \left[d_1 \lambda_1 M^{\rho_2} D^{\rho_3} \left(\frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \right) \right] - C_{3\beta b} \left[m_1 \lambda_2 D^{r_2} M^{r_3} \left(\frac{\lambda_{2t}}{\lambda_2} + r_2 \frac{D_t}{D} + r_3 \frac{M_t}{M} \right) \right]$$

β^* satisfies Case (i) under the following conditions. For $t \in [0, t_\beta)$, we have $\phi^* \psi \geq 0$ and $\beta_t^* \geq 0$. At $t = t_\beta$, we have $\phi^* \psi = 0$ and $\beta_t^* = 0$. For $t \in (t_\beta, T]$, we have $\phi^* \psi \leq 0$ and $\beta_t^* \leq 0$.

Finally, at $t = T$, we know $\beta(T)^* = 0$. β^* satisfies Case (ii) under the following conditions. For $t \in [0, T]$, we have $\phi^* \psi \leq 0$ and $\beta_t^* \leq 0$. We know that at $t = T$, $\beta(T)^* = 0$. Analogous conditions hold for b^* .

Next, we elaborate on a possible scenario that leads to a Case (ii) solution for β^* . Suppose $C_{1\beta\beta}C_{2bb} \geq C_{3\beta b}^2$, then $\phi \geq 0$. For $t \in [0, T]$, we know $\phi^* \psi \leq 0$ holds if $\psi \leq 0$. We obtain $\psi \leq 0$ under one of the following conditions for $t \in [0, T]$:

$$1. \frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \leq 0 \quad \text{and} \quad \frac{\lambda_{2t}}{\lambda_2} + r_2 \frac{D_t}{D} + r_3 \frac{M_t}{M} \geq 0;$$

$$2. \frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \leq 0, \quad \frac{\lambda_{2t}}{\lambda_2} + r_2 \frac{D_t}{D} + r_3 \frac{M_t}{M} \leq 0 \quad \text{and}$$

$$C_{2bb} \left[d_1 \lambda_1 M^{\rho_2} D^{\rho_3} \left(\frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \right) \right] \leq C_{3\beta b} \left[m_1 \lambda_2 D^{r_2} M^{r_3} \left(\frac{\lambda_{2t}}{\lambda_2} + r_2 \frac{D_t}{D} + r_3 \frac{M_t}{M} \right) \right];$$

$$3. \frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \geq 0, \quad \frac{\lambda_{2t}}{\lambda_2} + r_2 \frac{D_t}{D} + r_3 \frac{M_t}{M} \geq 0 \quad \text{and}$$

$$C_{2bb} \left[d_1 \lambda_1 M^{\rho_2} D^{\rho_3} \left(\frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \right) \right] \leq C_{3\beta b} \left[m_1 \lambda_2 D^{r_2} M^{r_3} \left(\frac{\lambda_{2t}}{\lambda_2} + r_2 \frac{D_t}{D} + r_3 \frac{M_t}{M} \right) \right].$$

Then, for $t \in [0, T]$, we have $\phi^* \psi \leq 0$ and $\beta_t^* \leq 0$. Since $\beta(T)^* = 0$, we obtain a Case (ii) solution for β^* . Analogous results hold for b^* .

To obtain a Case (i) or (ii) solution for γ^* consider the following. From Equations (2.12) and (2.13):

$$\gamma_t^* = \frac{d_2 \lambda_1 D^{\rho_4} \left(\frac{\lambda_{1t}}{\lambda_1} + \rho_4 \frac{D_t}{D} \right)}{C_{4\gamma\gamma}} \quad \text{and} \quad g_t^* = \frac{m_2 \lambda_2 M^{\rho_4} \left(\frac{\lambda_{2t}}{\lambda_2} + \rho_4 \frac{M_t}{M} \right)}{C_{5gg}}.$$

To simplify, let: $\theta := \frac{\lambda_{1t}}{\lambda_1} + \rho_4 \frac{D_t}{D}$. We obtain a Case (i) solution for γ^* if the following conditions hold. For $t \in [0, t_\gamma)$ we have $\theta \geq 0$ and $\gamma_t^* \geq 0$. At $t = t_\gamma$, we have $\theta = 0$ and $\gamma_t^* = 0$. For $t \in (t_\gamma, T]$, we have $\theta \leq 0$ and $\gamma_t^* \leq 0$. We know $\gamma(T)^* = 0$. In contrast, γ^* satisfies Case (ii) if the following conditions hold. For $t \in [0, T]$, we have $\theta \leq 0$ and $\gamma_t^* \leq 0$. Again, we know $\gamma(T)^* = 0$.

The proofs for g^* are analogous for Cases (i) and (ii). *Q.e.d.*

The solutions described in Corollary 1 are illustrated in Figures 2.2 and 2.3, respectively. Note that these figures are given for illustrative purposes only. ²

Proof of Corollary 2

Assume that $\gamma(t_\gamma) = 0$. Then we know that $\frac{\lambda_{1t}(t_\gamma)}{\lambda_1(t_\gamma)} + \rho_4 \frac{D_t(t_\gamma)}{D(t_\gamma)} = 0$. Also with $\rho_3 \geq \rho_4$, $0 \leq \rho_2$, ρ_3 ,

$\rho_4 \leq 1$ and $\rho_2 \frac{M_t}{M} \geq 0$ for all $t \in [0, T]$, we have $\frac{\lambda_{1t}}{\lambda_1} + \rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \geq \frac{\lambda_{1t}}{\lambda_1} + \rho_3 \frac{D_t}{D} \geq \frac{\lambda_{1t}}{\lambda_1} + \rho_4 \frac{D_t}{D}$.

This gives us

$$\frac{\lambda_{1t}(t_\gamma)}{\lambda_1(t_\gamma)} + \rho_2 \frac{M_t(t_\gamma)}{M(t_\gamma)} + \rho_3 \frac{D_t(t_\gamma)}{D(t_\gamma)} \geq \frac{\lambda_{1t}(t_\gamma)}{\lambda_1(t_\gamma)} + \rho_3 \frac{D_t(t_\gamma)}{D(t_\gamma)} \geq \frac{\lambda_{1t}(t_\gamma)}{\lambda_1(t_\gamma)} + \rho_4 \frac{D_t(t_\gamma)}{D(t_\gamma)}$$

and
$$\frac{\lambda_{1t}(t_\gamma)}{\lambda_1(t_\gamma)} + \rho_2 \frac{M_t(t_\gamma)}{M(t_\gamma)} + \rho_3 \frac{D_t(t_\gamma)}{D(t_\gamma)} \geq 0.$$

² For example, the solution in Case (i) may begin convex increasing, become concave increasing, and then is concave decreasing by T. Or, the solution in Case (ii) may start convex decreasing and change to concave decreasing by T.

Therefore, β is either increasing or at its maximum value at $t=t_\gamma$, as stated in Corollary 2.
Q.e.d.

Proof of Corollary 3

If D_0 is large, then $\gamma_t^*(0)=[d_2\lambda_{1t}(0)D(0)^{\rho_4}+d_2\lambda_1(0)\rho_4D(0)^{\rho_4-1}D_t(0)]/C_{4\gamma}(0)$ is relatively small.

For $t \in [0, T]$, we know that $\rho_4 \frac{D_t}{D} \leq -\frac{\lambda_{1t}}{\lambda_1}$ and $\gamma_t^* \leq 0$. Also, we know $\gamma[T]=0$. It follows that

$\gamma^*(0)$ is relatively large. However, since M_0 is small, we know that $\rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \geq -\frac{\lambda_{1t}}{\lambda_1}$

and $\beta_t^* \geq 0$ for $t \in [0, t_\beta)$. Therefore, we have the Case (i) solution for β^* . At $t=t_\beta$, $\rho_2 \frac{M_t}{M} + \rho_3$

$\frac{D_t}{D} = -\frac{\lambda_{1t}}{\lambda_1}$ and $\beta_t^* = 0$. For $t \in (t_\beta, T]$, we have $\rho_2 \frac{M_t}{M} + \rho_3 \frac{D_t}{D} \leq -\frac{\lambda_{1t}}{\lambda_1}$ and $\beta_t^* \leq 0$. *Q.e.d.*

Proof of Corollary 4

The proof of Corollary 4 is analogous to Corollary 3 and is omitted. *Q.e.d.*

Proof of Corollary 5

From Equation (2.7), we have $C_{2b}[b^*] = -C_{3b}[\beta^*] + m_1 \lambda_2 D^{\rho_2} M^{\rho_3}$. Also, recall that $C_{3\beta b} > 0$. If $C_3[\beta, b] < 0$, then $C_{3b}[\beta, b] < 0$. Here, larger β^* results in smaller $C_{3b}[\beta, b]$. This means that $-C_{3b}[\beta, b]$ is larger so that $C_{2b}[b]$ is larger. Since $C_{2bb}[b] \geq 0$, we know b^* is larger. Alternatively, if $C_3[\beta, b] > 0$, then $C_{3b}[\beta, b] > 0$. Thus, larger β^* results in larger $C_{3b}[\beta, b]$ giving us smaller $C_{2b}[b]$. Finally, since $C_{2bb}[b] \geq 0$, we know b^* is smaller. *Q.e.d.*

Proof of Corollary 6

From Theorem 1, we know $\lambda_1 \geq 0$, $\lambda_2 \geq 0$ and $\lambda_{1t}^*, \lambda_{2t}^* \leq 0$ for $t \in [0, T]$. Moreover, we have α , ρ_1 , D , β , M , ρ_2 , γ , ρ_3 , λ_2 , b , r_2 , $V_{X(T)}$, δ_1 , D_t and $M_t \geq 0$. In Figure A.1, we illustrate the impact of α and a on the marginal value of an additional unit of product (process) design

knowledge.³ The proof follows from Equations (2.6)-(2.9). Analogous proofs lead to the remaining results in Corollary 6. *Q.e.d.*

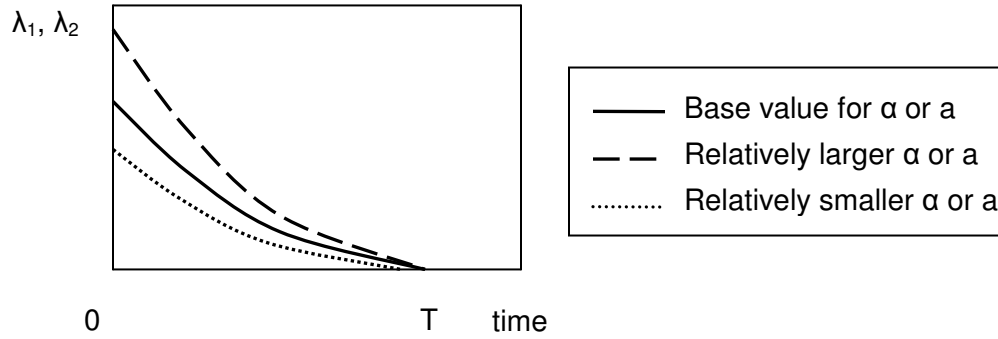


Figure A.1 The marginal value of an additional unit of product or process design knowledge

Proof of Corollaries 7 and 8

The proofs of Corollaries 7 and 8 are analogous to Corollary 6 and therefore are omitted. *Q.e.d.*

A.3 Optimal Product Launch Time

Proof of Theorem 3

From the terminal time transversality condition $H(T) + \partial V[X(T), Y(T), T] / \partial T = 0$, we have:

$$\begin{aligned}
 & -C_1[\beta(T)] - C_2[b(T)] - C_3[\gamma(T)] - C_4[g(T)] \\
 & + \lambda_1(T)\{\alpha[D(T)]^{\rho_1} + d_1\beta(T)[M(T)]^{\rho_2}[D(T)]^{\rho_3} + d_2\gamma(T)D(T)^{\rho_4}\} \\
 & + \lambda_2(T)\{a[M(T)]^{r_1} + m_1b(T)[D(T)]^{r_2}[M(T)]^{r_3} + m_2g(T)[M(T)]^{r_4}\} \\
 & + \lambda_3(T)\delta_1(T)D(T) + \lambda_4(T)\delta_2(T)M(T) + V_T = 0
 \end{aligned}$$

³ $\lambda_1(t)$ and $\lambda_2(t)$ can be convex or concave for $t \in [0, T)$, but are convex at T.

We know

$$C_1[\beta(T)] = C_2[b(T)] = C_3[\gamma(T)] = C_4[g(T)] = \lambda_1(T) = \lambda_2(T) = \lambda_3(T) = \lambda_4(T) = \beta(T) = b(T) = \gamma(T) = g(T) = 0.$$

Therefore, $V_{X(T)}(\delta_1(T)D(T)) + V_{Y(T)}(\delta_2(T)M(T)) + V_T = 0$. *Q.e.d.*

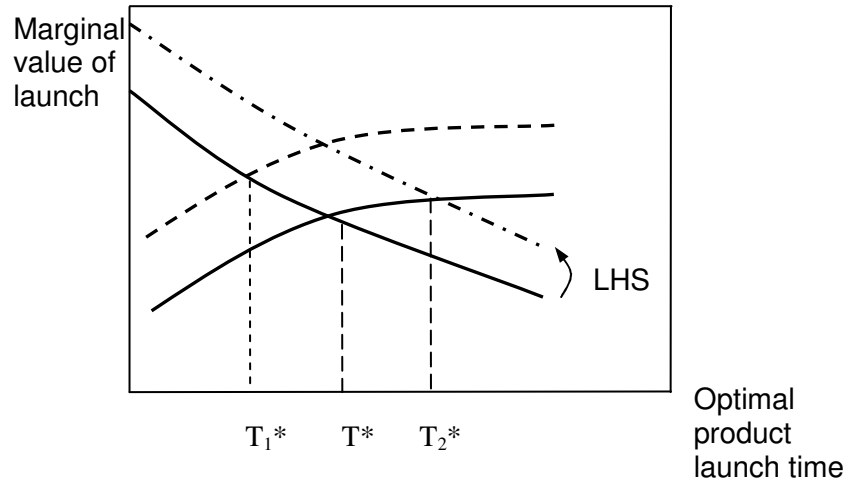


Figure A.2 The optimal launch time⁴

Proof of Corollary 9

The proof follows from Figure A.2 and the discussion preceding Corollary 9. *Q.e.d.*

⁴ To obtain a non-trivial solution ($T^* > 0$), we require $\delta_1(T)D(T)V_{X(T)} + \delta_2(T)M(T)V_{Y(T)} \tilde{V}_T > V_T$ for $T=0$.

A.4 Numerical Examples

We assume net revenue is a separable linear function of the cumulative levels of knowledge of the product and process design teams and the terminal time of the NPD project. (Similar assumptions appear in Carrillo and Gaimon 2000, Krishnan and Gupta 2001, and Moorthy and Png 1992.) We assume the costs for KA and KT (excluding the effect of simultaneous transfer) are quadratic reflecting the disproportionately large disruption that occurs at any single instant of time. Again, this assumption is common in the literature (see Carrillo and Gaimon 2000 and Lapre and Wassenhove 2001). The cost or benefit associated with the simultaneous transfer of knowledge between teams is multiplicative in β and b (i.e., $\beta > 0$ and $b > 0$ must hold for this cost to occur).

The particular functional forms employed in the numerical analysis are as follows:

$$\begin{aligned}
 V[X(T), Y(T), T] &= V_{X(T)}X(T) + V_{Y(T)}Y(T) + V_T T \\
 \delta_1(t) &= \phi_1(t/T)^{\phi_1} & \delta_2(t) &= \phi_2(t/T)^{\phi_2} & C_1[\beta(t)] &= c_1[\beta(t)]^2 & C_2[b(t)] &= c_2[b(t)]^2 \\
 C_4[\gamma(t)] &= c_4[\gamma(t)]^2 & C_5[g(t)] &= c_5[g(t)]^2 & C_3[\beta(t), b(t)] &= c_3\beta(t)b(t)
 \end{aligned}$$

If $C_3[\beta(t), b(t)] = 0$, then

$$\beta(t)^* = \frac{d_1 \lambda_1(t) [M(t)]^{\rho_2} [D(t)]^{\rho_3}}{2c_1} \tag{A.8}$$

If $C_3[\beta(t), b(t)] \neq 0$, then

$$\beta(t)^* = \frac{2c_2 d_1 \lambda_1(t) [M(t)]^{\rho_2} [D(t)]^{\rho_3} - c_3 d_2 \lambda_2(t) [D(t)]^{\rho_2} [M(t)]^{\rho_3}}{4c_1 c_2 - c_3^2} \tag{A.9}$$

The functional forms for $b(t)^*$ are analogous and are omitted. Numerical solutions are obtained with EXCEL using the ordinary shooting method for a discrete approximation of the continuous model.

Table A.2 Inputs common to Example 1 and variations

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
$D(0) = D_0$	8	ρ_2	0.01	r_3	0.8	$V_{X(T)}$	2
$M(0) = M_0$	8	ρ_3	0.8	r_4	0.01	$V_{Y(T)}$	2
$\alpha = a$	0.1	ρ_4	0.02	$c_1 = c_2 = c_4$ $= c_5$	2	V_T	-1500
$d_1 = d_2 = m_1$ $= m_2$	0.2	r_1	0.01	$\phi_1 = \phi_2$	0.785	T	10
ρ_1	0.01	r_2	0.05	$\phi_1 = \phi_2$	0.1		

Table A.3 Summary of results for Example 1 and variations

	Example 2	Example 2a	Example 2b	Example 2c
T	Given: 10	Optimized: 8.7	Optimized: 9.2	Optimized: 7.8
Profit	\$12,023	\$13,460	\$12,001	\$14,718
c_3	0	0	0.5	- 0.5

Table A.4 Inputs common to Example 2 and variations

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
$D(0) = D_0$	0.01	ρ_2	0.01	r_3	0.8	$V_{X(T)}$	10
$M(0) = M_0$	0.01	ρ_3	0.8	r_4	0.01	$V_{Y(T)}$	20
$\alpha = a$	0.1	ρ_4	0.02	$c_1 = c_2 = c_4$ $= c_5$	2	V_T	-7
$d_1 = d_2 = m_1$ $= m_2$	0.2	r_1	0.01	$\phi_1 = \phi_2$	0.785	T	3
ρ_1	0.01	r_2	0.05	$\phi_1 = \phi_2$	0.1		

Table A.5 Summary of results for Example 2 and variations

	Example 2	Example 2a	Example 2b	Example 2c
T	Given: 3	Optimized: 2.8	Optimized: 2.6	Optimized: 2.4
Profit	\$5,909	\$6,431	\$6,956	\$7,559
c_3	0.5	0.5	0	-0.5

APPENDIX B

Section B.1 provides the Hamiltonian and the Lagrangian to be maximized for the model presented in Chapter 3. Sections B.2 and A.3 includes the proofs for the Theorems and Corollaries presented in Chapter 3.

Table B.1 Model notation

Notation	Definition
T	Time; $t \in [0, T]$; 0 is the start of the development project; by T the end of the product life cycle has been reached.
D(t), (M(t))	Level of knowledge of the product (process) design team at time t; $D(0)=D_0 \geq 0$, $(M(0)=M_0 \geq 0)$; (state variable).
$\gamma(t)$	Rate of knowledge development (KD) efforts for the product design team at time t, $\gamma(t) \geq 0$; (control variable).
$\beta(t)$, (b(t))	Rate of knowledge transfer (KT) efforts at time t from the process (product) to the product (process) design team, $\beta(t) \geq 0$, ($b(t) \geq 0$); (control variable).
ρ_1	Indicates rate of returns from KD efforts of the product design team, $0 \leq \rho_1 \leq 1$.
ρ_2, ρ_3 (r₁, r₂)	Indicates rate of returns from KT efforts to the product (process) design team, $0 \leq \rho_2$, $\rho_3 \leq 1$ ($0 \leq r_1$, $r_2 \leq 1$)
X(t) (Y(t))	Cumulative level of useful knowledge of product (process) design team through time t; $X(0)=X_0 \geq 0$, $(Y(0)=Y_0 \geq 0)$; (state variable).
θ_1	Extent of errors uncovered by KD efforts of the product design team, $\theta_1 \geq 0$.
θ_2, θ_3	Extent of errors uncovered by KT efforts to the product (process) design team, θ_2 , $\theta_3 \geq 0$.
R[Y(t),t]	Net revenue earned by the product released at time t; $R \geq 0$.
F[X(t)]	Probability the new product is successfully released by time t; $F \in [0, 1]$.
C₁[$\gamma(t)$]	Cost of KD efforts at time t, $C_1 \geq 0$.

$C_2[\beta(t)],$ $(C_3[b(t)])$ $\Phi_1 (\Phi_2)$	Cost of KT efforts to the product (process) design team at time t, $C_2 \geq 0,$ ($C_3 \geq 0$). Marginal value of an additional unit of cumulative useful product (process) design knowledge for future NPD projects; $\Phi_1, \Phi_2 \geq 0$.
$\lambda_1(t), (\lambda_2(t))$	Marginal value of an additional unit of product (process) design team knowledge at time t; $\lambda_1(T)=0 (\lambda_2(T)=0)$; (adjoint variable).
$\lambda_3(t), (\lambda_4(t))$	Marginal value of an additional unit of cumulative useful product (process) design knowledge at time t; $\lambda_3(T)=\Phi_1 (\lambda_4(T)=\Phi_2)$; (adjoint variable).
$\eta_1(t) (\eta_2(t))$	Lagrange multipliers for the non-negativity of X(t) and Y(t) at time t, $\eta_1,$ $\eta_2 \geq 0$.

B.1 The Hamiltonian and The Lagrangian

The Hamiltonian (H) to be maximized appears in Equation (B.1). The Lagrangian (L) and the associated complementary slackness conditions that arise due to the non-negativity constraints on X(t) and Y(t) are given in Equations (B.2), (B.3) and (B.4). Functional notation is suppressed whenever possible. The superscript “*” denotes an optimal solution.

$$H = FR - C_1(\gamma) - C_2(\beta) - C_3(b) + \lambda_1[\gamma D^{\rho_1} + \beta M^{\rho_2} D^{\rho_3}] + \lambda_2[b D^{r_1} M^{r_2}] \quad (B.1)$$

$$L = H + \eta_1(D - \theta_1\gamma - \theta_2\beta) + \eta_2(M - \theta_3b) \quad (B.2)$$

$$\partial L / \partial \eta_1 = D - \theta_1\gamma - \theta_2\beta \geq 0; \quad \eta_1 \geq 0; \quad \eta_1(D - \theta_1\gamma - \theta_2\beta) = 0 \quad (B.3)$$

$$\partial L / \partial \eta_2 = M - \theta_3b \geq 0; \quad \eta_2 \geq 0; \quad \eta_2(M - \theta_3b) = 0 \quad (B.4)$$

The proofs of the theorems and corollaries that follow are based on the first order conditions for optimality of the control, state, and adjoint variables. Sufficiency is satisfied since the objective is concave in the control and state variables and the right sides of the state variable equations are concave with respect to the state variables and linear with respect to the control variables.

B.2 Proofs of Theorems and Corollaries

Proof of Theorem 1

The proof follows from the optimality conditions of the adjoint variables given below.

$$-\partial L/\partial D = \lambda_{1t} = -\lambda_1[\gamma\rho_1 D^{\rho_1-1} + \beta\rho_3 M^{\rho_2} D^{\rho_3-1}] - \lambda_2 b r_1 D^{r_1-1} M^{r_3} - \lambda_3 - \eta_1, \quad \lambda_1(T) = 0 \quad (\text{B.5})$$

$$-\partial L/\partial M = \lambda_{2t} = -\lambda_2 b r_2 D^{r_1} M^{r_2-1} - \lambda_1 \beta \lambda_2 M^{\rho_2-1} D^{\rho_3} - \lambda_4 - \eta_2, \quad \lambda_2(T) = 0 \quad (\text{B.6})$$

$$-\partial L/\partial X = \lambda_{3t} = -F_X R, \quad \lambda_3(T) = \Phi_1 \quad (\text{B.7})$$

$$-\partial L/\partial Y = \lambda_{4t} = -F_Y R, \quad \lambda_4(T) = \Phi_2 \quad (\text{B.8})$$

Recall $\gamma, D, \beta, M, b, \Phi_1, \Phi_2, F_X, R_Y, \eta_1$ and $\eta_2 \geq 0$ and $0 \leq \rho_1, \rho_2, \rho_3, \rho_4, r_1, r_2, r_3 \leq 1$. The solutions for $\lambda_3^*(t)$ and $\lambda_4^*(t)$ follow directly from Equations (B.7) and (B.8). From the optimality conditions in Equations (B.2)-(B.5), we have $\lambda_{1t} \leq 0$ for $t \in [0, T]$. The proof is analogous for $\lambda_{2t} \leq 0$ with $t \in [0, T]$. Given the terminal time conditions, we obtain $\lambda_1 \geq 0$, and $\lambda_2 \geq 0$ for $t \in [0, T]$. *Q.e.d.*

B.2.1 Optimal KD and KT Solutions

Equations (A.9)-(A.11) and γ, β , and $b \geq 0$ are the optimality conditions for the rate of KD for the product design team and the rates of KT to both the product and process design teams.

$$\partial H/\partial \gamma = -C_{1\gamma} + \lambda_1 D^{\rho_1} - (\lambda_3 + \eta_1)\theta_1 = 0 \quad (\text{B.9})$$

$$\partial H/\partial \beta = -C_{2\beta} + \lambda_1 M^{\rho_2} D^{\rho_3} - (\lambda_3 + \eta_1)\theta_2 = 0 \quad (\text{B.10})$$

$$\partial H/\partial b = -C_{3b} + \lambda_2 D^{r_1} M^{r_2} - (\lambda_4 + \eta_2)\theta_3 = 0 \quad (\text{B.11})$$

The implications of the complementary slackness conditions on the optimal solutions for γ, β and b are as follows: From Equation (A.3), when the non-negativity constraint for the cumulative level of useful product design knowledge is tight: (i) $\gamma^* = (D - \theta_2 \beta)/\theta_1$ and (ii) $\beta^* = (D - \theta_1 \gamma)/\theta_2$. Similarly, when the non-negativity constraint for the cumulative level of useful process design knowledge is tight, $b^* = M/\theta_3$. Therefore, a

positive value of η_1 (η_2) decreases the rates of γ and β (b) and thereby ensures the non-negativity of X (Y).

The non-negativity constraints on γ , β , and b offer additional insights. From Equation (A.9), we know $\lambda_1 D^{\rho_1} - (\lambda_3 + \eta_1)\theta_1 \geq 0$ giving us $\theta_1 \leq \lambda_1 D^{\rho_1} / (\lambda_3 + \eta_1)$. Since $\eta_1 \geq 0$ we obtain $\theta_1 < \lambda_1 D^{\rho_1} / (\lambda_3 + \eta_1)$ must hold. This inequality provides an upper bound on the extent of errors may be uncovered by KD. (For example, at $t=0$ if $\theta_1 \geq \lambda_1(0)D_0^{\rho_1} / (\Phi_1 + \int_0^T F_X R d\tau + \eta_1)$, then $\gamma(0)=0$.) Similarly, from Equations (A.10) and (A.11) we find $\theta_2 \leq \lambda_1 M^{\rho_2} D^{\rho_3} / (\lambda_3 + \eta_1)$ and $\theta_3 \leq \lambda_2 D^{\rho_1} M^{\rho_2} / (\lambda_4 \eta_2)$ hold. To interpret the upper bound on θ_1 we employ analytic sensitivity analysis. If D_0 is large, then KD is more effective at increasing the level of product design knowledge and thereby increasing the cumulative level of useful product design knowledge. As a result, the upper bound on θ_1 is larger. Thus, large D_0 compensates for the loss in the cumulative level of useful product design knowledge due to KD that uncovers errors. Similar interpretations can be developed to describe the impact on θ_1 due to other factors such as the initial levels of product or process design knowledge. Finally, analytic sensitivity analysis can also be applied to θ_2 and θ_3 (the extent of errors uncovered by KT to the product and process design teams, respectively).

In the above analysis we have presented and fully interpreted the optimality conditions for γ , β , and b including the effects of η_1 and η_2 . However, it is reasonable to assume that the manager would not optimally pursue KD or KT that drives the cumulative level of useful product or process design team knowledge to zero. Therefore, for simplicity hereafter in the Appendix and in the chapter, we assume the non-negativity constraints on X and Y hold in an optimal solution so that $\eta_1 = \eta_2 = 0$.

Proof of Theorem 2

This proof follows directly from Equations (B.9)-(B.11) in Section 4. *Q.e.d.*

Proof of Corollary 1

Recall $0 < \rho_1, \rho_2, \rho_3, r_1, r_2 < 1$; $M_t, M, D_t, D, \lambda_1, \lambda_2 \geq 0$; and $\lambda_{1t}, \lambda_{2t} \leq 0$. From Equations (3.12) and (3.14), we obtain Equations (B.12a)-(B.14b).

$$\gamma_t = [\lambda_{1t} D^{\rho_1} + \rho_1 \lambda_1 D^{\rho_1 - 1} D_t + F_X R \theta_1] / C_{1\gamma} \quad (\text{B.12a})$$

$$\gamma_t = [(\rho_1 - \rho_3)\lambda_1\beta M^{\rho_2} D^{\rho_3 + \rho_1 - 1} - r_1\lambda_2 b D^{r_1 + \rho_1 - 1} M^{r_2} - (\Phi_1 + \int_0^T F_X R d\tau) D^{\rho_1} + F_X R \theta_1] / C_{1\gamma\gamma} \quad (\text{B.12b})$$

$$\beta_t = [\lambda_{1t} M^{\rho_2} D^{\rho_3} + \rho_2 \lambda_1 M^{\rho_2 - 1} M_t D^{\rho_3} + \rho_3 \lambda_1 M^{\rho_2} D^{\rho_3 - 1} D_t + F_X R \theta_2] / C_{2\beta\beta} \quad (\text{B.13a})$$

$$\beta_t = [(\rho_3 - \rho_1)\lambda_1 \gamma D^{\rho_1 + \rho_3 - 1} M^{\rho_2} + (\lambda_1 \rho_2 / M - \lambda_2 r_1 / D) b D^{r_1 + \rho_3} M^{r_2 + \rho_3} - (\Phi_1 + \int_0^T F_X R d\tau) M^{\rho_2} D^{\rho_1} + F_X R \theta_2] / C_{2\beta\beta} \quad (\text{B.13b})$$

$$b_t = [\lambda_{2t} D^{r_1} M^{r_2} + r_1 \lambda_{2t} D^{r_1 - 1} D_t M^{r_2} + r_2 \lambda_{2t} D^{r_1} M^{r_2 - 1} M_t + F_R \gamma \theta_3] / C_{3bb} \quad (\text{B.14a})$$

$$b_t = [r_1 \lambda_2 \gamma D^{r_1 + \rho_1 - 1} M^{r_2} + (\lambda_2 r_1 / D - \lambda_1 \rho_2 / M) \beta D^{r_1 + \rho_3} M^{r_2 + \rho_2} - (\Phi_2 + \int_t^T F_R \gamma d\tau) D^{r_1} M^{r_2} + F_R \gamma \theta_3] / C_{2\beta\beta} \quad (\text{B.14b})$$

From Equations (B.12)-(B.14), we know:

$$\gamma_t \leq 0 \text{ if } \lambda_{1t} D^{\rho_1} + \rho_1 \lambda_1 D^{\rho_1 - 1} D + F_X R \theta_1 \leq 0 \text{ and}$$

$$\gamma_t > 0 \text{ if } \lambda_{1t} D^{\rho_1} + \rho_1 \lambda_1 D^{\rho_1 - 1} D + F_X R \theta_1 > 0;$$

$$\beta_t \leq 0 \text{ if } \lambda_{1t} M^{\rho_2} D^{\rho_3} + \rho_2 \lambda_1 M^{\rho_2 - 1} M_t D^{\rho_3} + \rho_3 \lambda_1 M^{\rho_2} D^{\rho_3 - 1} D_t + F_X R \theta_2 \leq 0 \text{ and}$$

$$\beta_t > 0 \text{ if } \lambda_{1t} M^{\rho_2} D^{\rho_3} + \rho_2 \lambda_1 M^{\rho_2 - 1} M_t D^{\rho_3} + \rho_3 \lambda_1 M^{\rho_2} D^{\rho_3 - 1} D_t + F_X R \theta_2 > 0;$$

$$b_t \leq 0 \text{ if } \lambda_{2t} D^{r_1} M^{r_2} + r_1 \lambda_{2t} D^{r_1 - 1} D_t M^{r_2} + r_2 \lambda_{2t} D^{r_1} M^{r_2 - 1} M_t + F_R \gamma \theta_3 \leq 0 \text{ and}$$

$$b_t > 0 \text{ if } \lambda_{2t} D^{r_1} M^{r_2} + r_1 \lambda_{2t} D^{r_1 - 1} D_t M^{r_2} + r_2 \lambda_{2t} D^{r_1} M^{r_2 - 1} M_t + F_R \gamma \theta_3 > 0.$$

Under the following conditions γ^* satisfies Case (i) of Corollary 1. For $t \in [0, T]$, we have $\lambda_{1t} D^{\rho_1} + \rho_1 \lambda_1 D^{\rho_1 - 1} D_t + F_X R \theta_1 \leq 0$ and $\gamma_t \leq 0$. Since $\gamma(T)^* = 0$, we obtain the Case (i) solution for γ^* . In contrast, we obtain the Case (ii) solution in Corollary 1 for γ^* under the following conditions. For $t \in [0, t_\gamma)$, we have $\lambda_{1t} D^{\rho_1} + \rho_1 \lambda_1 D^{\rho_1 - 1} D_t + F_X R \theta_1 > 0$ and $\gamma_t > 0$. At $t = t_\gamma$, we have $\lambda_{1t} D^{\rho_1} + \rho_1 \lambda_1 D^{\rho_1 - 1} D_t + F_X R \theta_1 = 0$. For $t \in [t_\gamma, T]$, we have $\lambda_{1t} D^{\rho_1} + \rho_1 \lambda_1 D^{\rho_1 - 1} D_t + F_X R \theta_1 \leq 0$ and $\gamma_t \leq 0$. Finally, at $t = T$, we know that $\gamma^*(T) = 0$. Analogous results hold for β^* and b^* .

Next, we introduce the inverse functions $C_{1\gamma}^{-1}[\cdot] = f_1[\cdot]$, $C_{1\beta}^{-1}[\cdot] = f_2[\cdot]$, and $C_{3b}^{-1}[\cdot] = f_3[\cdot]$. From Equations (B.9)-(B.11), we have:

$$\gamma^* = f_1[\lambda_1 D^{\rho_1} - \lambda_3 \theta_1] = f_1[\lambda_1 D^{\rho_1} - (\Phi_1 + \int_t^T F_X R d\tau) \theta_1] \quad (\text{B.15})$$

$$\beta^* = f_2[\lambda_1 M^{\rho_2} D^{\rho_3} - \lambda_3 \theta_2] = f_2[\lambda_1 M^{\rho_2} D^{\rho_3} - (\Phi_1 + \int_t^T F_X R d\tau) \theta_2] \quad (\text{B.16})$$

$$b^* = f_3[\lambda_2 D^{r_1} M^{r_2} - \lambda_4 \theta_3] = f_3[\lambda_2 D^{r_1} M^{r_2} - (\Phi_2 + \int_t^T FR_Y d\tau)\theta_3] \quad (B.17)$$

Note that $\partial f_1/\partial \lambda_1, \partial f_1/\partial D, \partial f_1/\partial \rho_1 \geq 0$ and $\partial f_1/\partial \Phi_1, \partial f_1/\partial F_X, \partial f_1/\partial R, \partial f_1/\partial \theta_1 \leq 0$. In addition, $\partial f_2/\partial \lambda_1, \partial f_2/\partial M, \partial f_2/\partial D, \partial f_2/\partial \rho_2, \partial f_2/\partial \rho_3 \geq 0, \partial f_2/\partial \Phi_1, \partial f_2/\partial F_X, \partial f_2/\partial R, \partial f_2/\partial \theta_2 \leq 0, \partial f_3/\partial \lambda_2, \partial f_3/\partial D, \partial f_3/\partial M, \partial f_3/\partial r_1, \partial f_3/\partial r_2 \geq 0,$ and $\partial f_3/\partial \Phi_2, \partial f_3/\partial F, \partial f_3/\partial R_Y, \partial f_3/\partial \theta_3 \leq 0$. From Equations (B.12)-(B.14), we have:

$$\begin{aligned} \gamma_i(0) = & \{(\rho_1 - \rho_3)\lambda_1(0)\beta(0)M_0^{\rho_2}D_0^{\rho_3+\rho_1-1} - r_1\lambda_2(0)b(0)D_0^{r_1+\rho_1-1}M_0^{r_2} \\ & - (\Phi_1 + \int_0^T F_X R d\tau)D_0^{\rho_1} + F_X(0)R(0)\theta_1\}/C_{1\gamma}(0) \end{aligned} \quad (B.18a)$$

$$\begin{aligned} \gamma_i(0) = & \{(\rho_1 - \rho_3)\lambda_1(0)f_2[\lambda_1(0)M_0^{\rho_2}D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]M_0^{\rho_2}D_0^{\rho_3+\rho_1-1} \\ & - r_1\lambda_2(0)f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - \Phi_2 + \int_0^T FR_Y d\tau]\theta_3]D_0^{r_1+\rho_1-1}M_0^{r_2} \\ & - (\Phi_1 + \int_0^T F_X R d\tau)D_0^{\rho_1} + F_X(0)R(0)\theta_1\}/C_{1\gamma}(0) \end{aligned} \quad (B.18b)$$

$$\begin{aligned} \beta_i(0) = & \{(\rho_3 - \rho_1)\lambda_1(0)\gamma(0)D_0^{\rho_1+\rho_3-1}M_0^{\rho_2} \\ & + [\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0]b(0)D_0^{r_1+\rho_3}M_0^{r_2+\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)M_0^{\rho_2}D_0^{\rho_1} + \\ & F_X(0)R(0)\theta_2\}/C_{2\beta}(0) \end{aligned} \quad (B.19a)$$

$$\begin{aligned} \beta_i(0) = & \{(\rho_3 - \rho_1)\lambda_1(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{\rho_1+\rho_3-1}M_0^{\rho_2} \\ & + [\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0]f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} \\ & - (\Phi_2 + \int_0^T FR_Y d\tau)\theta_3]D_0^{r_1+\rho_3}M_0^{r_2+\rho_3} \\ & - (\Phi_1 + \int_0^T F_X R d\tau)M_0^{\rho_2}D_0^{\rho_1} + F_X(0)R(0)\theta_2\}/C_{2\beta}(0) \end{aligned} \quad (B.19b)$$

$$\begin{aligned} b_i(0) = & \{r_1\lambda_2(0)\gamma(0)D_0^{r_1+\rho_1-1}M_0^{r_2} + [\lambda_2(0)r_1/D_0 - \lambda_1(0)\rho_2/M_0]\beta(0)D_0^{r_1+\rho_3}M_0^{r_2+\rho_2} \\ & - (\Phi_2 + \int_0^T FR_Y d\tau)D_0^{r_1}M_0^{r_2} + F_X(0)R(0)\theta_2\}/C_{2\beta}(0) \end{aligned} \quad (B.20a)$$

$$\begin{aligned} b_i(0) = & \{r_1\lambda_2(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{r_1+\rho_1-1}M_0^{r_2} \\ & + [\lambda_2(0)r_1/D_0 - \lambda_1(0)\rho_2/M_0]f_2[\lambda_1(0)M_0^{\rho_2}D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]D_0^{r_1+\rho_3}M_0^{r_2+\rho_2} \\ & - (\Phi_2 + \int_0^T FR_Y d\tau)D_0^{r_1}M_0^{r_2} + F_X(0)R(0)\theta_2\}/C_{2\beta}(0) \end{aligned} \quad (B.20b)$$

If we know the sign of $\gamma_i(0), \beta_i(0)$ or $b_i(0)$, we also know whether γ^*, β^* or b^* satisfy Case (i) or Case (ii). Recall that $\rho_1 > \rho_3$ and $\lambda_1(0), \lambda_2(0), D_0, M_0, \rho_1, \rho_2, \rho_3, r_1, r_2 \geq 0$. First, from Equation (B.12b), we know γ^* satisfies Case (i) if $\gamma_i(0) \leq 0$. From Equation (B.15b), we obtain $\gamma_i(0) \leq 0$ if the following holds:

$$\begin{aligned}
& (\rho_1 - \rho_3)\lambda_1(0)f_2[\lambda_1(0)M_0^{\rho_2}D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]M_0^{\rho_2}D_0^{\rho_3+\rho_1-1} \\
& - r_1\lambda_2(0)f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - (\Phi_2 + \int_0^T FR_Y d\tau)\theta_3]D_0^{r_1+\rho_1-1}M_0^{r_2} \\
& - (\Phi_1 + \int_0^T F_X R d\tau)D_0^{\rho_1} + F_X(0)R(0)\theta_1 \leq 0.
\end{aligned}$$

In contrast, γ^* satisfies Case (ii) if the direction of the inequality above is reversed giving us $\gamma_t(0) > 0$. Similarly, β^* satisfies Case (i) if $\beta_t(0) \leq 0$. From Equation (B.10b), we obtain $\beta_t(0) \leq 0$ if the following condition holds:

$$\begin{aligned}
& (\rho_3 - \rho_1)\lambda_1(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{\rho_1+\rho_3-1}M_0^{\rho_2} \\
& + [\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0]f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - (\Phi_2 + \int_0^T FR_Y d\tau)\theta_3]D_0^{r_1+\rho_3}M_0^{r_2+\rho_3} \\
& - (\Phi_1 + \int_0^T F_X R d\tau)M_0^{\rho_2}D_0^{\rho_1} + F_X(0)R(0)\theta_2 \leq 0.
\end{aligned}$$

In contrast, β^* satisfies Case (ii) if the above inequality sign is reversed giving us $\beta_t(0) > 0$. Finally, from Equation (B.14b), we know b^* satisfies Case (i) if $b_t(0) \leq 0$ which occurs if the following condition holds:

$$\begin{aligned}
& r_1\lambda_2(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{r_1+\rho_1-1}M_0^{r_2} \\
& + [\lambda_2(0)r_1/D_0 - \lambda_1(0)\rho_2/M_0]f_2[\lambda_1(0)M_0^{\rho_2}D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]D_0^{r_1+\rho_3}M_0^{r_2+\rho_3} \\
& - (\Phi_2 + \int_0^T FR_Y d\tau)D_0^{r_1}M_0^{r_2} + F_X(0)R(0)\theta_2 \leq 0.
\end{aligned}$$

From Equation (B.20b), if the above inequality is reversed we know b^* satisfies Case (ii) giving us $b_t(0) > 0$. *Q.e.d.*

The solutions described in Corollary 1 are illustrated in Figures A.2 and A.3, respectively. These figures are given for illustrative purposes only. At some time $t \in [0, T)$ the optimal solution in Case (i) may be either convex or concave decreasing. We do know, however, that the optimal solution is concave decreasing at T . Similarly, the optimal solution in Case (ii) may be convex or concave increasing early in the development project and convex or concave decreasing later. However, we do know that the optimal solution is concave at the maximum value and concave decreasing at T .

B.2.2 The Delay and Front Loading Strategies

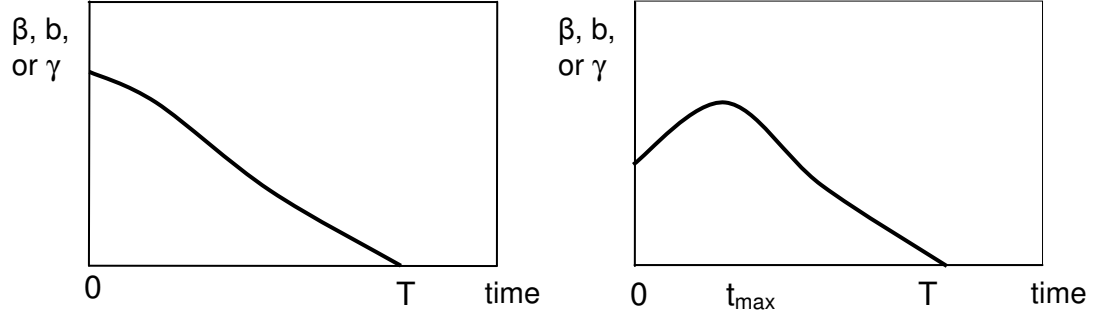


Figure B.1 Case (i) Delay strategy and Case (ii) Front-loading strategy

Proof of Corollary 2

From Equations (B.10) and (B.4), we know $(\int_0^T F_X R d\tau) M_0^{\rho_2} D_0^{\rho_1} > F_X(0) R(0) \theta_2$. From Equations (B.19a) and (B.19b), we have β^* satisfies Case (ii) (delay strategy) if $\beta_i(0) > 0$. Therefore, Case (ii) holds if and only if the following inequality holds:

$$\lambda_1(0) \rho_2 / M_0 - \lambda_2(0) r_1 / D_0 > 0 (\lambda_2(0) r_1 / D_0 - \lambda_1(0) \rho_2 / M_0 < 0).$$

Similarly, from Equations (B.11) and (B.5), we know $\Phi_2 + \int_0^T F R_Y d\tau D_0^{r_1} M_0^{r_2} > F_X(0) R(0) \theta_2$ holds. It follows that b^* satisfies Case (i) (front-loading strategy) if $b_i(0) \leq 0$. From Equations (B.20a)-(B.20b), if $\lambda_1(0) \rho_2 / M_0 - \lambda_2(0) r_1 / D_0 > 0 (\lambda_2(0) r_1 / D_0 - \lambda_1(0) \rho_2 / M_0 < 0)$ holds, then

$$r_1 \lambda_2(0) f_1 [\lambda_1(0) D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau) \theta_1] D_0^{r_1 + \rho_1 - 1} M_0^{r_2}$$

is relatively small compared to

$$(\lambda_2(0) r_1 / D_0 - \lambda_1(0) \rho_2 / M_0) f_2 [\lambda_1(0) M_0^{\rho_2} D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau) \theta_2] D_0^{r_1 + \rho_3} M_0^{r_2 + \rho_2}$$

giving us $b_i(0) \leq 0$. *Q.e.d.*

Proof of Corollary 3

The optimal solutions already given for γ and β hold and we now have $\beta^* = 0$ for $t \in [0, T]$.

The rates of change in γ^* and b^* satisfy Equations (B.21) and (B.22), below

$$\dot{\gamma}_t = [-r_1 \lambda_2 b D^{r_1 + \rho_1 - 1} M^{r_2} - (\Phi_1 + \int_0^T F_X R d\tau) D^{\rho_1} + F_X R \theta_1] / C_{1\gamma\gamma} \quad (B.21)$$

$$\dot{b}_t = [r_1 \lambda_2 \gamma D^{r_1 + \rho_1 - 1} M^{r_2} - (\Phi_2 + \int_t^T F R_Y d\tau) D^{r_1} M^{r_2} + F R_Y \theta_3] / C_{2\beta\beta} \quad (B.22)$$

We know $0 < \rho_1, \rho_2, \rho_3, r_1, r_2 < 1$; and $M, D, \lambda_1, \lambda_2, \Phi_1, \Phi_2, F_X, R, F, R_Y, \theta_1, \theta_3, C_{1\gamma\gamma}, C_{2\beta\beta} \geq 0$.

From Equation (B.18), it follows that $\dot{\gamma}_t \leq 0$ for $t \in [0, T]$. Since $\gamma(T) = 0$, we know γ^* satisfies Case (i).

From Equation (B.22), we know the following:

$$b_t \leq 0 \text{ if } r_1 \lambda_2 \gamma D^{r_1 + \rho_1 - 1} M^{r_2} - (\Phi_2 + \int_t^T F R_Y d\tau) D^{r_1} M^{r_2} + F R_Y \theta_3 \leq 0 \text{ and}$$

$$b_t > 0 \text{ if } r_1 \lambda_2 \gamma D^{r_1 + \rho_1 - 1} M^{r_2} - (\Phi_2 + \int_t^T F R_Y d\tau) D^{r_1} M^{r_2} + F R_Y \theta_3 > 0.$$

Using the inverse functions $C_{1\gamma}^{-1}[\cdot] = f_1[\cdot]$, $C_{1\beta}^{-1}[\cdot] = f_2[\cdot]$, and $C_{3\beta}^{-1}[\cdot] = f_3[\cdot]$, from Equations (B.21) and (B.22), we have

$$\begin{aligned} b_t(0) = & \{r_1 \lambda_2(0) f_1[\lambda_1(0) D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau) \theta_1] D_0^{r_1 + \rho_1 - 1} M_0^{r_2} \\ & - (\Phi_2 + \int_0^T F R_Y d\tau) D_0^{r_1} M_0^{r_2} + F_X(0) R(0) \theta_2\} / C_{2\beta\beta}(0) \end{aligned} \quad (B.23)$$

If the following condition holds, then $b_t(0) \leq 0$ so that b^* satisfies Case (i).

$$\begin{aligned} & r_1 \lambda_2(0) f_1[\lambda_1(0) D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau) \theta_1] D_0^{r_1 + \rho_1 - 1} M_0^{r_2} - (\Phi_2 + \int_0^T F R_Y d\tau) D_0^{r_1} M_0^{r_2} + \\ & F_X(0) R(0) \theta_2 \leq 0 \end{aligned}$$

If the inequality above is reversed, then $b_t(0) > 0$ giving us b^* satisfies Case (ii). *Q.e.d.*

Proof of Corollaries 4a and 4b

If D_0 is large, M_0 is small and $\rho_2 > r_1$ then $\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0 > 0$. In addition, Equation (B.24) is relatively large compared to Equation (B.25).

$$(\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0)f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - (\Phi_2 + \int_0^T FR_Y d\tau)\theta_3]D_0^{r_1+\rho_3}M_0^{r_2+\rho_3} \quad (B.24)$$

$$\begin{aligned} & (\Phi_1 + \int_0^T F_X R d\tau)M_0^{\rho_2}D_0^{\rho_1} - F_X(0)R(0)\theta_2 \\ & - (\rho_3 - \rho_1)\lambda_1(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{\rho_1+\rho_3-1}M_0^{\rho_2} \end{aligned} \quad (B.25)$$

From Equation (B.19b), we know the following is relatively large:

$$\begin{aligned} \beta_t(0) = & \{(\rho_3 - \rho_1)\lambda_1(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{\rho_1+\rho_3-1}M_0^{\rho_2} \\ & + (\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0)f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - (\Phi_2 + \int_0^T FR_Y d\tau)\theta_3]D_0^{r_1+\rho_3}M_0^{r_2+\rho_3} \\ & - (\Phi_1 + \int_0^T F_X R d\tau)M_0^{\rho_2}D_0^{\rho_1} + F_X(0)R(0)\theta_2\}/C_{2\beta\beta}(0) \end{aligned}$$

To summarize, for $t \in [0, t_\beta]$ we have $\beta_t > 0$. For $t \in [t_\beta, T]$, we have $\beta_t \leq 0$ and we know that $\beta(T) = 0$. Thus, β^* is driven to follow Case (ii).

Similarly, due to large D_0 , small M_0 and $\rho_2 > r_1$, we have $\lambda_2(0)r_1/D_0 - \lambda_1(0)\rho_2/M_0 < 0$ making $r_1\lambda_2(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{r_1+\rho_1-1}M_0^{r_2}$ relatively large. From Equation (B.20b), we obtain Equation (B.26) which we know is relatively large.

$$\begin{aligned} b_t(0) = & \{r_1\lambda_2(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{r_1+\rho_1-1}M_0^{r_2} \\ & + [\lambda_2(0)r_1/D_0 - \lambda_1(0)\rho_2/M_0]f_2[\lambda_1(0)M_0^{\rho_2}D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]D_0^{r_1+\rho_3}M_0^{r_2+\rho_2} \\ & - (\Phi_2 + \int_0^T FR_Y d\tau)D_0^{r_1}M_0^{r_2} + F_X(0)R(0)\theta_2\}/C_{2\beta\beta}(0) \end{aligned} \quad (B.26)$$

For $t \in [0, T]$, we know $b_t \leq 0$, $b(T) = 0$ and the following inequality holds giving us b^* satisfies Case (i).

$$r_1\lambda_2f_1[\lambda_1D^{\rho_1} - (\Phi_1 + \int_t^T F_X R d\tau)\theta_1]D^{r_1+\rho_1-1}M^{r_2} < (\Phi_2 + \int_t^T FR_Y d\tau)D^{r_1}M^{r_2} - F_X R\theta_2 - [\lambda_2r_1/D - \lambda_1\rho_2/M]f_2[\lambda_1M^{\rho_2}D^\rho - (\Phi_1 + \int_t^T F_X R d\tau)\theta_2]D^{r_1+\rho_3}M^{r_2+\rho_2}$$

Finally, recall $\rho_1 > \rho_3$. With D_0 is large, M_0 is small, $\rho_2 > r_1$ and $b^*(0)$ relatively large, from Equation (B.17a), we have $(\rho_1 - \rho_3)\lambda_1(0)\beta(0)M_0^{\rho_2}D_0^{\rho_3+\rho_1-1}$ is relatively large compared to

$$r_1\lambda_2(0)b(0)D_0^{r_1+\rho_1-1}M_0^{r_2} - (\Phi_1 + \int_0^T F_X R d\tau)D_0^{\rho_1} - F_X(0)R(0)\theta_1.$$

It follows that $\gamma_t(0)$ is relatively large giving us $\gamma_t \leq 0$ for $t \in [0, T]$. Since, $\gamma(T) = 0$, we conclude γ^* is driven to follow Case (i).

Proof of Corollaries 5a and 5b

The proofs of Corollaries 5a and 5b are analogous to Corollaries 4a and 4b and are omitted. *Q.e.d.*

The solutions described in Corollaries 4a-4b (5a-5b) are illustrated in Figure 4 (5). Note that these figures are given for illustrative purposes only.

Proof of Corollary 6a

From Theorem 1, we know $\lambda_1 \geq 0$, $\lambda_2 \geq 0$ and λ_{1t} , $\lambda_{2t} \leq 0$ for $t \in [0, T]$. Moreover, recall $0 < \rho_1$, ρ_2 , ρ_3 , r_1 , $r_2 < 1$; M_t , and M , D_t , D , λ_1 , λ_2 , Φ_1 , Φ_2 , F_X , R_Y , θ_1 , θ_2 , $\theta_3 \geq 0$. From Equations (B.5), (B.9), (B.10) and (B.11), we have

$$\begin{aligned} \lambda_{1t} = & -\lambda_1\{f_1[\lambda_1D^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]\rho_1D^{\rho_1-1} \\ & + f_2[\lambda_1M^{\rho_2}D^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]\rho_3M^{\rho_2}D^{\rho_3-1}\} \\ & - \lambda_2f_3[\lambda_2D^{r_1}M^{r_2} - (\Phi_2 + \int_t^T FR_Y d\tau)\theta_3]r_1D^{r_1-1}M^{r_3} - \lambda_3. \end{aligned}$$

Since $\partial f_1 / \partial \theta_1 \leq 0$, larger θ_1 results in smaller $f_1[\cdot]$ and larger $\lambda_{1t}(0)$. With $\lambda_1(T) = 0$, we know that for larger θ_1 then λ_1 is smaller. Thus, from Equations (B.9) and (B.10), larger θ_1 drives smaller γ^* . Proofs of the remaining results in Corollary 5a are analogous. *Q.e.d.*

Proof of Corollary 6b

From Corollary 6a, we know if θ_1 is large, then γ^* is relatively small. From Equations (B.5)-(B.8) and (B.16)-(B.18) and Corollary 6a, we know that larger θ_1 results in smaller λ_1 and λ_2 (and smaller β^* and b^*). However, from Equation (B.5)-(B.8) and (B.15)-(A.17), we see θ_1 has both a direct (first order) effect on λ_1 and an indirect (second order) effect through λ_2 . We reasonably assume that the first order effect dominates the second order effect. Since $\rho_1 > \rho_3$, from Equation (B.18b), we know the following expression is relatively large:

$$\begin{aligned} & \{(\rho_1 - \rho_3)\lambda_1(0)f_2[\lambda_1(0)M_0^{\rho_2}D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]M_0^{\rho_2}D_0^{\rho_3+\rho_1-1} \\ & - r_1\lambda_2(0)f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - (\Phi_2 + \int_0^T F_{R_Y} d\tau)\theta_3]D_0^{r_1+\rho_1-1}M_0^{r_2}. \end{aligned}$$

In addition, if θ_1 is large the last term of Equation (B.18a) is large, which gives us a relatively small $\gamma_t(0)$. Thus for $t \in [0, t_\gamma)$, $\gamma_t > 0$ and for $t \in [t_\gamma, T]$ $\gamma_t \leq 0$. Since we know $\gamma(T) = 0$, we find γ^* is driven to follow Case (ii).

If θ_1 is large, then from Equation (B.19b), we know the value of Equation (B.27) is relatively small. In addition, assuming the direct effects of θ_1 on λ_1 dominates the indirect effect observed through λ_2 , we know large θ_1 results in small $\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0)b(0)D_0^{r_1+\rho_3}M_0^{r_2+\rho_3}$ so that $\beta_t(0)$ is relatively small. It follows that for $t \in [0, T]$, $\beta_t \leq 0$ holds. Since we know $\beta(T) = 0$, we see that β^* is driven to follow Case (i).

$$\{(\rho_3 - \rho_1)\lambda_1(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{\rho_1+\rho_3-1}M_0^{\rho_2} \quad (B.27)$$

Alternatively, if θ_1 is large, from Equation (B.20b), we know the value of Equation (B.28) is relatively large. Assuming the direct effects dominate the indirect effects $(\lambda_2(0)r_1/D_0 - \lambda_1(0)\rho_2/M_0)\beta(0)D_0^{r_1+\rho_3}M_0^{r_2+\rho_2}$ is also relatively large so that $b_t(0)$ is relative large. Thus for $t \in [0, t_b)$, we have $b_t > 0$ and for $t \in [t_b, T]$ we have $b_t \leq 0$. Since we know $b(T) = 0$, we have b^* is driven to follow Case (ii).

$$r_1\lambda_2(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{r_1+\rho_1-1}M_0^{r_2} \quad (B.28)$$

The proof under the supposition that θ_1 is small is analogous and is omitted. *Q.e.d.*

Proof of Corollary 6c

The proof of Corollary 6c is analogous to Corollary 6b and is omitted. *Q.e.d.*

Proof of Corollary 6d

The proof of Corollary 6d is analogous to Corollary 6b and is omitted. *Q.e.d.*

Proof of Corollary 7a

From Theorem 1, we know $\lambda_1 \geq 0$, $\lambda_2 \geq 0$ and $\lambda_{1t}, \lambda_{2t} \leq 0$ for $t \in [0, T]$. Moreover, we have $0 < \rho_1, \rho_2, \rho_3, r_1, r_2 < 1$; and $M_t, M, D_t, D, \lambda_1, \lambda_2, \Phi_1, \Phi_2, F_X, R_Y, \theta_1, \theta_2, \theta_3 \geq 0$. From Equations (B.5) and (B.7), we see that if F_X is larger, then $\lambda_{1t}(0)$ is larger. Since $\lambda_1(T) = 0$, if F_X is larger we have λ_1 is larger. From Equations (B.9) and (B.10), larger F_X results in larger γ^* and β^* . In addition, from Equation (B.6) and (B.8), if F_X is larger then $\lambda_{2t}(0)$ is larger. Since $\lambda_2(T) = 0$, we know that if F_X is larger then λ_2 is larger. From Equation (B.11), larger F_X results in larger b^* . Analogous proofs lead to the remaining results in Corollary 7a. *Q.e.d.*

Proof of Corollary 7b

From Corollary 7a, we know that if $F_X(0)$ is large, then γ^* is relatively large. From Equations (B.5)-(B.8), (B.16)-(B.18) and Corollary 6a, we know that larger $F_X(0)$ results in larger λ_1 and λ_2 (and larger β^* and b^*). From Equation (B.18b), this means that the value of Equation (B.29) is relatively small.

$$\begin{aligned} & (\rho_1 - \rho_3)\lambda_1(0)f_2[\lambda_1(0)M_0^{\rho_2}D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]M_0^{\rho_2}D_0^{\rho_3+\rho_1-1} \\ & - r_1\lambda_2(0)f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - (\Phi_2 + \int_0^T F R_Y d\tau)\theta_3]D_0^{r_1+\rho_1-1}M_0^{r_2} \end{aligned} \quad (B.29)$$

Larger F_X results in smaller $-(\Phi_1 + \int_0^T F_X R d\tau)D_0^{\rho_1}$. The impact of large $F_X(0)$ on $\gamma_t(0)$ as observed through large $\lambda_1(0)$ and $\lambda_2(0)$ dominates the impact observed through larger $F_X(0)R(0)\theta_1$. We know this because large $F_X(0)$ drives large $\lambda_1(0)$ and $\lambda_2(0)$ through

$\int_0^T F_X R d\tau$ and from the proof of Corollary 2, we have $\int_0^T F_X R d\tau > F_X(0)R(0)\theta_1$. As a result,

$\gamma_t(0)$ is relatively small. It follows that $\gamma_t \leq 0$ for $t \in [0, T]$. Since $\gamma(T) = 0$, we see that γ^* is driven to follow the solution in Case (i).

If F_X is large, then from Equation (B.19b), the value of Equation (B.30) is relatively large. In addition, due to large $F_X(0)$ the following inequality is likely to hold: $\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0 > 0$. Since $\partial F/\partial X \geq 0$ and $\partial^2 F/\partial X^2 \leq 0$, $f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - (\Phi_2 + \int_0^T FR_Y d\tau)\theta_3]$ is relatively large. As a result, the value of Equation (B.31) is relatively large, as well.

$$\{(\rho_3 - \rho_1)\lambda_1(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{\rho_1 + \rho_3 - 1}M_0^{\rho_2}\} \quad (B.30)$$

$$(\lambda_1(0)\rho_2/M_0 - \lambda_2(0)r_1/D_0)f_3[\lambda_2(0)D_0^{r_1}M_0^{r_2} - (\Phi_2 + \int_0^T FR_Y d\tau)\theta_3]D_0^{r_1 + \rho_3}M_0^{r_2 + \rho_3} \quad (B.31)$$

It follows that $\beta_t(0)$ is relatively large. Thus for $t \in [0, t_\beta)$, we obtain $\beta_t > 0$ and for $t \in [t_\beta, T]$ we have $\beta_t \leq 0$. Since we know $\beta(T) = 0$, we know that β^* is driven to follow Case (ii). In contrast, if $F_X(0)$ is large, from Equation (B.17b), we know Equation (B.32) is relatively small in value. In addition, we know that large $F_X(0)$ drives large $\lambda_1(0)$ through $\int_0^T F_X R d\tau$

and drives large $\lambda_2(0)$ through large $\lambda_1(0)$. Thus, the impact of $F_X(0)$ on $\lambda_2(0)$ is a second order effect. Thus, it is reasonable to assume that first order effect dominate the second order effect, giving us: $\lambda_2(0)r_1/D_0 - \lambda_1(0)\rho_2/M_0 < 0$ so that the value of Equation (B.33) is relatively small.

$$r_1\lambda_2(0)f_1[\lambda_1(0)D_0^{\rho_1} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_1]D_0^{r_1 + \rho_1 - 1}M_0^{r_2} \quad (B.32)$$

$$(\lambda_2(0)r_1/D_0 - \lambda_1(0)\rho_2/M_0)f_2[\lambda_1(0)M_0^{\rho_2}D_0^{\rho_3} - (\Phi_1 + \int_0^T F_X R d\tau)\theta_2]D_0^{r_1 + \rho_3}M_0^{r_2 + \rho_2} \quad (B.33)$$

Finally, recall $\partial F/\partial X \geq 0$ and $\partial^2 F/\partial X^2 \leq 0$. If $F_X(0)$ is larger, then the value of the following inequality is relatively small so that $b_t(0)$ is relatively small.

$$- (\Phi_2 + \int_0^T FR_Y d\tau) D_0^{r1} M_0^{r2} + F(0) R_Y(0) \theta_2$$

Thus for $t \in [0, T]$, we have $b_t < 0$. Again, since $b(T) = 0$, we see that b^* is driven to follow Case (i).

APPENDIX C

Table C.1 Model notation

Competitive Development	
Notation	Definition
K_{ij}	Level of knowledge applied for NPD project by firm i at time j ; $i \in \{1,2\}$, $j \in \{0,1,2\}$, $K_{i0} \geq 0$.
KT_i	Period one change in the level of knowledge of firm i due to knowledge transfer.
KD_i	Period two change in the level of knowledge of firm i due to knowledge development.
Q	Amount of knowledge firm 2 buys from firm 1 in period one (decision variable).
$\beta^P[K_{10}, K_{20}]$	Firms' prediction of the portion of the knowledge transfer that firm 2 will be able to integrate with its own knowledge resources for NPD. $\beta^P[K_{10}, K_{20}]$ satisfies the probability density function $\Phi(z)$ with mean \bar{z} and standard deviation σ , where $\partial \bar{z} / \partial K_{10}, \partial \bar{z} / \partial K_{20} \geq 0$ and $\partial^2 \bar{z} / \partial K_{10}^2, \partial^2 \bar{z} / \partial K_{20}^2 \leq 0$, $\partial \sigma / \partial K_{10}, \partial \sigma / \partial K_{20} \leq 0$ and $\partial^2 \sigma / \partial K_{10}^2, \partial^2 \sigma / \partial K_{20}^2 \geq 0$. ($0 < \beta^P [K_{10}, K_{20}] < 1$).
θ_1, θ_2	Indicates rate of diminishing returns from firm 2's own level of knowledge and the level of KT to firm 2, respectively ($0 \leq \theta_1, \theta_2 \leq 1$).
γ_i	Period two efforts undertaken by firm i for knowledge development (decision variable).
μ_i	Indicates the rate of diminishing returns from knowledge development efforts of the firm i ($0 \leq \mu_i \leq 1$).
δ_i	Probability that the new product developed by firm i will have the features and functionality making it successful in the marketplace ($0 \leq \delta_i \leq 1$).
δ_2^N	Probability that the new product developed by firm 2 will have the features and functionality making it successful in the marketplace, if firm 2 does not cooperate with firm 1 in the first period ($0 \leq \delta_2^N \leq 1, \delta_2^N \leq \delta_2$).

v_i	Loyal customers' valuation of the knowledge embedded by firm i into the new product ($v_i \geq 0$).
w_i^P	Firm i 's prediction of switching customers' valuation of the knowledge embedded by firm i relative to the knowledge embedded by firm k into each firm's new product ($w_i^P \geq 0$).
z_i	Customers' valuation of the knowledge embedded by firm i into the new product under the condition that only firm i is able to successfully develop a new product ($z_i \geq 0$).
c_i	Marginal cost of KD pursued by firm i in the second period ($c_i \geq 0$).
$G[KT_i]$	Period two revenue earned or cost incurred due to knowledge transfer or sharing between firms.
P	Price charged by firm 1 (leader) for knowledge it sells to firm 2 in period one (decision variable).
m_1	Marginal cost incurred by firm 1 due to loss of proprietary knowledge for sharing knowledge ($m_1 \geq 0$).

Joint Development

Notation	Definition
K_{ij}	Level of knowledge applied for NPD project by firm i at time j ; $i \in \{1,2\}$, $j \in \{0,1,2\}$, $K_{i0} \geq 0$.
K_{JDj}	Level of knowledge applied for NPD project by the firms jointly at time j ; $j \in \{1,2\}$.
$\beta^P[K_{10}, K_{20}]$	Firms' prediction of the extent that knowledge resources shared by one firm can be integrated with the knowledge resources shared by the other firm. $\beta^P[K_{10}, K_{20}]$ satisfies the probability density function $\Phi(z)$ with mean \bar{z} and standard deviation σ , where $\partial \bar{z} / \partial K_{10} > 0$, $\partial \bar{z} / \partial K_{20} > 0$ and $\partial^2 \bar{z} / \partial K_{10}^2 > 0$, $\partial^2 \bar{z} / \partial K_{20}^2 > 0$, $\partial \sigma / \partial K_{10} < 0$, $\partial \sigma / \partial K_{20} < 0$ and $\partial^2 \sigma / \partial K_{10}^2 < 0$, $\partial^2 \sigma / \partial K_{20}^2 < 0$. ($0 < \beta^P [K_{10}, K_{20}] < 1$).
Q_i	Amount of knowledge contributed by firm i to the joint development project, where $i \in \{1,2\}$ (decision variable).
γ_{JD}	Extent of efforts to be jointly allocated to knowledge development in period two (decision variable).
μ_{JD}	Indicates the rate of diminishing returns from joint knowledge

	development efforts ($0 \leq \mu_{JD} \leq 1$).
θ_1, θ_2	Indicates rate of diminishing returns to joint knowledge level at the end of period one from the amount of knowledge shared by firm 1 and firm 2, respectively ($0 \leq \theta_1, \theta_2 \leq 1$).
δ_{JD}	Probability that the new product developed jointly by the firms will have the features and functionality making it successful in the marketplace ($0 \leq \delta_{JD} \leq 1$).
v_{JD}^P	Customers' valuation of the knowledge embedded jointly by the firms into the new product ($v_{JD}^P \geq 0$).
$\lambda, 1-\lambda$	Portions of net expected revenue earned at the end of period two, by firm 1 and firm 2, respectively (decision variable). ($0 \leq \lambda \leq 1$).
c_{JD}	Marginal cost of KD pursued jointly by the firms in the second period ($c_{JD} \geq 0$).
m_i	Marginal cost incurred by firm i due to loss of proprietary knowledge for sharing knowledge ($m_i \geq 0$).

C.1 Competitive Development

C.1.1 Analytical Solutions and Sensitivity Analysis

Proof of Proposition 1

In order to determine γ_1^* , firm 1 maximizes the expected profit function in Equation (4.9):

$$\begin{aligned} E\{\pi_1\} &= \delta_1 v_1 K_{12} + \delta_1 \delta_2 w_1^P (K_{12} - K_{22}) + \delta_1 (1 - \delta_2) z_1 K_{12} + G[KT_i] - c_1 (\gamma_1)^2 - m_1 Q \\ &= \delta_1 v_1 (K_{11} + K_{11}^{\mu_1} \gamma_1) + \delta_1 \delta_2 w_1^P \{K_{11} + K_{11}^{\mu_1} \gamma_1 - (K_{21} + K_{21}^{\mu_2} \gamma_2)\} \\ &\quad + \delta_1 (1 - \delta_2) z_1 (K_{11} + K_{11}^{\mu_1} \gamma_1) + PQ - c_1 (\gamma_1)^2 - m_1 Q \end{aligned}$$

$$\frac{\partial E\{\pi_1\}}{\partial \gamma_1} = \{\delta_1 v_1 + \delta_1 \delta_2 w_1^P + \delta_1 (1 - \delta_2) z_1\} K_{11}^{\mu_1} - 2c_1 \gamma_1 = 0$$

Thus, $\gamma_1^* = \frac{\delta_1 \{v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1\} K_{11}^{\mu_1}}{2c_1}$. In order to ensure concavity, $\frac{\partial^2 E\{\pi_1\}}{\partial \gamma_1^2} = -2c_1 < 0$.

Similarly, in order to determine γ_2^* , firm 2 maximizes the expected profit function in Equation (4.10):

$$E\{\pi_2\} = \delta_2 v_2 K_{22} + \delta_1 \delta_2 w_2^P (K_{22} - K_{12}) + \delta_2 (1 - \delta_1) z_2 K_{22} - PQ - c_2 (\gamma_2)^2$$

$$\begin{aligned}
&= \delta_2 v_2 (K_{21} + K_{21}^{\mu_2} \gamma_2) + \delta_1 \delta_2 w_2^P \{K_{21} + K_{21}^{\mu_2} \gamma_2 - (K_{11} + K_{11}^{\mu_1} \gamma_1)\} \\
&\quad + \delta_2 (1 - \delta_1) z_2 (K_{21} + K_{21}^{\mu_2} \gamma_2) - PQ - c_2 (\gamma_2)^2 \\
\partial E\{\pi_2\} / \partial \gamma_2 &= \{\delta_2 v_2 + \delta_1 \delta_2 w_2^P + \delta_2 (1 - \delta_1) z_2\} K_{21}^{\mu_2} - 2c_2 \gamma_2 = 0
\end{aligned}$$

Thus, $\gamma_2^* = \frac{\delta_2 \{v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2\} K_{21}^{\mu_2}}{2c_2}$. In order to ensure concavity, $\frac{\partial^2 E\{\pi_2\}}{\partial \gamma_2^2} = -2c_2 < 0$.

Q.e.d.

Proof of Proposition 2

In order to determine Q^* , firm 2 maximizes the expected profit function in Equation (4.10):

$$\begin{aligned}
E\{\pi_2\} &= \delta_2 v_2 K_{22} + \delta_1 \delta_2 w_2^P (K_{22} - K_{12}) + \delta_2 (1 - \delta_1) z_2 K_{22} - PQ - c_2 (\gamma_2)^2 \\
&= \delta_2 v_2 (K_{21} + K_{21}^{\mu_2} \gamma_2) + \delta_1 \delta_2 w_2^P \{K_{21} + K_{21}^{\mu_2} \gamma_2 - (K_{11} + K_{11}^{\mu_1} \gamma_1)\} \\
&\quad + \delta_2 (1 - \delta_1) z_2 (K_{21} + K_{21}^{\mu_2} \gamma_2) - PQ - c_2 (\gamma_2)^2 \\
&= (\delta_2 v_2 + \delta_1 \delta_2 w_2^P + \delta_2 (1 - \delta_1) z_2) \left\{ K_{21} + K_{21}^{\mu_2} \left(\frac{\delta_2 \{v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2\} K_{21}^{\mu_2}}{2c_2} \right) \right\} \\
&\quad - \delta_1 \delta_2 w_2^P \left(K_{11} + K_{11}^{\mu_1} \frac{\delta_1 \{v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1\} K_{11}^{\mu_1}}{2c_1} \right) \\
&\quad - PQ - c_2 \left(\frac{\delta_2 \{v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2\} K_{21}^{\mu_2}}{2c_2} \right)^2 \\
&= \delta_2 (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2) (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}) \\
&\quad + \{\delta_2 (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\}^2 \frac{(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^2 \mu_2}{4c_2} \\
&\quad - \delta_1 \delta_2 w_2^P K_{10} - \delta_1^2 \delta_2 w_2^P (v_1 + \delta_2 w_1^P (1 - \delta_2) z_1) \frac{K_{10}^{2\mu_1}}{2c_1} - PQ
\end{aligned}$$

$$\begin{aligned}
\partial E\{\pi_2\} / \partial Q &= \delta_2 (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2) \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \theta_2 Q^{\theta_2 - 1} \\
&+ \frac{\{\delta_2 (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\}^2 \mu_2 (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2 - 1} \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \theta_2 Q^{\theta_2 - 1}}{2c_2} \\
&\quad - P = 0
\end{aligned}$$

Thus, Q^* satisfies

$$\begin{aligned}
2c_2 + \{\delta_2 (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\} \mu_2 (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2 - 1} \\
= \frac{2c_2 P}{\{\delta_2 (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\} \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2 - 1}}
\end{aligned}$$

In order to ensure concavity,

$$\begin{aligned}
& \frac{\partial^2 E\{\pi_2\}}{\partial Q^2} \\
& = (\theta_2 - 1)\{\delta_2(v_2 + \delta_1 w_2^P \\
& + (1 - \delta_1)z_2)\}\beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} \theta_2 Q^{\theta_2 - 2} \frac{\{2c_2 + \mu_2(K_{20} + \beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2 - 1}\}}{2c_2} \\
& + \{\delta_2(v_2 + \delta_1 w_2^P + \\
& (1 - \delta_1)z_2)\}\beta^P [K_{10}, K_{20}] \theta_2\}^2 K_{20}^{\theta_1 + 1} Q^{\theta_2} \frac{\mu_2(2\mu_2 - 1)(K_{20} + \beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2 - 2}}{2c_2} < 0. \text{ Q.e.d.}
\end{aligned}$$

Proof of Proposition 3

In order to ensure that firms 1 and 2 will cooperate through CD mechanism rather than pursuing NPD project individually, the expected profit that each firm receives at the end of second period if it cooperates through CD mechanism must be greater than or equal to the value for the case that it doesn't cooperate. Let $E\{\pi_i^N\}$ denote the expected profit for firm i if the firms are non-cooperative during the NPD process. Similarly, let γ_i^N denote the optimal rate of knowledge development pursued by firm i if the firms are non-cooperative. The expected profit function of firms 1 and 2 if they do not cooperate are:

$$\begin{aligned}
E\{\pi_1^N\} & = \delta_1 v_1 K_{12} + \delta_1 \delta_2^N w_1^P (K_{12} - K_{22}) + \delta_1 (1 - \delta_2^N) z_1 K_{12} - c_1 (\gamma_1^N)^2 \\
& = \delta_1 v_1 (K_{10} + K_{10}^{\mu_1} \gamma_1^N) + \delta_1 \delta_2^N w_1^P \{K_{10} + K_{10}^{\mu_1} \gamma_1^N - (K_{20} + K_{20}^{\mu_2} \gamma_2^N)\} \\
& + \delta_1 (1 - \delta_2^N) z_1 (K_{10} + K_{10}^{\mu_1} \gamma_1^N) - c_1 (\gamma_1^N)^2
\end{aligned}$$

$$\begin{aligned}
E\{\pi_2^N\} & = \delta_2 v_2 K_{22} + \delta_1 \delta_2^N w_2^P (K_{22} - K_{12}) + \delta_2^N (1 - \delta_1) z_2 K_{22} - c_2 (\gamma_2^N)^2 \\
& = \delta_2 v_2 (K_{20} + K_{20}^{\mu_2} \gamma_2^N) + \delta_1 \delta_2^N w_2^P \{K_{20} + K_{20}^{\mu_2} \gamma_2^N - (K_{10} + K_{10}^{\mu_1} \gamma_1^N)\} \\
& + \delta_2^N (1 - \delta_1) z_2 (K_{20} + K_{20}^{\mu_2} \gamma_2^N) - c_2 (\gamma_2^N)^2
\end{aligned}$$

And if solve for γ_1^{N*} and γ_2^{N*} , we obtain:

$$\begin{aligned}
E\{\pi_1^N\} & = \delta_1 (v_1 + \delta_2^N w_1^P + (1 - \delta_2^N) z_1) K_{10} + \frac{\{\delta_1 (v_1 + \delta_2^N w_1^P + (1 - \delta_2^N) z_1)\}^2 K_{10}^{2\mu_1}}{4c_1} \\
& - \delta_1 \delta_2^N w_1^P \left(K_{20} + \frac{\{\delta_2^N (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\} K_{20}^{2\mu_2}}{2c_2} \right)
\end{aligned}$$

$$E\{\pi_2^N\} = \delta_2^N (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2) K_{20} + \frac{\{\delta_2^N (v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\}^2 K_{20}^{2\mu_2}}{4c_2}$$

$$- \delta_1 \delta_2 w_2^P \left(K_{10} + \frac{\{\delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N) z_1)\} K_{10}^{2\mu_1}}{2c_1} \right)$$

When we substitute γ_1^* and γ_2^* from Equation (4.16), we obtain the expected profit functions of firms 1 and 2 if the cooperate through CD mechanism:

$$\begin{aligned} E\{\pi_1\} &= \delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1) K_{10} + \frac{\{\delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1)\}^2 K_{10}^{2\mu_1}}{4c_1} \\ &- \delta_1 \delta_2 w_1^P \left(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2} + \frac{\{\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\} \{K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}\}^{2\mu_2}}{2c_2} \right) \\ &+ (P - m_1) Q \\ E\{\pi_2\} &= \delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2) (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}) \\ &+ \frac{\{\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\}^2 \{K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}\}^{2\mu_2}}{4c_2} \\ &- \delta_1 \delta_2 w_2^P \left(K_{10} + \frac{\{\delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1)\} K_{10}^{2\mu_1}}{2c_1} \right) - PQ \end{aligned}$$

Thus, the expected profit functions of firms 1 and 2 must satisfy:

$E\{\pi_1\} \geq E\{\pi_1^N\}$, or,

$$\begin{aligned} \delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1) K_{10} + \frac{\{\delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1)\}^2 K_{10}^{2\mu_1}}{4c_1} \\ - \delta_1 \delta_2 w_1^P \left(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2} \right. \\ \left. + \frac{\{\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\} \{K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}\}^{2\mu_2}}{2c_2} \right) \\ + (P - m_1) Q \geq \delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N) z_1) K_{10} + \frac{\{\delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N) z_1)\}^2 K_{10}^{2\mu_1}}{4c_1} \\ - \delta_1 \delta_2^N w_1^P \left(K_{20} + \frac{\{\delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1) z_2)\} K_{20}^{2\mu_2}}{2c_2} \right). \end{aligned}$$

Thus,

$$\begin{aligned} (P - m_1) Q &\geq (X^N - X) K_{10} + \frac{\{(X^N)^2 - X^2\} K_{10}^{2\mu_1}}{4c_1} + \delta_1 w_1^P (\delta_2 - \delta_2^N) K_{20} \\ &+ \delta_1 \delta_2 w_1^P \left(\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2} + \frac{Y(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2}}{2c_2} \right) \\ &- \delta_1 \delta_2^N w_1^P \left(\frac{Y^N K_{20}^{2\mu_2}}{2c_2} \right) \end{aligned}$$

where $X = \delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2) z_1)$

$$\begin{aligned}
Y &= \delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2) \\
X^N &= \delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N)z_1) \\
Y^N &= \delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2).
\end{aligned}$$

Also, $\{\pi_2\} \geq E\{\pi_2^N\}$, or,

$$\begin{aligned}
&\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}) \\
&+ \frac{\{\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)\}^2 (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2}}{4c_2} \\
&- \delta_1 \delta_2 w_2^P \left(K_{10} + \frac{\{\delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2)z_1)\} K_{10}^{2\mu_1}}{2c_1} \right) - PQ \geq \delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2) K_{20} \\
&+ \frac{\{\delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)\}^2 K_{20}^{2\mu_2}}{4c_2} - \delta_1 \delta_2^N w_2^P \left(K_{10} + \frac{\{\delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N)z_1)\} K_{10}^{2\mu_1}}{2c_1} \right).
\end{aligned}$$

Thus,

$$\begin{aligned}
PQ &\geq Y^N K_{20} + \frac{Y^N K_{20}^{2\mu_2}}{4c_2} - \delta_1 \delta_2^N w_2^P \left(K_{10} + \frac{X^N K_{10}^{2\mu_1}}{2c_1} \right) - Y(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}) \\
&+ \frac{Y^2 (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2}}{4c_2} - \delta_1 \delta_2 w_2^P \left(K_{10} + \frac{X K_{10}^{2\mu_1}}{2c_1} \right)
\end{aligned}$$

where $X = \delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2)z_1)$

$$\begin{aligned}
Y &= \delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2) \\
X^N &= \delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N)z_1) \\
Y^N &= \delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2).
\end{aligned}$$

Thus,

$$\begin{aligned}
PQ &\geq \delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2) K_{20} + \frac{\{\delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)\}^2 K_{20}^{2\mu_2}}{4c_2} \\
&- \delta_1 \delta_2^N w_2^P \left(K_{10} + \frac{\{\delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N)z_1)\} K_{10}^{2\mu_1}}{2c_1} \right) - \delta_2(v_2 + \delta_1 w_2^P + (1 - \\
&\delta_1)z_2)(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2}) \\
&- \frac{\{\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)\}^2 (K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2})^{2\mu_2}}{4c_2} \\
&+ \delta_1 \delta_2 w_2^P \left(K_{10} + \frac{\{\delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2)z_1)\} K_{10}^{2\mu_1}}{2c_1} \right). \quad \text{Q.e.d.}
\end{aligned}$$

Proof of Proposition 4

If $\mu_1 = \mu_2 = \frac{1}{2}$, then $Y_1^* = \frac{\delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2)z_1)K_{11}^{1/2}}{2c_1}$ and $Y_2^* = \frac{\delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)K_{21}^{1/2}}{2c_2}$

from Equation (4.16).

Let $X = \delta_1(v_1 + \delta_2 w_1^P + (1 - \delta_2)z_1)$

$Y = \delta_2(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)$

Thus, in order to determine Q^* , firm 2 maximizes the expected profit function:

$$E\{\pi_2\} = \frac{Y(4c_2 + Y)(K_{20} + \beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} Q^{\theta_2})}{4c_2} - \frac{\delta_1 \delta_2 w_2^P (2c_1 + X)K_{10}}{2c_1} - PQ$$

$$\frac{\partial E\{\pi_2\}}{\partial Q} = \frac{Y(4c_2 + Y)(K_{20} + \beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} \theta_2 Q^{\theta_2 - 1})}{4c_2} - P = 0$$

$$\text{Thus, } Q^* = \left[\frac{4c_2 P}{Y(4c_2 + Y)\beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} \theta_2} \right]^{\frac{1}{\theta_2 - 1}}$$

In order to ensure concavity,

$$\frac{\partial^2 E\{\pi_2\}}{\partial Q^2} = \frac{Y(4c_2 + Y)(K_{20} + \beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} \theta_2 (\theta_2 - 1) Q^{\theta_2 - 2})}{4c_2} < 0.$$

If $\mu_1 = \mu_2 = \frac{1}{2}$, in order to determine P^* , firm 1 maximizes the expected profit function:

$$E\{\pi_1\} = \frac{X(4c_1 + X)K_{10}}{2c_1} - \frac{\delta_1 \delta_2 w_1^P (2c_2 + Y)(K_{20} + \beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} Q^{\theta_2})}{2c_2} + (P - m_1)Q$$

Let $\psi = \left[\frac{4c_2}{Y(4c_2 + Y)\beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} \theta_2} \right]^{\frac{1}{\theta_2 - 1}}$. Then $Q^* = \psi P^{\frac{1}{\theta_2 - 1}}$. If we substitute Q^* into the expected profit function for firm 1, we get:

$$E\{\pi_1\} = \frac{X(4c_1 + X)K_{10}}{2c_1} - \frac{\delta_1 \delta_2 w_1^P (2c_2 + Y)(K_{20} + \beta^P [K_{10}, K_{20}]K_{20}^{\theta_1} \psi^{\theta_2} P^{\frac{\theta_2}{\theta_2 - 1}})}{2c_2} + \psi P^{\frac{\theta_2}{\theta_2 - 1}} - m_1 \psi P^{\frac{1}{\theta_2 - 1}}$$

Firm 1 determines P^* that maximizes the above profit function:

$$\frac{\partial E\{\pi_1\}}{\partial P} = -\frac{\delta_1 \delta_2 w_1^P (2c_2 + Y)(K_{20} + \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \psi^{\theta_2} \left(\frac{\theta_2}{\theta_2 - 1}\right) P^{\frac{1}{\theta_2 - 1}})}{2c_2} + \psi \left(\frac{\theta_2}{\theta_2 - 1}\right) P^{\frac{1}{\theta_2 - 1}} - m_1 \psi \left(\frac{1}{\theta_2 - 1}\right) P^{\frac{2 - \theta_2}{\theta_2 - 1}} = 0$$

Thus, $P^* = \frac{2c_2 m_1}{\theta_2 \{2c_2 - \delta_1 \delta_2 w_1^P (2c_2 + Y) \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \psi^{\theta_2 - 1}\}}$, or

$$P^* = \frac{m_1 Y (4c_2 + Y)}{\theta_2 Y (4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y)}$$

In order to ensure concavity,

$$\frac{\partial^2 E\{\pi_1\}}{\partial P^2} = -\frac{\delta_1 \delta_2 w_1^P (2c_2 + Y) \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \psi^{\theta_2} \left(\frac{\theta_2}{\theta_2 - 1}\right) \left(\frac{1}{\theta_2 - 1}\right) P^{\frac{2 - \theta_2}{\theta_2 - 1}}}{2c_2} + \psi \left(\frac{\theta_2}{\theta_2 - 1}\right) \left(\frac{1}{\theta_2 - 1}\right) P^{\frac{2 - \theta_2}{\theta_2 - 1}} - m_1 \psi \left(\frac{1}{\theta_2 - 1}\right) \left(\frac{2 - \theta_2}{\theta_2 - 1}\right) P^{\frac{3 - 2\theta_2}{\theta_2 - 1}} < 0.$$

Thus, $P < \frac{m_1 (2 - \theta_2) c_2}{\theta_2 \{2c_2 - \delta_1 \delta_2 w_1^P (2c_2 + Y) \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \psi^{\theta_2 - 1}\}}$

In addition, we know that $Q \leq K_{10}$. Thus, $\psi P^{\frac{1}{\theta_2 - 1}} \leq K_{10}$. If we substitute ψ into this inequality and rearrange:

$$P \leq \frac{K_{10}^{\theta_2 - 1} (4c_2 + v_2 + w_2^P) (v_2 + w_2^P) \beta^P K_{20}^{\theta_1} \theta_2}{2c_2}.$$

Through substituting P^* into the Q^* Equation, we obtain:

$$Q^* = \left[\frac{4c_2 m_1}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \theta_2 \{ \theta_2 Y (4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y) \}} \right]^{\frac{1}{\theta_2 - 1}}$$

And finally, through substituting Q^* into the γ_1^* and γ_2^* equation, we obtain:

$$\gamma_1^* = \frac{X K_{10}^{1/2}}{2c_1}$$

$$\gamma_2^* = \frac{Y \left[K_{20} + \left\{ \frac{1}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \left(\theta_2 Y (4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y) \right) \right\}^{\theta_2} \right]^{\frac{1}{\theta_2 - 1}}}{2c_2}$$

Note that when we substitute P^* , Q^* , γ_1^* and γ_2^* into the $E\{\pi_1\}$ and $E\{\pi_2\}$ equations, we obtain:

$$\begin{aligned}
E\{\pi_1\} &= \frac{X(2c_1 + X)K_{10}}{2c_1} - \frac{X^2 K_{10}}{2c_1} \\
&\quad - \frac{\delta_1 \delta_2 w_1^P (2c_2 + Y)}{4c_2^2} \left\{ K_{20} + \left[\frac{1}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1}} \left(\frac{4c_2 m_1}{\theta_2 Y (4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y)} \right)^{\theta_2} \right]^{\frac{1}{\theta_2 - 1}} \right\} \\
&\quad + \left(\frac{4c_2 m_1}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1}} \right)^{\frac{1}{\theta_2 - 1}} \frac{m_1 \{Y(4c_2 + Y)(1 - \theta_2) + 2\theta_2 \delta_1 \delta_2 w_1^P (2c_2 + Y)\}}{\{\theta_2 Y (4c_2 + Y) - 2\theta_2 \delta_1 \delta_2 w_1^P (2c_2 + Y)\}^{\frac{\theta_2}{\theta_2 - 1}}} \\
E\{\pi_2\} &= \frac{Y(2c_2 + Y)}{2c_2} \left\{ K_{20} + \left[\frac{1}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1}} \left(\frac{4c_2 m_1}{\theta_2 Y (4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y)} \right)^{\theta_2} \right]^{\frac{1}{\theta_2 - 1}} \right\} - \frac{\delta_1 \delta_2 w_2^P K_{10}}{2c_1} \\
&\quad - \frac{Y^2 \left[K_{20} + \left\{ \frac{1}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1}} \left(\frac{4c_2 m_1}{\theta_2 Y (4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y)} \right)^{\theta_2} \right\}^{\frac{1}{\theta_2 - 1}} \right]}{4c_2} \\
&\quad - Y(4c_2 + Y) \left\{ \left(\frac{4c_2}{\beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} \theta_2} \right) \left(\frac{m_1}{\theta_2 Y (4c_2 + Y) - 2\delta_1 \delta_2 w_1^P (2c_2 + Y)} \right)^{\theta_2} \right\}^{\frac{1}{\theta_2 - 1}}
\end{aligned}$$

Suppose $\mu_1 = \mu_2 = \frac{1}{2}$. Firm 1 enters into a cooperative agreement if the following inequality holds:

$$\begin{aligned}
(P - m_1)Q^{\theta_2} &\geq \frac{\{(X^N - X)4c_1 + (X^N)^2 - X^2\}K_{10}}{4c_1} - \delta_1 \delta_2 w_1^P \left(\frac{2c_2 + Y}{2c_2} \right) \beta^P [K_{10}, K_{20}] K_{20}^{\theta_1} Q^{\theta_2} \\
&\quad + \delta_1 w_1^P \left(\frac{(\delta_2 - \delta_2^N)(2c_2 + Y)}{2c_2} \right) K_{20}
\end{aligned}$$

and

Note that, when $\mu_1 = \mu_2 = \frac{1}{2}$, the expected profit function of firms 1 and 2 if they do not cooperate are:

$$\begin{aligned}
E\{\pi_1^N\} &= \frac{X^N(4c_1 + X^N)K_{10}}{4c_1} - \delta_1 \delta_2^N w_1^P \frac{(2c_2 + Y^N)K_{20}}{2c_2} \\
E\{\pi_2^N\} &= \frac{Y^N(4c_2 + Y^N)K_{20}}{4c_2} - \delta_1 \delta_2^N w_2^P \frac{(2c_1 + X^N)K_{10}}{2c_1}
\end{aligned}$$

where $X^N = \delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N)z_1)$

$Y^N = \delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2)$. *Q.e.d.*

Proof of Proposition 5

This proof follows directly from Equation (4.21).

Proof of Proposition 6

This proof follows directly from Equation (4.22).

Proof of Proposition 7

This proof follows directly from Equation (4.23).

Proof of Proposition 8

This proof follows directly from Equation (4.24).

C.1.2 Numerical Examples: Example 1 and Its Variations

For the numerical analysis introduced in Section 4.5.1.2, we assume $\mu_1=\mu_2=1/2$. As noted $\beta^P[K_{10},K_{20}]$ satisfies the probability density function $\Phi(z)$ with mean \bar{z} and standard deviation σ , \bar{z} is a function of K_{10} and K_{20} . We assume the functional form below for \bar{z} . For the numerical analysis included in Chapter 4 no functional form the relationship between σ and K_{10} and K_{20} was necessary. All the other functional forms employed are derived from Equations (4.21)-(4.24). Numerical solutions are obtained with EXCEL.

$$\bar{z} = e^{-\varphi(K_{10}+K_{20})}$$

Table C.2 Input values for Example 1

Parameter	Value	Parameter	Value	Parameter	Value
K_{10}	100	δ_2^N	0.4	v_2	100
K_{10}	80	θ_1	0.5	w_2^P	20
$\beta^P[K_{10},K_{20}]$	0.593	θ_2	0.5	z_2	10
φ	0.005	v_1	100	c_1	100
δ_1	0.5	w_1^P	20	c_2	100
δ_2	0.5	z_1	10	m_1	40

Table C.3 Summary of results for Example 1

P	Q	γ_1	γ_2	$E\{\pi_1\}$	$E\{\pi_2\}$	$E\{\pi_1^N\}$	$E\{\pi_2^N\}$
96.95	3.08	2.88	2.72	6187.47	4930.29	6099.88	3589.21

C.1.2.1 Impact of w_2^P

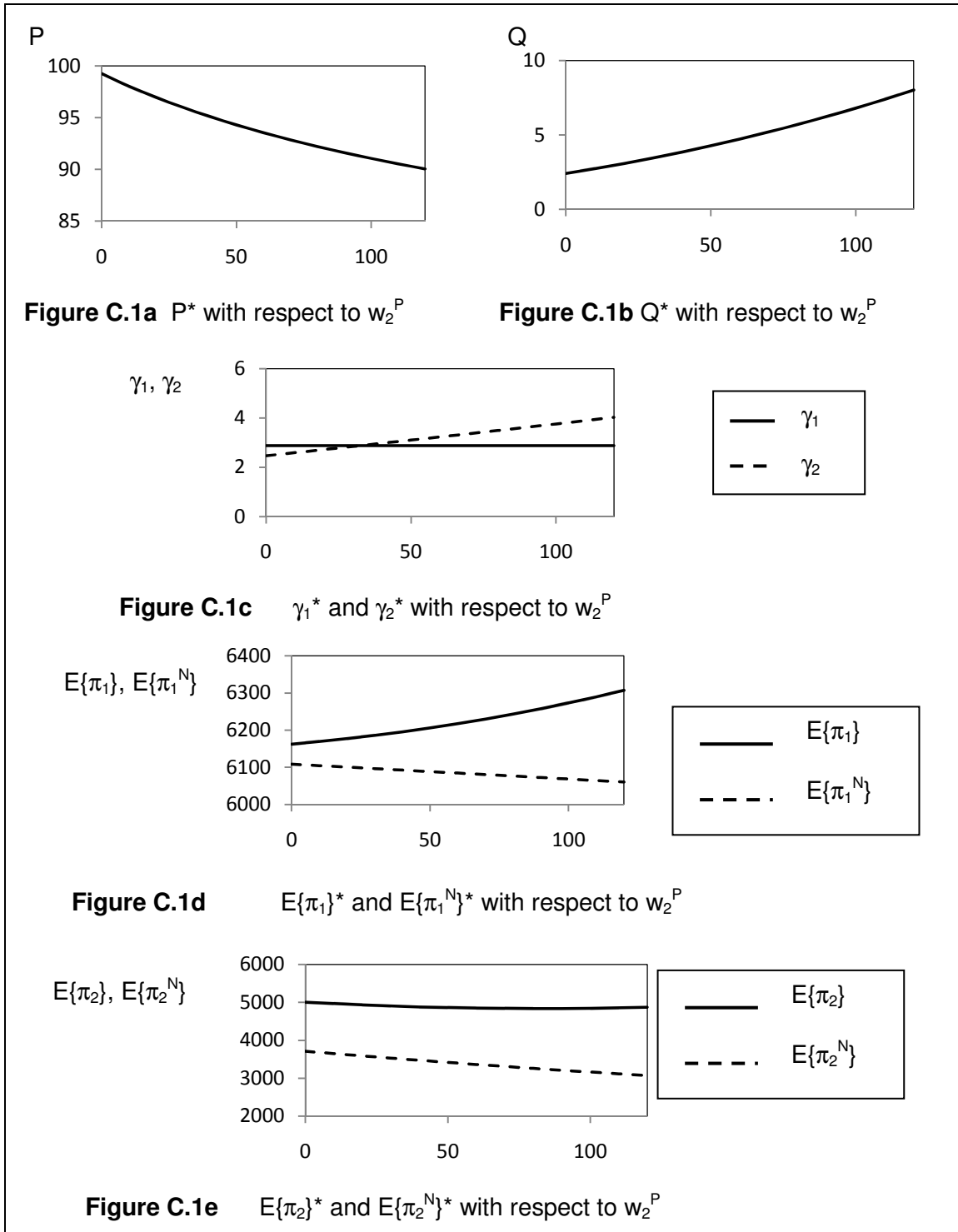


Figure C.1 KT and KD decisions and the expected profits of firms 1 and 2 with respect to w_2^P

C.1.2.2 Impact of z_2

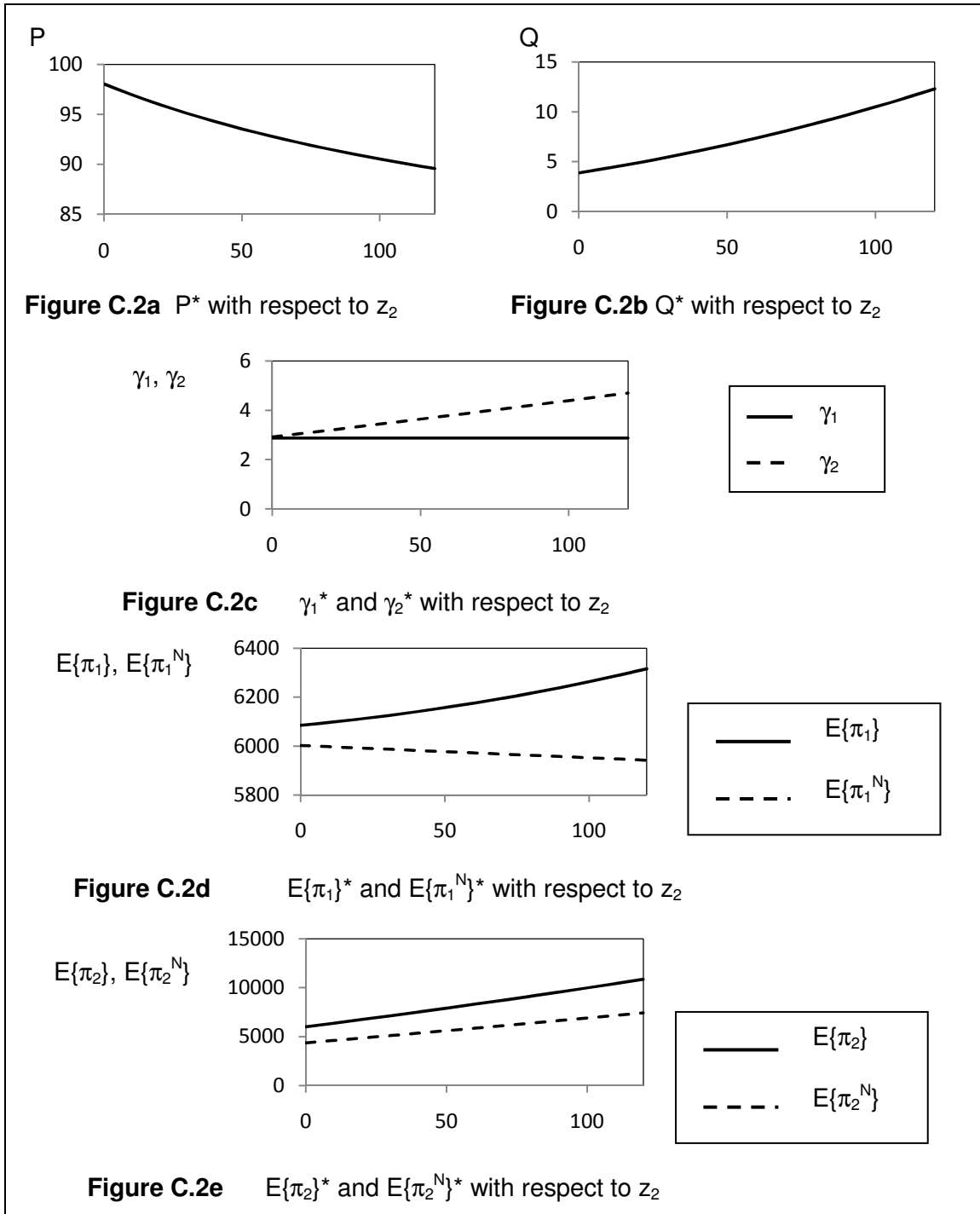


Figure C.2 KT and KD decisions and the expected profits of firms 1 and 2 with respect to z_2

C.1.3 Experimental Analysis of Impact of Uncertainty

For the experimental analysis introduced in Section 4.5.1.3, we assume $\mu_1 = \mu_2 = 1/2$. As noted for w_1^P and $\beta^P[K_{10}, K_{20}]$ we assume a triangular distribution, where the mean of the distribution of $\beta^P[K_{10}, K_{20}]$, \bar{z} , is a function of K_{10} and K_{20} . These values and other relevant data are given in Table C.4. All the other functional forms employed are derived from Equations (4.21)-(4.24). Numerical solutions are obtained with EXCEL.

$$\bar{z} = e^{-\varphi(K_{10} + K_{20})}$$

Table C.4 Triangular distribution settings for w_1^P and w_2^P

Triangular distribution	Low uncertainty	High uncertainty symmetric	High uncertainty skewed
Lower value	19	15	14
Upper value	21	25	28
Mode	20	20	18
Mean	20	20	20
Standard deviation	0.41	2.04	2.95

Table C.5 Summary of results for the experimental analysis of uncertainty associated with w_1^P and w_2^P

(a) Summary of results for the experimental analysis of uncertainty associated with w_1^P

P	Q	γ_1	γ_2	$E\{\pi_1\}$	$E\{\pi_2\}$	$E\{\pi_1^N\}$	$E\{\pi_2^N\}$
Low uncertainty							
96.95	3.08	2.88	2.72	6187.47	4930.29	6099.88	3589.21
High uncertainty symmetric							
97.04	3.08	2.86	2.72	6148.64	4935.68	6097.95	3589.23
High uncertainty skewed							
97.21	3.07	2.91	2.71	6259.73	4921.72	6101.45	3589.15

(b) Summary of results for the experimental analysis of uncertainty associated with w_2^P

P	Q	γ_1	γ_2	$E\{\pi_1\}$	$E\{\pi_2\}$	$E\{\pi_1^N\}$	$E\{\pi_2^N\}$
Low uncertainty							
96.97	3.08	2.88	2.72	6177.07	4931.81	6100.24	3589.38
High uncertainty symmetric							
96.99	3.07	2.88	2.71	6176.92	4919.59	6100.31	3583.33
High uncertainty skewed							
97.03	3.06	2.88	2.71	6176.06	4936.15	6100.45	3590.31

Table C.6 Triangular distribution settings for $\beta^P[K_{10}, K_{20}]$

Triangular distribution	Low uncertainty	High uncertainty symmetric	High uncertainty skewed
Lower value	0.591	0.356	0.292
Upper value	0.595	0.836	0.987
Mode	0.593	0.593	0.500
Mean	0.593	0.593	0.593
Standard deviation	0.000	0.42	0.62

Table C.7 Summary of results for the experimental analysis of uncertainty associated with $\beta^P[K_{10}, K_{20}]$

P	Q	γ_1	γ_2	$E\{\pi_1\}$	$E\{\pi_2\}$	$E\{\pi_1^N\}$	$E\{\pi_2^N\}$
Low uncertainty							
96.13	3.08	2.88	2.72	6174.34	4933.67	6100.25	3210.29
High uncertainty symmetric							
96.13	3.47	2.88	2.74	6189.10	4984.88	6100.25	3210.89
High uncertainty skewed							
96.13	3.25	2.88	2.71	6177.03	4918.43	6100.25	3210.02

C.2 Joint Development

C.2.1 Analytical Solutions and Sensitivity Analysis

Proof of Proposition 9

In order to determine γ_{JD}^* , the firms maximize the total expected profit function of the system ($E\{\pi_{JD}\}$):

$$E\{\pi_{JD}\} = \delta_{JD} v_{JD}^P K_{JD2} - c_{JD} (\gamma_{JD})^2 = v_{JD}^P (K_{JD1} + K_{JD1}^{\mu_{JD}} \gamma_{JD}) - c_{JD} (\gamma_{JD})^2$$

$$\frac{\partial E\{\pi_{JD}\}}{\partial \gamma_{JD}} = \delta_{JD} v_{JD}^P K_{JD1}^{\mu_{JD}} - 2c_{JD} \gamma_{JD} = 0.$$

Thus, $\gamma_{JD}^* = \delta_{JD} v_{JD}^P K_{JD1}^{\mu_{JD}} / 2c_{JD}$. In order to ensure concavity, $\frac{\partial^2 E\{\pi_{JD}\}}{\partial \gamma_{JD}^2} = -2c_{JD} < 0$.

Since $K_{JD1} = \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2}$, we can conclude that

$$\gamma_{JD}^* = \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{\mu_{JD}}}{2c_{JD}}. \text{ Q.e.d.}$$

Proof of Proposition 10

In order to determine Q_2^* , firm 2 maximizes the profit function in Equation (4.14):

$$E\{\pi_2\} = (1 - \lambda) \{ \delta_{JD} v_{JD}^P K_{JD2} - c_{JD} (\gamma_{JD})^2 \} - m_2 Q_2$$

$$= (1 - \lambda) \left\{ \delta_{JD} v_{JD}^P \left[\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} + \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{2c_{JD}} \right] - \frac{(\delta_{JD} v_{JD}^P)^2 (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{4c_{JD}} \right\} - m_2 Q_2$$

$$= (1 - \lambda) \delta_{JD} v_{JD}^P \left[\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} + \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{4c_{JD}} \right] - m_2 Q_2$$

$$\frac{\partial E\{\pi_2\}}{\partial Q_2} = (1 - \lambda) \delta_{JD} v_{JD}^P \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2 Q_2^{\theta_2-1} \left[1 + \frac{\mu_{JD} \delta_{JD} v_{JD}^P \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}-1}}{2c_{JD}} \right] - m_2 = 0.$$

Thus, Q_2^* satisfies:

$$1 + \frac{\mu_{JD} \delta_{JD} v_{JD}^P \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}-1}}{2c_{JD}} = \frac{m_2}{(1-\lambda) \delta_{JD} v_{JD}^P \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2 Q_2^{\theta_2-1}}.$$

In order to ensure concavity,

$$\frac{\partial^2 E\{\pi_2\}}{\partial Q_2^2} = (1 - \lambda) \delta_{JD} v_{JD}^P \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2 (\theta_2 - 1) Q_2^{\theta_2-2}$$

$$+ \frac{(1-\lambda) (\delta_{JD} v_{JD}^P)^2 (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1})^{2\mu_{JD}} \theta_2 \mu_{JD} (2\theta_2 \mu_{JD} - 1) Q_2^{2(\theta_2 \mu_{JD} - 1)}}{2c_{JD}} < 0. \text{ Q.e.d.}$$

Proof of Proposition 11

In order to ensure that firms 1 and 2 will cooperate through CD mechanism rather than pursuing NPD project individually, the expected profit that each firm receives at the end of second period, if it cooperates through JD mechanism, must be greater than or equal to the value for the case that it doesn't cooperate. Let $E\{\pi_i^N\}$ denote the expected profit for firm i if the firms are non-cooperative during the NPD process. Similarly, let γ_i^N denote the optimal rate of knowledge development pursued by firm i if the firms are non-cooperative. From the proof of Proposition 1, the expected profit function of firms 1 and 2 if they do not cooperate are:

$$E\{\pi_1^N\} = X^N K_{10} + \frac{(X^N)^2 K_{10}^{2\mu_1}}{4c_1} - \delta_1 \delta_2^N w_1^P \left(K_{20} + \frac{Y^N K_{20}^{2\mu_2}}{2c_2} \right)$$

$$E\{\pi_2^N\} = Y^N K_{20} + \frac{(Y^N)^2 K_{20}^{2\mu_2}}{4c_2} - \delta_1 \delta_2^N w_2^P \left(K_{10} + \frac{X^N K_{10}^{2\mu_1}}{2c_1} \right)$$

$$\text{Where } X^N = \delta_1(v_1 + \delta_2^N w_1^P + (1 - \delta_2^N)z_1)$$

$$Y^N = \delta_2^N(v_2 + \delta_1 w_2^P + (1 - \delta_1)z_2).$$

From the proof of Proposition 5, the expected profit functions of firms 1 and 2 if they cooperate through the JD mechanism are:

$$\begin{aligned} E\{\pi_1\} &= \lambda\{\delta_{JD} v_{JD}^P K_{JD2} - c_{JD}(Y_{JD})^2\} - m_1 Q_1 \\ &= \lambda\{\delta_{JD} v_{JD}^P \left[\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} + \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{4c_{JD}} \right] - m_1 Q_1 \end{aligned}$$

$$\begin{aligned} E\{\pi_2\} &= (1 - \lambda)\{\delta_{JD} v_{JD}^P K_{JD2} - c_{JD}(Y_{JD})^2\} - m_2 Q_2 \\ &= (1 - \lambda)\{\delta_{JD} v_{JD}^P \left[\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} + \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{4c_{JD}} \right] - m_2 Q_2 \end{aligned}$$

Thus, firms to enter into a joint development agreement, the expected profit functions of firms 1 and 2 must satisfy:

$$E\{\pi_1\} \geq E\{\pi_1^N\}, \text{ or,}$$

$$\begin{aligned} &\lambda\{\delta_{JD} v_{JD}^P \left[\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} + \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{4c_{JD}} \right] - m_1 Q_1 \\ &\geq X^N K_{10} + \frac{(X^N)^2 K_{10}^{2\mu_1}}{4c_1} - \delta_1 \delta_2^N w_1^P \left(K_{20} + \frac{Y^N K_{20}^{2\mu_2}}{2c_2} \right) \end{aligned}$$

Also, $E\{\pi_2\} \geq E\{\pi_2^N\}$, or,

$$(1 - \lambda)\{\delta_{JD}v_{JD}^P \left[\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2} + \frac{\delta_{JD}v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{2\mu_{JD}}}{4c_{JD}} \right] - m_2 Q_2} \\ \geq Y^N K_{20} + \frac{(Y^N)^2 K_{20}^{2\mu_2}}{4c_2} - \delta_1 \delta_2^N w_2^P \left(K_{10} + \frac{X^N K_{10}^{2\mu_1}}{2c_1} \right). \text{ Q.e.d.}$$

Proof of Proposition 12

If $\mu_1 = \mu_2 = \frac{1}{2}$, then $\gamma_{JD}^* = \frac{\delta_{JD}v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{1/2}}{2c_{JD}}$. Thus, in order to determine Q_2^* ,

firm 2 maximizes the profit function:

$$E\{\pi_2\} = (1 - \lambda)\delta_{JD}v_{JD} \frac{(4c_{JD} + \delta_{JD}v_{JD}^P)\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2}}{4c_{JD}} - m_2 Q_2$$

$$\frac{\partial E\{\pi_2\}}{\partial Q_2} = (1 - \lambda)\delta_{JD}v_{JD} \frac{(4c_{JD} + \delta_{JD}v_{JD}^P)\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2 Q_2^{\theta_2-1}}{4c_{JD}} - m_2 = 0$$

$$\text{Thus, } Q_2^* = \left[\frac{4m_2 c_{JD}}{(1-\lambda)\delta_{JD}v_{JD}(4c_{JD}+v_{JD}^P)\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2} \right]^{\frac{1}{\theta_2-1}}.$$

In order to ensure concavity,

$$\frac{\partial^2 E\{\pi_2\}}{\partial Q_2^2} = (1 - \lambda)\delta_{JD}v_{JD} \frac{(4c_{JD} + \delta_{JD}v_{JD}^P)\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2 (\theta_2 - 1) Q_2^{\theta_2-2}}{4c_{JD}} < 0.$$

In addition, we know that $Q_1^* \leq K_{10}$. If we rearrange the solution for Q_2^* , we obtain

$$Q_2^* \leq \left[\frac{4m_2 c_{JD}}{(1-\lambda)\delta_{JD}v_{JD}^P (4c_{JD} + v_{JD}^P)\beta^P [K_{10}, K_{20}] K_{10}^{\theta_1} \theta_2} \right]^{\frac{1}{\theta_2-1}}.$$

Next, in order to determine Q_1^* , firm 1 maximizes the profit function:

$$E\{\pi_1\} = \lambda\delta_{JD}v_{JD}^P \frac{(4c_{JD} + \delta_{JD}v_{JD}^P)\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2}}{4c_{JD}} - m_1 Q_1$$

Let $\Delta = \left[\frac{4m_2 c_{JD}}{(1-\lambda)\delta_{JD}v_{JD}^P (4c_{JD} + v_{JD}^P)\beta^P [K_{10}, K_{20}] \theta_2} \right]^{\frac{1}{\theta_2-1}}$. Then $Q_2^* = \Delta Q_1^{\frac{-\theta_1}{\theta_2-1}}$. If we substitute Q_2^*

into the expected profit function for firm 1, we get:

$$E\{\pi_1\} = \lambda\delta_{JD}v_{JD}^P \frac{(4c_{JD} + \delta_{JD}v_{JD}^P)\beta^P [K_{10}, K_{20}] Q_1^{\frac{-\theta_1}{\theta_2-1} \Delta^{\theta_2}}}{4c_{JD}} - m_1 Q_1$$

Firm 1 determines Q_1^* that maximizes the above profit function:

$$\frac{\partial E\{\pi_1\}}{\partial Q_1} = \lambda \delta_{JD} v_{JD}^P \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] \Delta^{\theta_2}}{4c_{JD}} \left(\frac{-\theta_1}{\theta_2 - 1} \right) Q_1^{\frac{1-\theta_1-\theta_2}{\theta_2-1}} - m_1 = 0.$$

Thus, $Q_1^* = \left[\frac{4m_1 c_{JD} (1-\theta_2)}{\lambda \delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] \Delta^{\theta_2} \theta_1} \right]^{\frac{\theta_2-1}{1-\theta_1-\theta_2}}$, or

$$Q_1^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD}} \left(\frac{\lambda \theta_1}{m_1 (1-\theta_2)} \right)^{1-\theta_2} \left(\frac{(1-\lambda)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1-\theta_1-\theta_2}}$$

In order to ensure concavity,

$$\frac{\partial^2 E\{\pi_2\}}{\partial Q_2^2} = \lambda \delta_{JD} v_{JD}^P \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] \Delta^{\theta_2}}{4c_{JD}} \left(\frac{-\theta_1}{\theta_2 - 1} \right) \left(\frac{1-\theta_1-\theta_2}{\theta_2-1} \right) Q_1^{\frac{2-\theta_1-2\theta_2}{\theta_2-1}} < 0.$$

Thus, $1 - \theta_1 - \theta_2 > 0$ and $\theta_1 + \theta_2 < 1$.

Since $Q_2^* = \Delta Q_1^{\frac{-\theta_1}{\theta_2-1}}$, if we substitute Δ and Q_1^* into the solution of Q_2^* , we obtain:

$$Q_2^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD}} \left(\frac{(1-\lambda)\theta_2}{m_2} \right)^{1-\theta_1} \left(\frac{\lambda \theta_1}{m_1 (1-\theta_2)} \right)^{\theta_1} \right]^{\frac{1}{1-\theta_1-\theta_2}}$$

We know that $\gamma_{JD}^* = \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{1/2}}{2c_{JD}}$. If we substitute Q_1^* and Q_2^* solutions

into the from γ_{JD}^* solution, we obtain:

$$\gamma_{JD}^* = \left[\left(\frac{\delta_{JD} v_{JD}^P}{c_{JD}} \right)^{2-\theta_1-\theta_2} (4c_{JD} + \delta_{JD} v_{JD}^P)^{\theta_1+\theta_2} \left(\frac{\lambda \theta_1}{m_1 (1-\theta_2)} \right)^{\theta_1} \left(\frac{(1-\lambda)\theta_2}{m_2} \right)^{\theta_2} \frac{\beta^P [K_{10}, K_{20}]}{4} \right]^{\frac{1}{2(1-\theta_1-\theta_2)}}$$

Firm 1 determines λ that maximizes $E\{\pi_1\}$:

$$E\{\pi_1\} = \lambda \delta_{JD} v_{JD}^P \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] Q_1^{\frac{-\theta_1}{\theta_2-1}} \Delta^{\theta_2}}{4c_{JD}} - m_1 Q_1$$

If we substitute the Q_1^* and Q_2^* solutions, we obtain:

$$E\{\pi_1\} = [A(1-\lambda)^{\theta_2} \lambda^{1-\theta_2}]^\rho - [B(1-\lambda)^{\theta_2} \lambda^{1-\theta_2}]^\rho$$

where

$$A = \frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] \theta_2}{4c_{JD} m_2} \left(\frac{\theta_1}{m_1 (1-\theta_2)} \right)^{\theta_1}$$

$$B = \frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] \theta_2^{\theta_2}}{4c_{JD} m_1^{\theta_1} m_2^{\theta_2}} \left(\frac{\theta_1}{(1-\theta_2)} \right)^{1-\theta_2}$$

$$\rho = \frac{1}{1 - \theta_1 - \theta_2}$$

Then

$$\begin{aligned} \frac{\partial E\{\pi_1\}}{\partial \lambda} = & -A^\rho \rho \theta_2 (1 - \lambda)^{\rho \theta_2 - 1} \lambda^{\rho(1 - \theta_2)} + A^\rho (1 - \lambda)^{\rho \theta_2} \rho (1 - \theta_2) \lambda^{\rho(1 - \theta_2) - 1} \\ & + B^\rho \rho \theta_2 (1 - \lambda)^{\rho \theta_2 - 1} \lambda^{\rho(1 - \theta_2)} - B^\rho (1 - \lambda)^{\rho \theta_2} \rho (1 - \theta_2) \lambda^{\rho(1 - \theta_2) - 1} = 0. \end{aligned}$$

Thus,

$$\lambda = \frac{2\theta_2 - 1}{1 - \theta_2}$$

When we substitute the λ solution into the Q_1^* , Q_2^* and γ_{JD}^* equations, we obtain:

$$Q_1^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD} (1 - \theta_2)^{2 - \theta_2}} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{1 - \theta_2} \left(\frac{(2 - 3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1 - \theta_1 - \theta_2}}$$

$$Q_2^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD} (1 - \theta_2)^{\theta_1 + 1}} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2 - 3\theta_2)\theta_2}{m_2} \right)^{1 - \theta_1} \right]^{\frac{1}{1 - \theta_1 - \theta_2}}$$

γ_{JD}^*

$$= \left[\left(\frac{\delta_{JD} v_{JD}^P}{c_{JD}} \right)^{2 - \theta_1 - \theta_2} \frac{\beta^P [K_{10}, K_{20}] (4c_{JD} + \delta_{JD} v_{JD}^P)^{\theta_1 + \theta_2}}{4 (1 - \theta_2)^{2\theta_1 + \theta_2}} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2 - 3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{2(1 - \theta_1 - \theta_2)}}$$

Note that when we substitute λ^* , Q_1^* , Q_2^* and γ_{JD}^* into the $E\{\pi_1\}$, $E\{\pi_2\}$ and $E\{\pi_{JD}\}$ equations, we obtain:

$$\begin{aligned} E\{\pi_1\} = & \left[\frac{\beta^P [K_{10}, K_{20}] \delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) (2\theta_2 - 1)^{1 - \theta_2} \theta_1^{\theta_1}}{4c_{JD} (1 - \theta_2)^{\theta_1 + 1} m_1^{\theta_1}} \left(\frac{(2 - 3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1 - \theta_1 - \theta_2}} \\ & - \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD} (1 - \theta_2)^{2 - \theta_2}} \frac{\{(2\theta_2 - 1)\theta_1\}^{1 - \theta_2}}{m_1^{\theta_1}} \left(\frac{(2 - 3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1 - \theta_1 - \theta_2}} \end{aligned}$$

$$\begin{aligned} E\{\pi_2\} = & \left[\frac{\beta^P [K_{10}, K_{20}] \delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P)}{4c_{JD} (1 - \theta_2)^{\theta_1 + 1}} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{\theta_1} \frac{(2 - 3\theta_2)^{1 - \theta_1} \theta_2^{\theta_2}}{m_2^{\theta_2}} \right]^{\frac{1}{1 - \theta_1 - \theta_2}} \\ & - \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD} (1 - \theta_2)^{\theta_1 + 1} m_2^{\theta_2}} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2 - 3\theta_2)\theta_2}{m_2} \right)^{1 - \theta_1} \right]^{\frac{1}{1 - \theta_1 - \theta_2}} \end{aligned}$$

$$E\{\pi_{JD}\} = \left[\frac{\beta^P [K_{10}, K_{20}] \delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P)}{4 (1 - \theta_2)^{2\theta_1 + \theta_2}} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2 - 3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1 - \theta_1 - \theta_2}}$$

Suppose $\mu_1 = \mu_2 = \frac{1}{2}$: the expected profit function of firms 1 and 2 if they do not cooperate are:

$$E\{\pi_1^N\} = X^N K_{10} + \frac{(X^N)^2 K_{10}^{2\mu_1}}{4c_1} - \delta_1 \delta_2^N w_1^P \left(K_{20} + \frac{Y^N K_{20}^{2\mu_2}}{2c_2} \right)$$

$$E\{\pi_2^N\} = Y^N K_{20} + \frac{(Y^N)^2 K_{20}^{2\mu_2}}{4c_2} - \delta_1 \delta_2^N w_2^P \left(K_{10} + \frac{X^N K_{10}^{2\mu_1}}{2c_1} \right). \quad Q.e.d.$$

Proof of Proposition 13

This proof follows directly from Equation (4.29).

Proof of Proposition 14

This proof follows directly from Equations (4.30), (4.31) and (4.32).

C.2.2 Numerical Examples: Example 2 and Its Variations

For the numerical analysis introduced in Section 4.5.2.2, we assume $\mu_1 = \mu_2 = 1/2$. As noted $\beta^P[K_{10}, K_{20}]$ satisfies the probability density function $\Phi(z)$ with mean \bar{z} and standard deviation σ , \bar{z} is a function of K_{10} and K_{20} . We assume the functional form below for \bar{z} . For the numerical analysis included in Chapter 4 no functional form the relationship between σ and K_{10} and K_{20} was necessary. All the other functional forms employed are derived from Equations (4.21)-(4.24). Numerical solutions are obtained with EXCEL.

$$\bar{z} = e^{-\varphi(K_{10} + K_{20})}$$

Table C.8 Input values for Example 2

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
K_{10}	100	δ_{JD}	0.8	δ_2^N	0.4	z_2	10
K_{10}	80	v_{JD}	400	v_1	100	c_1	100
$\beta^P[K_{10}, K_{20}]$	0.59	c_{JD}	100	w_1^P	20	c_2	100
φ	0.005	m_1	40	z_1	10		
θ_1	0.2	m_2	40	v_2	100		
θ_2	0.62	δ_1	0.5	w_2^P	20		

Table C.9 Summary of results for Example 2

λ	Q_1	Q_2	γ_{JD}	$E\{\pi_1\}$	$E\{\pi_2\}$	$E\{\pi_1^{N_1}\}$	$E\{\pi_2^N\}$	$E\{\pi_{JD}\}$
0.63	79.90	61.55	27.59	17902.79	6053.52	6100.25	3589.2	18294.31

C.2.3 Experimental Analysis of Impact of Uncertainty

For the experimental analysis introduced in Section 4.5.2.3, we assume $\mu_1 = \mu_2 = 1/2$. As noted for w_1^P and $\beta^P[K_{10}, K_{20}]$ we assume a triangular distribution, where the mean of the distribution of $\beta^P[K_{10}, K_{20}]$, \bar{z} , is a function of K_{10} and K_{20} . These values and other relevant data are given in Table C.10. All the other functional forms employed are derived from Equations (4.27)-(4.32). Numerical solutions are obtained with EXCEL.

$$\bar{z} = e^{-\varphi(K_{10} + K_{20})}$$

Table C.10 Triangular distribution settings for v_{JD}^P

Triangular distribution	Low uncertainty	High uncertainty symmetric	High uncertainty skewed
Lower value	399.9	350	330
Upper value	401.1	450	500
Mode	400	400	370
Mean	400	400	400

Standard deviation	0.04	20.41	36.29
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Table C.11 Summary of results for the experimental analysis of uncertainty associated with v_{JD}^P

λ	Q_1	Q_2	γ_{JD}	$E\{\pi_1\}$	$E\{\pi_2\}$	$E\{\pi_1^N\}$	$E\{\pi_2^N\}$
Low uncertainty							
0.63	79.90	61.55	27.59	17902.79	6053.52	6100.25	3589.21
High uncertainty symmetric							
0.63	82.56	63.14	30.84	17635.81	5949.23	6100.25	3589.21
High uncertainty skewed							
0.63	90.11	2.91	36.24	17856.32	5999.54	6100.25	3589.21

Table C.12 Triangular distribution settings for $\beta^P[K_{10}, K_{20}]$

Triangular distribution	Low uncertainty	High uncertainty symmetric	High uncertainty skewed
Lower value	0.591	0.356	0.292
Upper value	0.595	0.836	0.987
Mode	0.593	0.593	0.500
Mean	0.593	0.593	0.593
Standard deviation	0.000	0.42	0.62

Table C.13 Summary of results for the experimental analysis of uncertainty associated with $\beta^P[K_{10}, K_{20}]$

λ	Q_1	Q_2	γ_{JD}	$E\{\pi_1\}$	$E\{\pi_2\}$	$E\{\pi_1^N\}$	$E\{\pi_2^N\}$
Low uncertainty							
0.63	79.90	61.55	27.59	17902.79	6053.52	6100.25	3589.21
High uncertainty symmetric							
0.63	75.65	52.64	23.89	14526.37	5846.32	6100.25	3589.21
High uncertainty skewed							

C.2.4 Joint Development: Simultaneous Decision Making

Proof of Proposition 15

If $\mu_1 = \mu_2 = \frac{1}{2}$, then $\gamma_{JD}^* = \frac{\delta_{JD} v_{JD}^P (\beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2})^{1/2}}{2c_{JD}}$. Thus, in order to determine Q_2^* ,

firm 2 maximizes the profit function:

$$E\{\pi_2\} = (1 - \lambda) \delta_{JD} v_{JD} \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2}}{4c_{JD}} - m_2 Q_2$$

$$\frac{\partial E\{\pi_2\}}{\partial Q_2} = (1 - \lambda) \delta_{JD} v_{JD} \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2 Q_2^{\theta_2 - 1}}{4c_{JD}} - m_2 = 0$$

$$\text{Thus, } Q_2^* = \left[\frac{4m_2 c_{JD}}{(1 - \lambda) \delta_{JD} v_{JD} (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2} \right]^{\frac{1}{\theta_2 - 1}}.$$

In order to ensure concavity,

$$\frac{\partial^2 E\{\pi_2\}}{\partial Q_2^2} = (1 - \lambda) \delta_{JD} v_{JD} \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} \theta_2 (\theta_2 - 1) Q_2^{\theta_2 - 2}}{4c_{JD}} < 0.$$

Next, in order to determine Q_1^* , firm 1 maximizes the profit function:

$$E\{\pi_1\} = \lambda \delta_{JD} v_{JD}^P \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2}}{4c_{JD}} - m_1 Q_1$$

$$\frac{\partial E\{\pi_1\}}{\partial Q_1} = \lambda \delta_{JD} v_{JD}^P \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] \theta_1 Q_1^{\theta_1 - 1} Q_2^{\theta_2}}{4c_{JD}} - m_1 = 0$$

$$\text{Thus, } Q_1^* = \left[\frac{4m_1 c_{JD}}{\lambda \delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] Q_2^{\theta_2} \theta_1} \right]^{\frac{1}{\theta_1 - 1}}.$$

When Q_1^* and Q_2^* are solved simultaneously, we obtain:

$$Q_1^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD}} \left(\frac{\lambda \theta_1}{m_1} \right)^{1 - \theta_2} \left(\frac{(1 - \lambda) \theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1 - \theta_1 - \theta_2}}$$

and

$$Q_2^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD}} \left(\frac{(1-\lambda)\theta_2}{m_2} \right)^{1-\theta_1} \left(\frac{\lambda\theta_1}{m_1} \right)^{\theta_1} \right]^{\frac{1}{1-\theta_1-\theta_2}}$$

Firm 1 determines λ that maximizes $E\{\pi_1\}$:

$$E\{\pi_1\} = \lambda \delta_{JD} v_{JD}^P \frac{(4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] Q_1^{\theta_1} Q_2^{\theta_2}}{4c_{JD}} - m_1 Q_1$$

If we substitute the Q_1^* and Q_2^* solutions, we obtain:

$$E\{\pi_1\} = [A_1(1-\lambda)^{\theta_2} \lambda^{1-\theta_2}]^\rho - [B_1(1-\lambda)^{\theta_2} \lambda^{1-\theta_2}]^\rho$$

where

$$A_1 = \frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD}} \left(\frac{\theta_1}{m_1} \right)^{\theta_1} \left(\frac{\theta_2}{m_2} \right)^{\theta_2}$$

$$B_1 = \frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}] \theta_2^{\theta_2} \theta_1^{1-\theta_2}}{4c_{JD} m_1^{\theta_1} m_2^{\theta_2}}$$

$$\rho = \frac{1}{1-\theta_1-\theta_2}$$

Then

$$\begin{aligned} \frac{\partial E\{\pi_1\}}{\partial \lambda} &= -A_1^\rho \rho \theta_2 (1-\lambda)^{\rho\theta_2-1} \lambda^{\rho(1-\theta_2)} + A_1^\rho (1-\lambda)^{\rho\theta_2} \rho (1-\theta_2) \lambda^{\rho(1-\theta_2)-1} \\ &\quad + B_1^\rho \rho \theta_2 (1-\lambda)^{\rho\theta_2-1} \lambda^{\rho(1-\theta_2)} - B_1^\rho (1-\lambda)^{\rho\theta_2} \rho (1-\theta_2) \lambda^{\rho(1-\theta_2)-1} = 0. \end{aligned}$$

Thus,

$$\lambda = \frac{2\theta_2 - 1}{1 - \theta_2}$$

When we substitute the λ solution into the Q_1^* , Q_2^* and γ_{JD}^* equations, we obtain:

$$Q_1^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD} (1-\theta_2)} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{1-\theta_2} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{1-\theta_1-\theta_2}}$$

$$Q_2^* = \left[\frac{\delta_{JD} v_{JD}^P (4c_{JD} + \delta_{JD} v_{JD}^P) \beta^P [K_{10}, K_{20}]}{4c_{JD} (1-\theta_2)} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{1-\theta_1} \right]^{\frac{1}{1-\theta_1-\theta_2}}$$

γ_{JD}^*

$$= \left[\left(\frac{\delta_{JD} v_{JD}^P}{c_{JD}} \right)^{2-\theta_1-\theta_2} \frac{\beta^P [K_{10}, K_{20}] (4c_{JD} + \delta_{JD} v_{JD}^P)^{\theta_1+\theta_2}}{4(1-\theta_2)} \left(\frac{(2\theta_2 - 1)\theta_1}{m_1} \right)^{\theta_1} \left(\frac{(2-3\theta_2)\theta_2}{m_2} \right)^{\theta_2} \right]^{\frac{1}{2(1-\theta_1-\theta_2)}}$$

Q.e.d.

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