ESSAYS ON KNOWLEDGE OUTSOURCING

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ESSAYS ON KNOWLEDGE OUTSOURCING

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To my beloved wife, Jihyun,

and my daughters, Chaeyul and Soyul.

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SUMMARY

Due to rapid changes in technology, science, and the marketplace, while recognizing knowledge as a key resource for competitive advantage, many firms lack the internal knowledge resources to achieve their goals. To address this challenge, firms increasingly rely on outsourcing knowledge from external entities such as consultancies. Since I personally observed this global trend at Samsung, I could fully understand the importance of this challenge. While there is a substantial amount of literature examining supplier-buyer interactions for physical components and finished goods in Operations Management, studies that provide managerial implications on the interactions between a buyer (she) and a supplier (he) for knowledge outsourcing are limited. In this dissertation, I study how firms effectively manage knowledge outsourcing. In particular, I focus on investigating how factors such as absorptive capacity, uncertainty, information asymmetry, and competition impact firms' decisions and the outcomes of knowledge outsourcing.

Using a game-theoretic formulation, the first essay (Chapter 2) studies how a buyer's ability to understand and apply outsourced knowledge (i.e., absorptive capacity) affects the interactions between the buyer and the supplier. It also investigates the impact of uncertainty about the amount of knowledge needed and asymmetric information regarding a key element of absorptive capacity on firms' decisions and the outcomes of knowledge outsourcing. To build further implications on knowledge outsourcing, the second essay (Chapter 3) incorporates market competition between two buyers who outsource knowledge from a common supplier. It examines how competition in the downstream market impacts the buyers'

knowledge outsourcing decisions and the supplier's service strategies. As the current literature on knowledge outsourcing remains in the early stages, the third essay (Chapter 4) reviews current studies to identify what is known and unknown about knowledge outsourcing at present, and provides a future research agenda. Overall, my dissertation contributes a significant building-block for Operation Management to better address managerial challenges in the knowledge economy.

CHAPTER 1. INTRODUCTION

Many firms lack the critical knowledge resources necessary to successfully meet their innovation goals, which may include higher yield or new component designs. Increasingly, such firms pursue knowledge outsourcing to obtain scientific, engineering, analytic, and technical services. Motivated by personal experience interacting with internal R&D managers and external consultancies in the field, this doctoral dissertation, entitled "Essays on Knowledge Outsourcing," examines issues related to knowledge outsourcing. This dissertation consists of three essays studying how firms can effectively manage knowledge outsourcing.

To define the scope of this dissertation on knowledge outsourcing, the third essay (Chapter 4), entitled "Knowledge Outsourcing: A Literature Review and Future Research Agenda," reviews the current literature on knowledge outsourcing, which includes the first essay (Chapter 2) and the second essay (Chapter 3), and provides a future research agenda. To this end, we clarify the external sources of knowledge and environmental forces which jointly impact the firms' decisions and outcomes of knowledge outsourcing. We also propose a conceptual framework, consisting of five phases, to manage knowledge outsourcing projects: Phase 1 – Initiate, Phase 2 – Plan, Phase 3 – Execute, Phase 4 – Utilize, and Phase 5 – Check. Based on this knowledge outsourcing framework, the third essay discusses current studies in detail and provides future research opportunities for each phase of knowledge outsourcing.

In Phase 1 (Initiate), we find that current studies consistently report that knowledge outsourcing is more suitable to incremental innovation due to the relatively low risk of knowledge leakage. In Phase 2 (Plan), during which a buyer selects a supplier and makes a contractual agreement, current studies show that the buyer may be better off choosing a highly capable supplier or a known supplier with whom they have previously worked. Firms' critical challenges in this phase include uncertainty, information asymmetry, and competition, which we partly address in essays 1 (Chapter 2) and 2 (Chapter 3). In Phase 3 (Execute), the supplier's knowledge leakage and opportunistic behavior are critical risks that the buyer faces and further research is required to better understand how to ensure trustworthy behavior from the supplier.

In Phase 4 (Utilize), the buyer integrates and utilizes the knowledge outsourced from the supplier to generate value. Current studies consistently report that higher absorptive capacity leads to higher performance of the buyer's knowledge integration. However, the buyer's behavioral factors, such as NIH syndrome, may reduce the effectiveness of the buyer's internal knowledge integration process. The first essay (chapter 2) studies some of the unanswered questions in this phase, which includes the impact of different elements of absorptive capacity. In Phase 5 (Check), the buyer evaluates the performance of the knowledge outsourcing project and plans ways to reuse the knowledge developed by the supplier in future projects. For most performance measures, the current literature has not yet reached a consensus. Therefore, further research may investigate under which conditions pursuing knowledge outsourcing improves each measure of performance. Overall, it is difficult to derive a consensus for many of the issues involved in knowledge outsourcing from only a small group of studies, and a number of important managerial challenges remain unaddressed.

Paradoxically, while knowledge outsourcing is meant to compensate for a lack of existing internal knowledge, the buyer (she) must rely on existing knowledge to understand and apply the knowledge purchased from the supplier (he). The buyer's ability to understand and apply the outsourced knowledge is limited by her absorptive capacity (one of the critical challenges in Phase 4 – Utilize), which increases in relation to her existing knowledge, the quality of communication with the supplier, and the buyer's willingness to accept external knowledge. In the first essay (Chapter 2), entitled "An Economic Model of Knowledge Outsourcing," three Stackelberg games are introduced providing important managerial insights on the knowledge outsourcing problem. The profit-maximizing supplier leads by determining his price for knowledge outsourcing, while considering the buyer's response as well as the extent to which he can leverage his own prior knowledge. The buyer determines the amount of knowledge to outsource versus develop internally to minimize the cost of meeting her performance goal.

Through this study, we first show that when a buyer has superior absorptive capacity, a supplier can increase his price and still benefit from higher demand for outsourcing. Second, if a buyer pursues a highly novel innovation project, we find that both the buyer and the supplier may benefit from the corresponding uncertainty in the buyer's goal. Moreover, conditions are given in which the total cost of the supply chain decreases as uncertainty increases. Third, when the buyer keeps a key element of her absorptive capacity as private information, we identify conditions whereby the supplier focuses on serving a superior type of buyer by charging a high price.

In the second essay (Chapter 3), entitled "Knowledge Outsourcing for Competing Buyers," we attempt to answer intriguing questions that arise when one common knowledge supplier serves two buyers (1 and 2) competing in the downstream market. (Competition is a critical challenge that firms face in Phase 2 – Plan.) Under what conditions do either of the buyers pursue knowledge outsourcing from the supplier? In a situation where only one of the two buyers outsources knowledge from the supplier, how does that buyer's knowledge outsourcing influence both buyers' decisions concerning knowledge development and their retail prices in the downstream market? Under what conditions does the supplier prefer to serve only one buyer, as opposed to both buyers? Specifically, in what ways is the supplier better off serving one buyer instead of both buyers?

To answer these critical questions, we build on our analysis by considering different competition scenarios: monopoly (only buyer 1 exists in the downstream market) and duopoly (buyers 1 and 2 compete in the downstream market). In the monopoly case, we find that buyer 1 chooses to outsource knowledge only if her in-house knowledge development cost is sufficiently high, in order to reduce her total knowledge acquisition cost. We also find that a buyer's desire to pursue knowledge outsourcing depends on the competition structure (i.e., monopoly or duopoly) in the downstream market. When the supplier commits to serving only one buyer (buyer 1), we find that buyer 1 who competes with buyer 2 in duopoly is more inclined to outsource knowledge than in monopoly. This is because buyer 2, who does not have the option of knowledge outsourcing in the duopoly case, makes the strategic decision to keep her level of product performance lower than that of buyer 1. This indicates that buyer 1's knowledge outsourcing effectively discourages buyer 2 from pursuing in-house knowledge development and gives buyer 1 an advantage as the higher quality manufacturer. Lastly, we investigate the situation where the supplier attempts to serve both buyers 1 and 2. If the buyers' in-house knowledge development costs are sufficiently low, we find that the supplier is better off charging a higher wholesale price of knowledge and serving only one of the buyers. This is because the supplier can benefit more from charging a high price to one buyer than from obtaining a large amount of knowledge outsourcing tasks from both buyers.

CHAPTER 2. AN ECONOMIC MODEL OF KNOWLEDGE OUTSOURCING

2.1 Introduction

Due to rapid changes in technology, science and the marketplace, many firms lack the internal knowledge resources to conduct the problem solving required to reach their manufacturing or marketing goals, which may include increasing the manufacturing yield or quality, developing new components, or performing scientific or engineering experiments (Grant 1996). Increasingly, these firms rely on outsourcing knowledge from external entities to obtain scientific, engineering, analytic and technical services (Quinn 1999; Carson 2010; Grimpe and Kaiser 2010; Cui et al. 2012; Gaimon et al. 2017b). The U.S. census data indicates that the knowledge-intensive service industry more than doubled its contribution to GDP from 1998 to 2016 (BEA, 2016). Similarly, the value of knowledge outsourcing contracts grew from \$12.5B in 2000 to \$37B in 2017 (Weber, 2017). According to Booz, the “hot” sectors for knowledge outsourcing include product development and design, engineering services, R&D, and analytic services (Couto et al., 2007). Nevertheless, despite its growing importance, while a great deal is known about component outsourcing, the challenges and decision-making processes for firms engaged in knowledge outsourcing are not well understood.

In part, this research is motivated by one of the co-author's experiences as a member of an engineering team in a major Korean electronics firm. Upper management directed the team to improve the manufacturing yield to reach a specific performance goal. Recognizing that it lacked the internal knowledge necessary to meet this goal, the team identified the portion of knowledge it would develop internally through its own problem solving efforts (prototyping, simulation, experiments (see Ozkan-Seely et al. (2015)), as well as the portion of knowledge to outsource from a highly respected (external) consultancy. By leveraging prior experience from another engagement, the consultancy was able to charge a moderate price to the electronics firm for the outsourced knowledge. The two firms contractually agreed to the unit price for outsourcing (set by the consultancy), the quantity of outsourcing (problems to be solved set by the buyer), and the deliverables (reporting mechanism such as a written report, software, or design drawings, and due date). Unfortunately, due to its limited knowledge and poor communication with the consultancy, the engineering team at the Korean electronics firm required a full six-months to understand and apply the outsourced knowledge to increase yield and thereby reach upper management's goal.

The above example illustrates a particularly interesting phenomenon of knowledge outsourcing. While outsourcing knowledge is meant to compensate for a lack of internal knowledge resources, the buyer must rely on that internal knowledge to understand and apply the outsourced knowledge purchased from the supplier. Cohen and Levinthal (1990) refer to absorptive capacity as the “ability of a firm to recognize the value of new external information, assimilate it, and apply it to commercial ends.” Empirically, it has been shown that a buyer with a larger amount of existing knowledge is better able to understand and apply the outsourced knowledge received from a supplier, subject to diminishing returns (Cohen and Levinthal, 1989). Moreover, if the buyer is highly motivated to accept the outsourced knowledge (as opposed to displaying the “not invented here syndrome”) then she is better able to understand and apply it (Osterloh and Frey 2000; Ko et al. 2005). The buyer’s ability to benefit from outsourced knowledge also improves if the buyer and the supplier have established methods of communication (such as shared terminology) as well as trust based on past experience working together (Levin and Cross 2004). We refer to the buyer's motivation to accept external knowledge and the quality of communication and trust between the buyer and the supplier as the buyer's integration factor. Therefore, absorptive capacity is driven by both the buyer's existing knowledge and the buyer's integration factor.

Many intriguing questions must be answered to understand the complex and interrelated decision-making processes of the knowledge buyer (she) and the knowledge supplier (he). What drives the buyer’s determination of the portion of knowledge to develop internally versus outsource to a supplier? How are the buyer’s decisions impacted by her existing internal knowledge and the price charged by the supplier for outsourcing knowledge? What are the buyer’s key considerations when selecting a supplier for outsourced knowledge? How does the quality of communication between the buyer and the supplier (integration factor) affect the buyer’s reliance on internal knowledge development versus knowledge outsourcing to meet her goal? Similarly, how does the quality of communication between the two firms impact the supplier’s price? How is the supplier’s price affected by knowledge he accumulated from prior engagements versus the cost he incurs to internally develop new knowledge to meet the buyer’s demand for outsourcing? How does uncertainty in the buyer's goal as she pursues a novel project impact both firms’ decision-making? In particular, why might both the buyer and the supplier benefit from uncertainty in the buyer’s goal? Naturally, the buyer provides considerable information to the supplier so that he meets her outsourcing deliverables. But, does the buyer possess some information that should remain private to drive the supplier to charge a lower price? How should the supplier respond to this information asymmetry?

To analyze these critical questions, we introduce three Stackelberg games of knowledge outsourcing. At the outset of each game, upper management directs mid-level managers to meet a performance goal (such as improving manufacturing yield, creating component designs, or completing scientific or engineering experiments). The mid-level managers (referred to hereafter as “the buyer”) identify the project scope (expressed in hours of effort) needed to meet the goal, which is reduced by the extent of relevant knowledge she already possesses. The supplier (leader) sets the price (per hour effort) for outsourcing. In response, the buyer (follower) determines the amount of knowledge to outsource from the supplier (hours of effort) and the amount of knowledge to develop internally (hours of effort) to reach her project scope. The deliverables the supplier provides to the buyer include the specific problems to be solved or experiments to be performed, the reporting mechanism (e.g., written report, prototype, design drawing, software), and the due date.

The buyer’s ability to understand and apply the outsourced knowledge (e.g., her absorptive capacity) is a function of the buyer’s existing knowledge and her integration factor, which reflects the quality of communication between the buyer and the supplier as well as the buyer's motivation to accept external knowledge. The buyer minimizes the total cost incurred to meet her project scope from outsourcing and internal knowledge development. When the profit-maximizing supplier sets the price, he considers the buyer’s response as well as the extent to which he can leverage his own prior knowledge versus the cost he incurs to develop new knowledge (hours of effort) to meet the buyer's demand for outsourcing. Note that the above-mentioned approach to measurement in terms of hours of effort is consistent with the project management literature (Clark 1989; Tavares 2002; Cui et al. 2012).

In a deterministic model with full information we show that, if the buyer has a larger level of existing knowledge, her minimum cost objective is always lower but the supplier's profit maximizing objective may either improve or worsen. Conversely, we show that the objectives of both the buyer and the supplier always improve when the supplier has more prior knowledge. This latter result demonstrates the critical importance that the buyer selects a knowledgeable supplier. Second, we obtain key managerial insights from analysis of a stochastic game with complete information. If the buyer pursues a highly novel goal, the efforts required to meet the project scope may be uncertain. Importantly, we identify situations where a supplier charges a lower versus a higher price in response to more project scope uncertainty. Moreover, we find that both the buyer and the supplier may benefit from uncertainty in the buyer's project scope. As such, conditions are given whereby the total cost of the supply chain decreases as uncertainty increases. Of course, these results contrast the detrimental impact of uncertainty in the component outsourcing literature. In a third game formulation, we analyze how information asymmetry impacts the supplier's pricing scheme. When information asymmetry exists regarding the buyer's integration factor, we identify conditions whereby the supplier serves only the superior type of buyer by charging a high price.

The remainder of this paper is organized as follows. We discuss the related literature in Section 2.2. In Section 2.3, we introduce the deterministic Stackelberg game of knowledge outsourcing in which both firms have complete information. We analyze the game theoretic solutions for the buyer and the supplier when the buyer's project scope is uncertain in Section 2.4. The impact of information asymmetry is explored in Section 2.5 whereby the supplier does not know with certainty the buyer's integration factor at the outset of the game. We conclude with a discussion of the key managerial implications for a buyer and a supplier engaged in knowledge outsourcing in Section 2.6.

2.2 Related Literature

A great deal is known in the supply chain management literature concerning a buyer and a supplier engaged in outsourcing components or finished goods. Valuable insights have been developed regarding coordination between partners (Cachon and Lariviere 2005), optimal contract types (Van Mieghem 1999), and negotiation and bargaining (Feng and Lu 2012). In contrast, despite its importance to a firm's performance, the sourcing of intangible resources such as knowledge has received little attention in the literature.

Recently, research in operations management has considered two situations in which a firm might engage an external entity in knowledge intensive projects: a firm can collaborate with a partner to jointly create value (Bhaskaran and Krishnan 2009; Roels et al. 2010), or a firm can outsource a problem partly or entirely to an external service provider (Xue and Field 2008; Rahmani and Ramachandran 2017). While Roels et al. (2010) show how the choice of contract type depends on the verifiability of effort in a knowledge-intensive joint development project, Bhaskaran and Krishnan (2009) study collaboration mechanisms for a new product development alliance in which two firms jointly contribute effort and share the outcome. Closer to our paper, Rahmani and Ramachandran (2017) consider a firm that entirely delegates the solution generation task to an external agent, while Xue and Field (2008) study how the workload (tasks) should be allocated between the client and the consultant to complete the client's knowledge development project under different contractual relationships. We contribute to this stream by examining how a profit maximizing supplier sets his price for outsourced knowledge and how a cost minimizing buyer meets her performance goal by allocating resources to outsourced knowledge versus internal knowledge development.

Because knowledge is an intellectual resource as opposed to a physical output, the recipient of knowledge outsourcing (buyer) faces the challenge of understanding and applying the knowledge purchased from an external source (supplier) (Grant 1996; Sanchez and Heene 1997; Anderson and Parker, 2013). Cohen and Levinthal (1990) describe absorptive capacity "as the ability of the buyer to understand and apply the knowledge obtained from an external supplier." A considerable empirical literature identifies drivers of absorptive capacity. It has been shown that absorptive capacity is larger for a buyer with more existing knowledge (subject to diminishing returns) (Cohen and Levinthal 1989; Graves 1989). Essentially, the buyer leverages her existing knowledge to understand and apply the knowledge purchased from a supplier (Cassiman and Veugelers 2006; Weigelt 2009; Grimpe and Kaiser 2010; Berchicci 2013). Additionally, it has been shown that absorptive capacity suffers due to problems associated with communication and a lack of trust between the buyer and the supplier. For example, the supplier's deliverable may be poorly documented or employ different terminology than that used by the buyer. Furthermore, the buyer may lack motivation to learn new concepts (e.g., "not invented here syndrome") (Katz and Allen 1982; Dyer and Singh 1998; Osterloh and Frey 2000; Hult et al., 2004; Ko et al. 2005; Martinez-Noya et al. 2013). We refer to these dimensions of absorptive capacity as the recipient's integration factor.

Beyond the above-mentioned empirical literature, the notion of absorptive capacity has also been captured in recent normative research. Ozkan-Seely et al. (2015) examine the impact of absorptive capacity when knowledge is transferred between a product design team and a process design team during the design of a single new product development project. Xiao (2012) examines the evolution of knowledge development, forward knowledge transfer and backward knowledge transfer during a three-stage new product development project. These authors demonstrate the importance of absorptive capacity on a new product development manager's pursuit of knowledge development and knowledge transfer. Cui et al. (2012) show that it is important for the buyer to properly identify her project scope and subsequently to define the contractual deliverables to the supplier when pursuing knowledge outsourcing. In our Stackelberg game models, we leverage insights from the empirical literature to extend the above-mentioned single firm normative research by analyzing the role of absorptive capacity on the decisions of a buyer and a supplier who engage in a knowledge outsourcing.

The supplier's prior knowledge is also important in our knowledge outsourcing game since he may reuse his stock of knowledge repeatedly without incurring additional development costs (Alavi and Leidner 2001; Haefliger et al. 2008; Eccles et al. 2013). According to Majchrzak et al. (2004), there are two modes of reusing existing knowledge. "Replication" occurs when a firm transfers existing knowledge between related research programs, whereas "leveraging existing knowledge for innovation" emphasizes integration and recombination of prior knowledge. Haefliger et al. (2008) find that leveraging existing knowledge in the form of computer code is common in software development projects. Wu (2015) examines the implications of organizational structure and product position on the benefits and the costs of replication when a manager transfers her superior knowledge to different teams engaged in new product development projects. We examine the impact on knowledge outsourcing decisions for a supplier and a buyer when the supplier reuses his stock of knowledge to meet the buyer's outsourcing demand. Our results provide insights on how a buyer should select a supplier of knowledge outsourcing.

Much of our terminology is anchored in the project management literature. A variety of performance goals have been addressed in the project management literature including reducing processing times, improving quality, increasing capacity, or enhancing product features such as ease of use (Clark 1989; Mukherjee et al. 1998; Krishnan and Ulrich 2001; Browning and Ramasesh 2007). In three knowledge outsourcing games, a buyer (mid-level managers) is directed to achieve a specific performance goal set by upper management. Consistent with the project management literature, the buyer "translates" the performance goal into the project scope, expressed in hours of effort (Clark 1989; Clark and Fujmoto 1991). According to the Project Management Institute (PMI, 2014), "project scope" represents the "work that must be done to deliver a product (or service) with the specified features and functions." Of course, the buyer's existing knowledge reduces the extent to which new activities must be performed to meet the project scope. Said differently, a large project scope suggests that the buyer's goal is substantial or the buyer's existing knowledge is small. As expected, we show a buyer always lowers her total cost if she is able to leverage more existing knowledge. Interestingly, we provide conditions whereby a supplier is worse versus better off when engaging with a buyer that has more existing knowledge.

In our second knowledge outsourcing game, we consider a buyer who engages in highly novel activities to meet her goal so that her project scope is uncertain (Dodin 1985; Keisler and Bordley 2014). We identify conditions in which uncertainty in the buyer's project scope is beneficial to the buyer or the supplier. Importantly, the analytical results we obtain on the impact of uncertainty for our knowledge outsourcing problem contrast those in the component outsourcing literature. Lastly, in a third knowledge outsourcing game, we examine the impact on the decisions of both the buyer and the supplier when the supplier does not have full information regarding the buyer’s integration factor. Analytic results are obtained providing insights on when a buyer of knowledge outsourcing is better off not to provide full information to a supplier.

2.3 Deterministic Model

In this section, we introduce a Stackelberg game of knowledge outsourcing between a buyer and a supplier with complete and perfect information (each firm knows her or his own decisions and payoff as well as those of the other firm) and where the buyer's project scope is known (deterministic). The sequence of decision-making is as follows. The profit-maximizing supplier (leader, he) determines a price per unit knowledge outsourcing to charge the buyer (follower, she). After observing the price, the cost-minimizing buyer determines the quantity of knowledge to develop internally versus outsource from the supplier to meet her project scope. The problems for both the buyer and the supplier are given in Section 2.3.1. The solutions for the knowledge outsourcing game are analyzed in Section 2.3.2. The terminology and notation are given in Table 1.

Table 1. Terminology and notation for the deterministic model.

Goal	Buyer's performance goal set by upper management such as an increase in yield, an increase in quality, the creation of component designs, or the results of scientific experiments.
J	Buyer's project scope defined as hours of effort needed to meet her goal, $J > 0$.
K_b	Buyer's existing knowledge relevant to meeting the project scope expressed in hours, $K_b > 0$.
S	Buyer's knowledge outsourcing from a supplier expressed in hours (buyer's decision), $S \geq 0$.
δ	Integration factor connotes the fraction of supplied knowledge integrated into the buyer's project, $\delta \in (0,1]$.
ϕ	Buyer's absorptive capacity (e.g., buyer's ability to understand and apply outsourced knowledge from the supplier), $\phi = \delta\left[K_b\right]^{\sigma} \in (0,1)$, where σ denotes the rate of diminishing returns in relation to the buyer's existing knowledge. Note that $\phi < 1$ gives us $0 < \delta < \frac{1}{\left[K_b\right]^{\sigma}}$.
D_b	Buyer's internal knowledge development expressed in hours, $D_b \geq 0$.
c_b	Parameter indicating the buyer's cost for internal knowledge development, $c_b > 0$.
p	Supplier's price per unit knowledge outsourced to the buyer (supplier's decision), $p > 0$.
Deliverables	Element of the contractual agreement between the buyer and the supplier specifying the quantity of the knowledge outsourcing (problems to solve or experiments to perform), the reporting mechanism (written report, design drawings, physical prototypes, software), and the due date.
K_s	Supplier's prior knowledge relevant to meeting the buyer's demand for outsourcing expressed in hours, $K_s > 0$.
D_s	Supplier's internal knowledge development needed to meet the buyer's demand for outsourcing expressed in hours, $0 \leq D_s < S$.
c_s	Parameter indicating the supplier's cost for internal knowledge development, $c_s > 0$.

2.3.1 Modeling Features

The Buyer's Problem

At the outset of the game, a firm's upper management sets a performance goal such as an increase in yield or quality, the creation of design drawings, or the execution of scientific or engineering experiments. The firm's mid-level managers responsible for meeting the goal (e.g., the buyer) identify the project scope, denoted by $J > 0$, which represents the hours of effort required to meet the goal. In this deterministic game, we assume the buyer knows with certainty how to convert the goal to the project scope (we relax this assumption in Section 2.4). The buyer identifies the existing knowledge she already has that is relevant to meeting her project scope, denoted by $K_b > 0$. The existing knowledge is subtracted from the project scope to determine the hours of additional effort the buyer needs to reach her goal. Naturally, we are interested in the situation where $K_b < J$, such that the buyer needs to increase her level of knowledge to meet her project scope.

The buyer can meet the demand for new knowledge from internal knowledge development ($D_b \geq 0$) and from outsourcing knowledge from a supplier ($S \geq 0$), both expressed in hours. The supplier specifies the price per unit knowledge outsourced to the buyer, denoted by $p > 0$. The buyer and supplier enter into a contractual agreement that specifies the unit price and the amount of outsourcing (such as the problem to be solved) as well as the project deliverables (the due date and the reporting mechanism such as engineering design drawings, physical prototypes, or software).

While internal knowledge development directly contributes to the buyer's project scope, depending on her absorptive capacity (see Section 2.2), the buyer may have difficulty to understand and apply the supplier's outsourced knowledge. Empirically, it has been shown that if the buyer's existing knowledge is large, then she has a greater ability to absorb outsourced knowledge (Cohen and Levinthal 1994; Osterloh and Frey 2000; Hult et al. 2004), subject to diminishing returns denoted by $\sigma \in (0,1)$ (Cohen and Levinthal 1989; Graves 1989). Additionally, the buyer has more absorptive capacity if her integration factor (denoted by $\delta > 0$) is large, which captures her motivation to accept outsourced knowledge as well as the quality of communication and trust with the supplier. Since the buyer cannot understand and apply more knowledge than the supplier delivers, absorptive capacity is less than one. Mathematically, we define the buyer's absorptive capacity as $\phi = \delta [K_b]^\sigma \in (0,1)$, from which we obtain the upper bound $0 < \delta < \frac{1}{[K_b]^\sigma}$. It follows that S hours of outsourcing from the supplier provides the buyer with ϕS units of knowledge (expressed in hours) to meet her project scope.

Equation (1) mathematically summarizes the above discussion on how the buyer meets her project scope from her existing knowledge, internal knowledge development, and outsourcing knowledge from the supplier. Therefore, the buyer's problem is to meet her project scope while minimizing the sum of the costs incurred for: internal knowledge development ($c_b D_b^2$) and knowledge outsourcing from the supplier (pS), as given in Equation (2). The cost of internal knowledge development is convex increasing with respect to D_b reflecting the additional complexity, coordination, and overuse of the buyer's limited knowledge resources as more internal knowledge development occurs (Gaimon et al. 2011; Ozkan-Seely et al. 2015). In practice, the buyer (and supplier) has capacity limitations to develop knowledge in-house. This convex increasing in-house knowledge development cost allows us to capture capacitated knowledge development without explicit capacity constraint in the model (Eliashberg and Steinberg 1991; Bhaskaran et al. 2010). Lastly, in this deterministic model, the buyer's internal knowledge development (D_b) is simply inferred from Equation (1), given J, K_b, and ϕS. Therefore, internal knowledge development and outsourcing are substitute knowledge resources the buyer relies on to reach her project scope.

$$J = K_b + D_b + \phi S \tag{1}$$

$$Min_{S, D_b \geq 0} TC = c_b D_b^2 + pS \tag{2}$$

The Supplier's Problem

The supplier determines the unit price for knowledge outsourcing to charge the buyer ($p > 0$) to maximize profit. In addition to the revenue obtained from the buyer's outsourcing (pS), the supplier incurs a cost to internally develop any new knowledge needed to meet the buyer's demand for outsourcing. In other words, if the supplier's relevant prior knowledge gleaned from past contractual engagements (expressed in hours and denoted by $K_s > 0$) is not sufficient to meet the buyer's demand for outsourcing, then the supplier invests in internal knowledge development (expressed in hours and denoted by $0 \leq D_s < S$) (see Equation (3)). In practice, the supplier's reuse of prior knowledge to meet the buyer's demand for outsourcing is commonplace (Christensen and Baird 1998; Eccles et al. 2013; Eccles et al. 2014). Lastly, analogous to the buyer's cost, the cost incurred by the supplier for internal knowledge development is given by $c_s D_s^2$. The supplier's profit-maximizing objective appears in Equation (4).

$$D_s = Max\left\{S - K_s, 0\right\} \tag{3}$$

$$Max_{p\geq 0}\Pi = pS - c_s D_s^2 \tag{4}$$

2.3.2 Analysis of the Optimal Decisions

To obtain a Subgame Perfect Nash equilibrium, we use backward induction (Gibbons 1992; Mas-Colell et al. 1995). The solutions for the buyer and the supplier are given in Proposition 1. The first row in the table is the solution when the supplier's prior knowledge is sufficient to meet the buyer's demand for outsourcing ($D_s^* = 0$). However, in the remainder of our analysis, we focus on the more interesting solution (second row in the table) when the supplier needs to internally develop new knowledge to satisfy the buyer's demand for outsourcing so that $D_s^* > 0$. The results presented in the remainder of Section 2.3 are important because they provide key managerial insights on how the buyer's absorptive capacity and the supplier's prior knowledge impact the equilibrium decisions and both firm's objective values. (All proofs appear in the Appendix.)

Proposition 1. *The equilibrium decisions in the knowledge outsourcing game are as follows.*

	p^*	D_s^*	S^*	D_b^*
(i) $D_s^* = 0$	$c_b\phi(J - K_b)$	0	$\frac{J - K_b}{2\phi}$	$\frac{J - K_b}{2}$
(ii) $D_s^* > 0$	$\frac{2c_b\phi\left\{(J - K_b)(\phi^2 c_b + c_s) - c_s\phi K_s\right\}}{2c_b\phi^2 + c_s}$	$\frac{c_b\phi\left\{(J - K_b) - 2\phi K_s\right\}}{2c_b\phi^2 + c_s}$	$\frac{c_b\phi(J - K_b) + c_s K_s}{2c_b\phi^2 + c_s}$	$\frac{(J - K_b)(c_b\phi^2 + c_s) - c_s\phi K_s}{2c_b\phi^2 + c_s}$

Effect of the Supplier's Prior Knowledge

A supplier with more prior knowledge (larger K_s) has less need to develop new knowledge to meet the buyer's demand for outsourcing. The reduced cost incurred for his own knowledge development allows the supplier to charge a lower price to entice more knowledge outsourcing from the buyer. In response, the buyer increases her reliance on knowledge outsourcing and reduces her own knowledge development to meet her project scope. These key results appear in Corollary 1*(i)*. Moreover, we find that the buyer's total cost (TC^*) always decreases because the lower price and reduction in internal knowledge development compensate for the increase in knowledge outsourcing. This demonstrates an important insight: a buyer always benefits from selecting a supplier with more prior knowledge to meet her demand for outsourcing. Lastly, we show that a supplier with more prior knowledge always earns higher profit (Π^*) for two reasons. First, despite his lower price, the supplier's revenue increases due to the increase in the buyer's outsourcing. Second, with more prior knowledge and despite the increase in outsourcing, the supplier's cost for his own knowledge development decreases. Clearly, both firms benefit when the supplier has more prior knowledge. The results on how the supplier's prior knowledge impacts the objective values of both firms appear in Corollary 1*(ii)*.

Corollary 1. *An increase in the supplier's prior knowledge (K_s) impacts the equilibrium decisions and the objective values of both the buyer and the supplier in the knowledge outsourcing defined by Equations (2) and (4) as follows:*

(i) $\frac{\partial D_s^*}{\partial K_s} < 0$; $\frac{\partial p^*}{\partial K_s} < 0$; $\frac{\partial S^*}{\partial K_s} > 0$; $\frac{\partial D_b^*}{\partial K_s} < 0$;

(ii) $\frac{\partial TC^*}{\partial K_s} < 0$; $\frac{\partial \Pi^*}{\partial K_s} > 0$.

Effect of Absorptive Capacity

To understand the impact of the buyer's absorptive capacity, we first consider the effect of an increase in the buyer's integration factor (δ) as summarized in Corollary 2. The buyer's integration factor is larger if she introduces processes to establish and maintain high quality communication with the supplier (Dyer and Singh 1998; Martinez-Noya et al. 2013). Also, the buyer may introduce incentives that facilitate the acceptance and application of the outsourced knowledge from the supplier (Osterloh and Frey 2000; Ko et al. 2005). Lastly, the buyer can increase trust by selecting a supplier she has successfully worked with in the past (Levin and Cross 2004).

For the sake of analytic tractability, we assume $\sigma = \frac{1}{2}$ from which we obtain the buyer's absorptive capacity $\phi = \delta \left[K_b \right]^{\frac{1}{2}}$ (Pacheco-de-Almeida and Zemsky 2007). Corollary 2 summarizes the impact of an increase in δ on the solutions for the buyer and the supplier. In a key result, we find that if the integration factor increases, then while her internal knowledge development always decreases, the buyer's knowledge outsourcing may increase or decrease. If the buyer needs a sufficiently large increase in knowledge to meet her project scope (large project scope, $J > \overline{J}_1$, where $\overline{J}_1$ is defined in Corollary 2*(i)*), then as her integration factor increases outsourcing is more desirable and increases, as well (Corollary 2*(i)*). Through backward induction, the supplier knows that outsourcing is more desirable to the buyer and charges a higher price. As a result, the buyer's increase in outsourcing is moderated by the higher price. Alternatively, if the buyer's project scope is sufficiently small ($J < \overline{J}_1$), then the higher integration factor allows the buyer to reduce outsourcing (Corollary 2*(i)*).

To compensate for his loss in revenue, the supplier charges a higher price for knowledge outsourcing. Therefore, regardless of whether the buyer's need for knowledge to meet her project scope is large or small, we show that an increase in δ always drives the supplier to charge a higher price (see Corollary 2*(ii)*). (We have discussed the solutions obtained for the inequality condition on J. Therefore, here and in the remainder of the paper, we do not explore the much less interesting case where $J = \overline{J}_1$ which indicates that the buyer's need for outsourcing is independent from her integration factor).

The impact of an increase in the integration factor on both firm's objective values is given in Corollary 2*(iii)*. Interestingly, we find that the higher integration factor always allows the buyer to reduce her total cost despite the supplier's higher price and regardless of whether she increases or decreases knowledge outsourcing. The reduction in the buyer's total cost is driven by her cost savings from less internal knowledge development. Moreover for two reasons, the supplier's profit always increases when the buyer's integration factor increases. First, given the higher price, if the buyer's knowledge outsourcing increases then the supplier's total revenue increases and thereby compensates for the additional cost he incurs for knowledge development. Second, if the buyer's knowledge outsourcing decreases then the increase in price is sufficiently large such that, along with his savings from less internal knowledge development, the supplier's profit increases. In conclusion, we show that both firms who participate in the knowledge outsourcing game benefit when the buyer's integration factor is larger.

Corollary 2. *An increase in the buyer's integration factor (δ) impacts the equilibrium decisions and the objective values of both the buyer and the supplier in the knowledge outsourcing game defined by Equations* (2) *and* (4) *as follows:*

(i) $\frac{\partial D_b^*}{\partial \delta} < 0$; *If* $J > \bar{J}_1$, *then* $\frac{\partial S^*}{\partial \delta} > 0$; *Otherwise,* $\frac{\partial S^*}{\partial \delta} < 0$, *where* $\bar{J}_1 = \left(K_b + \frac{4c_s \phi K_s}{c_s - 2c_b \phi^2} \right)^+$;

(ii) $\frac{\partial p^*}{\partial \delta} > 0$;

(iii) $\frac{\partial TC^*}{\partial \delta} < 0$; $\frac{\partial \Pi^*}{\partial \delta} > 0$.

To complete our analysis of the impact of the buyer's absorptive capacity on the solutions for both firms, we consider the effect of an increase in the buyer's existing knowledge (K_b) as summarized in Corollary 3. We find that the impact of the buyer's existing knowledge on equilibrium outcomes is not straightforward and differs from the impact of her integration factor (Corollary 2). The detailed discussion of the corollary follows.

Corollary 3. *There exist thresholds* $\bar{J}_2$, $\bar{J}_3$, $\bar{J}_4$ *such that* $\bar{J}_2 \le \bar{J}_4 \le \bar{J}_3$, *and the effects of an increase in the buyer's existing knowledge* (K_b) *on the equilibrium decisions and the objective values in the knowledge outsourcing game defined in Equations* (2) *and* (4) *are as follows:*

(i) $\frac{\partial D_b^*}{\partial K_b} < 0$; $\frac{\partial TC^*}{\partial K_b} < 0$;

(ii) *If* $J > \bar{J}_2$, *then* $\frac{\partial p^*}{\partial K_b} > 0$; *Otherwise,* $\frac{\partial p^*}{\partial K_b} < 0$;

(iii) *If* $J > \bar{J}_3$, *then* $\frac{\partial S^*}{\partial K_b} > 0$; *Otherwise,* $\frac{\partial S^*}{\partial K_b} < 0$;

(iv) *If* $J > \bar{J}_4$, *then* $\frac{\partial \Pi^*}{\partial K_b} > 0$; *Otherwise,* $\frac{\partial \Pi^*}{\partial K_b} < 0$;

where $\bar{J}_2 = \frac{7c_b c_s \phi^2 K_b + 6c_b^2 \phi^4 K_b + c_s^2 (3K_b + 2\phi K_s)}{c_s^2 + c_b c_s \phi^2 + 2c_b^2 \phi^4}$, $\bar{J}_3 = \left(\bar{J}_1 + \frac{2K_b (2c_b \phi^2 + c_s)}{c_s - 2c_b \phi^2} \right)^+$, and $\bar{J}_4 = K_b \left(3 + \frac{4c_b \phi^2}{c_s} \right) + 2\phi K_s$.

If the buyer's existing knowledge increases, she benefits from an increase in absorptive capacity and a decrease in the need for new knowledge to meet her project scope. As such, the buyer always decreases her internal knowledge development so that her total cost decreases despite any increase in her cost of knowledge outsourcing

(Corollary 3*(i)*). In contrast, the effects of the buyer's existing knowledge on the supplier's price, the buyer's knowledge outsourcing, and the supplier's profit (Corollary 3 *(ii)*, *(iii)*, and *(iv)*) depends on the relative dominance of the two forces illustrated in Figure 1. In region 1, since the buyer's project scope is sufficiently large ($J > \overline{J}_3$ from which we know $J > \overline{J}_2$ and $J > \overline{J}_4$), the effect of the increase in absorptive capacity significantly dominates the effect of the decrease in the buyer's need for new knowledge. Leveraging this information, the supplier charges a higher price while still attracting more knowledge outsourcing and thereby increases his profit. At the other extreme, in region 4, since the buyer's project scope is sufficiently small ($J < \overline{J}_2$ from which we know $J < \overline{J}_3$ and $J < \overline{J}_4$) , the effect of the decrease in the need for new knowledge significantly dominates the effect of the increase in absorptive capacity. In this situation, the supplier lowers his price to limit the buyer's reduction in knowledge outsourcing. Naturally, the supplier's profit is lower due to the decrease in both the price and quantity of knowledge outsourcing.

If the buyer's need for new knowledge is moderate, the equilibrium solution lies in either in region 3 ($\overline{J}_2 < J < \overline{J}_4$ from which we know $J < \overline{J}_3$) or region 2 ($\overline{J}_4 < J < \overline{J}_3$ from which we know $J > \overline{J}_2$). In both regions, while the supplier's price increases and the buyer's knowledge outsourcing decreases, the supplier's profit may either increase or decrease depending on the relative dominance of either the increase in absorptive capacity or the decrease in the buyer's need for new knowledge. Lastly, by comparing the results of Corollaries 2 and 3, we obtain an important insight: while the supplier and the buyer always benefit from a larger integration factor, if the buyer's existing knowledge is moderately small (moderately large) and increases, then the supplier's profit decreases (increases).

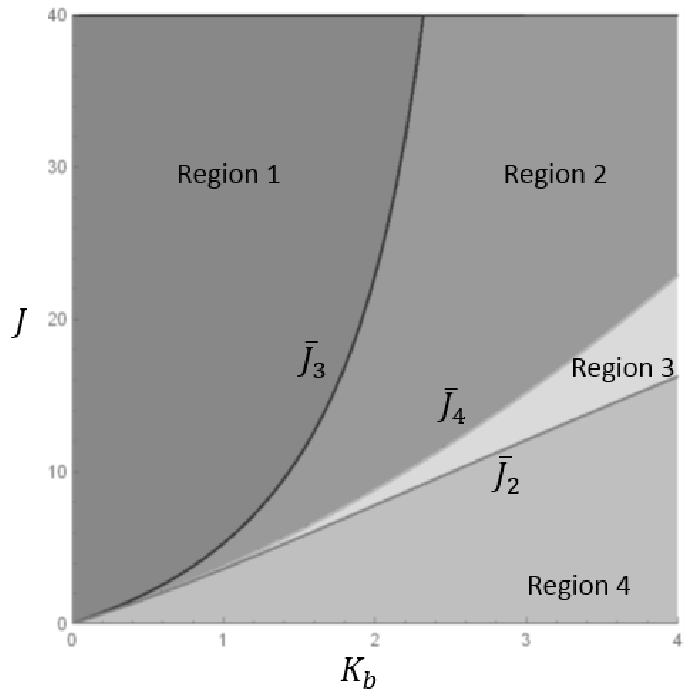


Figure 1. Relationships among the thresholds on the buyer's project scope.
$J \in (4,40)$, $K_b \in (0,4)$, $\delta = 0.5$, $c_b = 1$, $K_s = 0.1$, $c_s = 1.5$

2.4 Uncertain Project Scope

In this section, we extend the insights obtained from the deterministic game of knowledge outsourcing and consider a buyer who must undertake highly novel activities to meet a performance goal set by upper management. Since this novelty prevents the buyer from precisely converting the performance goal into her project scope, she faces project scope uncertainty. Let $J > 0$ denote the true project scope the buyer needs to meet her performance goal, which is uncertain at the outset of the game and only observed after all the decisions are made. The true project scope J is uniformly distributed from $\hat{J} - t$ to $\hat{J} + t$, with $\hat{J} > 0$ representing the mean of the uniform distribution ($E[J] = \hat{J}$) and t with $0 \le t \le \hat{J}$ captures the extent of uncertainty ($Var[J] = t^2 / 3$).

The sequence of decisions is the same as the deterministic model. First, the supplier determines the price for outsourced knowledge to maximize profit, as defined in Section 2.3.1 (see Equations (3) and (4)). Second, however, since the buyer's true project scope is unknown at the outset of the game, her response differs from the deterministic solution. In the stochastic game, the buyer determines both the levels of internal knowledge development (D_b) and outsourcing (S) simultaneously from which we obtain the planned project scope J_A, where J_A is given in Equation (6). This formulation contrasts the deterministic model, where the buyer determines only knowledge outsourcing and internal knowledge development is inferred since the project scope is known before the game begins.

After all the decisions are made, the true project scope is revealed. If the true project scope is smaller than the planned project scope ($J_A > J$), the buyer earns value from the knowledge surplus. In contrast, if the true project scope is larger than the planned project scope ($J_A < J$), the buyer must meet the knowledge shortage by expediting the completion of the shortfall.[1] Let c_e denote the marginal cost for expedited knowledge when faced with a shortage, and $v > 0$ denote the marginal value for surplus knowledge. We assume $c_e > p$ and $c_e > v$ to focus on non-trivial situations. The buyer determines D_b and S jointly to minimize her expected total cost for knowledge outsourcing, internal knowledge development, and expediting to meet an expected knowledge shortage, minus the value of an expected knowledge surplus. The buyer's expected total cost is given by Equation (5) below. The new

[1] We assume that the buyer cannot meet the knowledge shortage from the original supplier. Therefore, we prevent the knowledge supplier from "gaming" the solution by inducing the buyer to pursue a shortage, which the supplier can exploit later.

terminology and notation introduced in this section are summarized in Table 7 of proof of A.5.

$$Min_{S,D_b\geq 0}E\left[TC\right]=c_bD_b^2+pS+\frac{c_e}{2t}\int_{J_A}^{\hat{J}+t}\left(J-J_A\right)dJ-\frac{v}{2t}\int_{\hat{J}-t}^{J_A}\left(J_A-J\right)dJ \tag{5}$$

$$\textit{subject to } J_A=K_b+D_b+\phi S \tag{6}$$

In Proposition 2 below, we characterize the buyer's best response to the supplier's price p. This provides insights on how the level of uncertainty about project scope and the supplier's price jointly determine whether the buyer should pursue a planned surplus or planned shortage. Note that S^t and D_b^t denote optimal values of these variables for a given price p.

Proposition 2. *For a given price* p*:*

(i) The optimal decisions of the buyer are $D_b^t=\dfrac{p}{2\phi c_b}$ *and*

$$S^t=\frac{2\phi c_b\left(c_e-v\right)\left(\hat{J}+t-K_b\right)-p\left(c_e-v\right)-4c_btp}{2c_b\phi^2\left(c_e-v\right)};$$

(ii) The total amount of knowledge is given by $J_A^t=\hat{J}+\dfrac{t\left\{\phi\left(c_e+v\right)-2p\right\}}{\phi\left(c_e-v\right)}$*, where* $J_A^t=K_b+D_b^t+\phi S^t$*;*

(iii) Further, the buyer pursues a planned surplus ($J_A^t>\hat{J}$ *) if* $c_e+v>\dfrac{2p}{\phi}$*; otherwise, the buyer pursues a planned shortage (* $J_A^t\leq\hat{J}$ *).*

In contrast to the deterministic model (Section 2.3), the buyer's balance between knowledge outsourcing and internal knowledge development is affected by the degree of project scope uncertainty (t) as well as the supplier's price p. From Proposition 2, we observe that the amount of internal knowledge development D_b^t

always increases with p, while the amount of outsourced knowledge S^t decreases with p. Further, for a given price p, a buyer with greater absorptive capacity ϕ optimally reduces both internal knowledge development and the level of outsourcing from the supplier. These results are consistent with expectation.

2.4.1 Effect of Project Scope Uncertainty

Proposition 2 analyzes the buyer's best response for a given price. In contrast, Lemma 1 (appendix A6) provides the equilibrium solutions for both the supplier (price) and the buyer (knowledge outsourcing and internal knowledge development). Despite the complexity of Lemma 1, several insights are obtained regarding how both firms' equilibrium decisions are impacted by uncertainty. In particular, the key question remaining is how should the buyer respond to an increase in project scope uncertainty t? To understand this, we consider an interesting parallel between the buyer's knowledge outsourcing problem and the canonical problem of the newsvendor, which has been studied in great depth in the Operations Management literature (Arrow et al. 1951; Porteus 1990). In the newsvendor model, the optimal quantity stocked by a retailer has two properties: if the underage (overage) cost is higher than the overage (underage) cost, the optimal stocking level is larger (smaller) than the expected demand; further, the optimal quantity increases (decreases) as demand uncertainty increases. Remarkably, the knowledge buyer in our context has a similar response to uncertainty. We find that when either the expediting cost (c_e) or the value of excess knowledge (v) is sufficiently large, the buyer should pursue a planned surplus, meaning the overall quantity of usable knowledge obtained J_A^t is larger than the anticipated project scope ($J_A^t > \hat{J}$); otherwise, the buyer pursues a planned shortage ($J_A^t \leq \hat{J}$). In addition, we find that as t increases, the buyer's knowledge outsourcing decreases (increases) if she pursues a planned shortage (surplus).

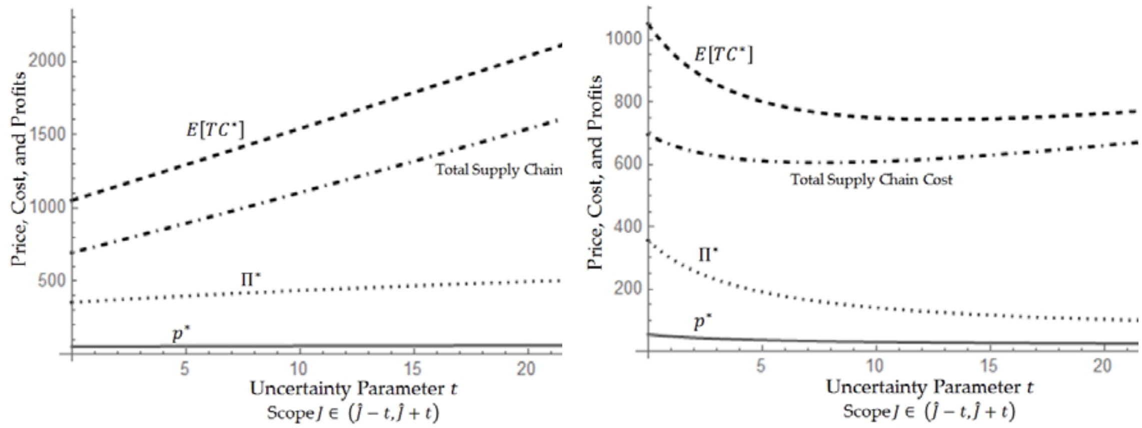
Building further on Lemma 1, we examine how uncertainty impacts the supplier's profit and the buyer's expected total cost. One might reasonably expect that an increase in uncertainty will increase the buyer's total expected cost of the project; however, this is not always the case. Proposition 3 below identifies an interesting and potentially valuable implication of uncertainty. The interpretation follows.

Proposition 3. *The level of uncertainty associated with the buyer's project scope affects the supplier's profit and the buyer's expected total cost as follows:*

$$\text{(i)} \quad \frac{\partial \Pi^*}{\partial t} = \begin{cases} \geq 0 & \text{if } S^* \dfrac{\partial p^*}{\partial t} + \dfrac{\partial S^*}{\partial t} \left\{ p^* - 2c_s \left(S^* - K_s \right) \right\} \geq 0 \\ < 0 & \text{otherwise} \end{cases};$$

$$\text{(ii)} \quad \frac{\partial E\left[TC^*\right]}{\partial t} = \begin{cases} \leq 0 & \text{if } S^* \dfrac{\partial p^*}{\partial t} + \dfrac{\left(c_e - v\right)\left\{t^2 - \left(J_A^* - \hat{J}\right)^2\right\}}{4t^2} \leq 0 \\ > 0 & \text{otherwise} \end{cases}.$$

Proposition 3*(i)* provides conditions whereby the supplier's profit may increase or decrease when uncertainty (t) increases. More interestingly, Proposition 3*(ii)* shows that under certain conditions, the buyer's total expected cost of the project may even decrease with the amount of uncertainty (t). These analytical results are best explained by the numerical examples illustrated in Figure 2. For two different values of c_e, the two panels in the figure show the effect of t on the supplier's profit and price, and the buyer's expected total cost; the figures also show the overall expected project cost, which we refer to as the "Total Supply Chain Cost". We discuss each numerical example, below.[2]



(a) $c_e = 200$: Planned surplus (b) $c_e = 40$: Planned shortage

Figure 2. Effect of project scope uncertainty on price, cost, and profit. $\hat{J} = 25$, $K_b = 1$, $K_s = 1$, $\delta = 0.8$, $\phi = 0.8$, $c_b = 2$, $c_s = 2$, $v = 2$

First, consider Figure 2(a), where the expediting cost c_e is sufficiently high, leading the buyer to pursue a planned surplus at the outset of the game. Said differently, the buyer's desire not to incur c_e makes her behave as if the project has a deterministic scope of $\hat{J} + t$ (upper bound of the estimated true project scope). Clearly, as uncertainty (t) increases, the supplier exploits the large c_e, which drives the buyer's desire for a large knowledge surplus, by increasing the price for outsourcing (p). Moreover, we find that the supplier's equilibrium price and profit (Π^*) increase monotonically with t (see Appendix A6). The buyer's total expected

[2] A peculiar aspect of the figure is worth noting: The buyer's total expected cost always appears to be higher than the total supply chain cost and the supplier's profit. This occurs because, by construction in our model, the buyer's total cost includes her cost of knowledge outsourcing and the supplier's revenue, which has a net effect of zero.

cost ($E\left[TC^*\right]$) increases with t , as well, reflecting the increase in the supplier's price and an increase in both the buyer's internal knowledge development and knowledge outsourcing. Not surprisingly, the overall cost incurred by the supply chain also increases with t .

A contrasting picture emerges when the buyer's cost of expediting is small, as shown in Figure 2(b). In this situation, the buyer deliberately pursues a planned shortage at the outset of the game. Further, if t is small and increases, the buyer reduces the amount of internal knowledge development as well as knowledge outsourcing (again, note the parallel to the newsvendor model). Anticipating the buyer's desire for a planned shortage, the supplier lowers his price p to limit the buyer's reduction in knowledge outsourcing. For these reasons, both the buyer's total expected cost $E\left[TC^*\right]$ and the supplier's profit Π^* decrease. Interestingly, the fact that more uncertainty improves the performance of the supply chain when t is small and increases is a result that is unique to the knowledge outsourcing problem (as opposed to the component outsourcing problem).

2.5 Asymmetric Information about Integration Factor

In this section, we consider a game-theoretic model in which information asymmetry exists such that the buyer's integration factor remains her private information; all other information is common knowledge to both firms. Specifically, while the supplier knows the deliverables, he does not know with certainty the extent to which the buyer is capable of understanding and utilizing the outsourced knowledge. The impact of this lack of information is clear since the supplier sets his price in relation to the buyer's outsourcing response which includes the integration factor.

We assume the supplier believes the buyer has a high integration factor denoted by δ_H with a probability of θ and a low integration factor denoted by δ_L with the probability $1-\theta$, where $0<\phi_L<\phi_H<1$. We refer to an H-type (L-type) buyer as having a high (low) integration factor. While the buyer still focuses on minimizing her total cost, the supplier determines the equilibrium price to maximize his expected profit. To focus on the difference between the H-type and L-type integration factors, we assume that all other parameters are the same for both types of buyers. The additional notation used in this section appears in Table 2.

Table 2. Additional notation for the information asymmetry model.

δ_H (δ_L)	Integration factor of the H-type (L-type) buyer, $\delta_L<\delta_H<1$.
θ	Probability that the buyer is H-type, $0<\theta<1$.

The remainder of this section is organized as follows. First, we consider the situation where the supplier serves both the H-type and the L-type buyers. Second, conditions are given whereby the supplier serves only the H-type buyer. It will be shown that the supplier never serves only the L-type buyer so that the supplier pursues one of two pricing schemes (both buyers served; only H-type buyer served).

2.5.1 Buyer and Supplier Problems under Asymmetric Information

We refer to the equilibrium decisions of the supplier and the buyer in the asymmetric information game with the subscript A. Suppose the supplier serves both buyer types. His objective and constraints appear in Equations (7), (8), and (9), where p_A denotes the supplier's price, S_{Ai} denotes the buyer's level of knowledge outsourcing, and D_{sAi} denotes the supplier's level of internal knowledge development corresponding to the i-type buyer, with $i = H$ or L. The cost-minimizing objective and constraints for each buyer type are given in Equations (10) and (11), where the i-type buyer's integration factor equals δ_i and D_{bAi} denotes her level of internal knowledge development, with $i = H$ or L.

Alternatively, suppose the supplier chooses to serve only the H-type buyer. In this situation, he maximizes the expected profit (Equation (7)) with the second term in the objective function eliminated, subject to the constraint in Equation (8) (i.e., $\theta = 1$). As such, for this pricing scheme, the supplier's problem is analogous to the base (deterministic) model except that his expected profit is now proportional to the probability that the buyer is H-Type. The buyer's problem is given by Equations (10) and (11) with $i = H$ and $S_L = 0$.

$$Max_{p_A \geq 0} E\left[\Pi_A\right] = \theta\left(p_A S_{AH} - c_s D_{sAH}^2\right) + \left(1-\theta\right)\left(p_A S_{AL} - c_s D_{sAL}^2\right) \tag{7}$$

$$s.t.\ D_{sAH} = \max\left\{S_{AH} - K_s, 0\right\} \tag{8}$$

$$D_{sAL} = \max\left\{S_{AL} - K_s, 0\right\} \tag{9}$$

$$Min_{S_{Ai},\, D_{bAi} \geq 0} TC_{Ai} = c_b D_{bAi}^2 + p_A S_{Ai},\ i \in \left\{H, L\right\} \tag{10}$$

$$s.t.\ J = K_b + D_{bAi} + \phi_i S_{Ai} \tag{11}$$

2.5.2 Supplier's Pricing and Selection Decisions

Using backward induction to solve the sequential game, we obtain the Perfect Bayesian Nash Equilibrium (Gibbons, 1992; Mas-Colell et al., 1995). First, for the situation where the supplier serves both types of buyers, his price (p_A^*) is depicted in Proposition 4. Intuitively, the supplier maximizes his expected profit by charging a sufficiently low price such that both types of buyers participate. As stated in Proposition 4, the equilibrium price is the weighted average between the (high) price (p_H^*) charged if the buyer were H-type with a probability of one (δ_H with $\theta = 1$) and the (low) price (p_L^*) charged if the buyer were L-type with a probability of one (δ_L with $\theta = 0$). Before stating Proposition 4, we introduce the following notation. Let $\phi_L = \delta_L K_b^\sigma$, $\phi_H = \delta_H K_b^\sigma$, $\Lambda_H = \theta\phi_L^4\left(c_s + 2c_b\phi_H^2\right)$, $\Lambda_L = \left(1-\theta\right)\phi_H^4\left(c_s + 2c_b\phi_L^2\right)$, and p_H^* and p_L^* satisfy Proposition 4 with $\delta = \delta_H$ and $\delta = \delta_L$, respectively.

Proposition 4. *Pricing under information asymmetry: both buyer types served.*

When the supplier serves both types of buyers, the equilibrium price is given by

$$p_A^* = \left(\frac{\Lambda_H}{\Lambda_H + \Lambda_L}\right)p_H^* + \left(\frac{\Lambda_L}{\Lambda_H + \Lambda_L}\right)p_L^*.$$

Second, for the situation where only the H-type buyer is served, the supplier's price is sufficiently high such that the L-type buyer's outsourcing quantity is zero. The equilibrium price for this situation appears in Proposition 5. Before stating this proposition, we introduce the following notation. Let $\phi_H = \delta_H K_b^\sigma$, $\delta = \delta_H$, and $\Lambda_H = \theta\phi_L^4\left(c_s + 2c_b\phi_H^2\right)$.

Proposition 5. *Pricing under information asymmetry: only h-type buyer served.*

When the supplier serves only the H-type buyer, p_H^* is given by Proposition 1.

It is interesting to observe the relationship between Corollary 2 and Propositions 4 and 5. From Corollary 2 in the deterministic model with complete information, we know that the supplier's price increases as the buyer's (known) integration factor increases (for $\theta = 0$ or $\theta = 1$). It follows that $p_L^* < p_A^* < p_H^*$ for $\theta \in (0,1)$. While Propositions 4 and 5 provide the equilibrium solutions for the two pricing schemes, Proposition 6 identifies when each occurs. Moreover, the results of Proposition 6 indicate that the supplier never chooses to serve only the L-type buyer. An important insight from Proposition 6 is that if the probability that the buyer is H-type is sufficiently large, the supplier charges a sufficiently high price to exclude the L-type buyer. Essentially, the increase in the supplier's expected profit from the higher price charged to the H-type buyer dominates the decrease in his expected profit from not serving the L-type buyer.

Proposition 6. *Optimal pricing scheme under information asymmetry.*

If the supplier is not informed about the buyer's integration factor, he optimally chooses to serve both types of buyer only if $0 < \theta < \theta_A$*; Otherwise, serving only the H-type buyer is optimal, where* $\Pi_{Ai}^*\left(p_A^*\right) = p_A^* S_{Ai}^* - c_s\left(D_{sAi}^*\right)^2$ *and* $i \in \{H, L\}$. *The threshold is given by* $\theta_A = \dfrac{\Pi_{AL}^*\left(p_A^*\right)}{\Pi_{AL}^*\left(p_A^*\right) + \Pi_H^*\left(p_H^*\right) - \Pi_{AH}^*\left(p_A^*\right)}$

To better understand this threshold θ_A and its connection to other factors, consider Figure 3. The figure illustrates how the supplier's pricing scheme is jointly determined by the difference between integration factors of the H-type and L-type buyers and the probability that the buyer is H-type. In the figure, the vertical axis represents the difference given as $\Delta = \delta_H - \delta_L$, whereas the horizontal axis represents θ.

We observe that if the difference between the high and low integration factors is relatively small, then regardless of the probability the buyer is H-type, the supplier optimally serves both types of buyers. In this situation, the price reduction needed to entice the L-type buyer to outsource knowledge is sufficiently small so that the supplier's gain from serving only the H-type supplier does not compensate for the loss of excluding the L-type buyer. In contrast, if the difference between the high and low integration factors is relatively large, then as the probability the buyer is H-type increases, the supplier optimally chooses to serve only that buyer. Here, the supplier is able to charge a high price by focusing on the H-type buyer, which automatically dissuades the L-type buyer from outsourcing knowledge.

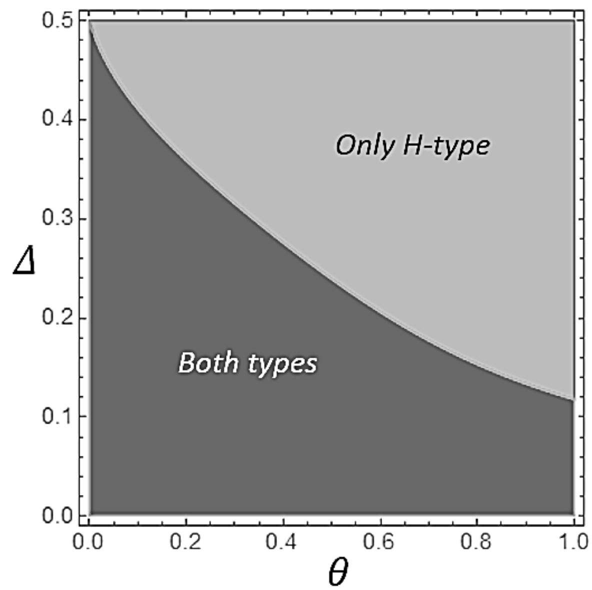


Figure 3. Impact of the buyer's integration factor on the supplier's pricing scheme.
$J=15$, $K_b=1$, $K_s=3$, $c_b=3$, $c_s=1$, $\theta \in (0,1)$, $\delta_H=0.5+\Delta$, $\delta_L=0.5-\Delta$

2.6 Discussion and Conclusions

To our knowledge, we are the first to characterize a buyer-supplier game in the context of knowledge outsourcing. Three Stackelberg games are introduced in which the supplier (leader, he) sets the price for knowledge outsourcing and the buyer (follower, she) determines the extent to which her project scope is met from knowledge outsourcing or internal knowledge development. The knowledge outsourcing game is markedly different from the standard component (or finished good) outsourcing game in three respects. First, the quantities of knowledge outsourcing, internal knowledge development, and project scope are measured in hours of effort. Second, the buyer only obtains benefits from outsourcing to the extent that she has the ability to absorb external knowledge (absorptive capacity). In other words, the S units of knowledge that are outsourced from the supplier do not reduce the buyer's need to meet the project scope by S units. Third, once developed by either the buyer or the supplier, knowledge is not consumed and can be reused. Specifically, to meet the needs of the current buyer, the supplier may leverage related knowledge he "produced" to meet the needs of prior customers. In the same way, the buyer leverages her existing knowledge directly toward fulfilling her current project scope and indirectly as a key element of her absorptive capacity.

Deterministic Game with Complete Information

We develop analytic results that provide important insights to three realistic situations. First, we consider a deterministic Stackelberg game of complete information. We show that the two drivers of absorptive capacity, (the buyer's existing knowledge and her integration factor) impact each firm's equilibrium decisions differently. If the buyer's project scope is sufficiently large, we find that her equilibrium knowledge outsourcing increases with respect to both her existing knowledge and her integration factor. The fact that outsourcing may increase despite the fact that the buyer has a larger amount of existing knowledge demonstrates the importance of modeling the two drivers of absorptive capacity. However, whereas the supplier's price always increases as the buyer's integration factor increases, we show that the supplier's price may increase or decrease when the buyer's existing knowledge increases. Intuitively, since the buyer's need for outsourcing decreases as her existing knowledge increases, under certain conditions, the supplier is driven to lower his price.

With respect to each firm's objective value, we have the following important insights. As expected, the buyer's total cost always decreases if either driver of her absorptive capacity increases. Additionally, the supplier's profit always increases if the buyer's integration factor increases. In contrast, since an increase in the buyer's level of existing knowledge not only increases her absorptive capacity but also reduces her need for new knowledge to meet her project scope, we show the supplier's price and profit may decrease or increase.

The above results have implications for the buyer when she selects a supplier. In particular, the buyer should select a supplier that provides a superior integration factor. This analytical insight is consistent with empirical studies that find that greater familiarity, trust, and mutual understanding between a buyer and a supplier results in a more effective knowledge outsourcing (Mowery et al. 1996; Tzabbar et al. 2013). Also, we show that the buyer's total cost is smaller if she selects a supplier capable of leveraging more prior knowledge. It is worth noting that, despite the lower price set by this supplier, the supplier's profit increases due to the buyer's increase in knowledge outsourcing and the decrease in the supplier's cost of internal knowledge development.

Effect of a Buyer's Uncertain Project Scope

In a second model, we investigate the impact of uncertainty associated with the buyer's project scope, which may occur if she pursues a highly novel project. Specifically, we consider the situation where the buyer's true project scope is uncertain (satisfying a uniform distribution with a known mean and standard deviation) and revealed only after all decisions are made. While the supplier's profit maximizing objective does not change from the deterministic game, the buyer now minimizes the expected total cost which includes the cost of internal knowledge development, the cost of outsourcing, the expected cost of expediting to meet any shortage of knowledge, minus the expected value of surplus knowledge.

We show that the effect of uncertainty on the equilibrium decisions is driven by the marginal cost to expedite if a knowledge shortage occurs after the true project scope is revealed. Consistent with intuition, if the expediting cost is sufficiently large, the buyer pursues a planned knowledge surplus. We show that if the buyer's planned project scope is sufficiently large, then both the buyer's knowledge outsourcing and internal knowledge development increase as uncertainty in the true project scope increases. Moreover, recognizing the buyer's drive to accumulate more knowledge, the supplier charges a higher price. Therefore, if the marginal cost of expediting is sufficiently large, as uncertainty in the true project scope increases, the total cost incurred by a buyer increases as does the profit obtained by the supplier.

In contrast, also consistent with intuition, if the marginal cost of expediting is sufficiently small, the buyer pursues a planned knowledge shortage. As a result, the supplier is forced to lower his price to limit the reduction in the buyer's knowledge outsourcing. Naturally, the buyer also reduces her internal knowledge development as uncertainty increases. Importantly, we show that, in this situation, the extent of project scope uncertainty plays a critical role in the equilibrium solutions. First, if the extent of project scope uncertainty is large, then both the supplier's price reduction and the buyer's reduction in knowledge outsourcing are modest. As a result, the buyer's total expected cost increases and the supplier's profit increases. Therefore, the total cost of the supply chain increases when uncertainty increases. However, if the extent of project scope uncertainty is small, then the supplier is forced to substantially lower his price while the buyer pursues much less knowledge outsourcing. It follows that the buyer's total expected cost decreases and the supplier's profit decreases.

Remarkably, our latter result is counter to the inventory management literature. Song (1994) shows that when lead-time uncertainty increases, a single firm pursuing a base-stock policy incurs a higher average cost. In a Stackelberg game formulation similar to ours, Lariviere and Porteus (2001) find that if the uncertainty in market demand increases, the supplier's profit always decreases while the buyer's profit always increases. In stark contrast, in our knowledge outsourcing game, when uncertainty increases, we obtain conditions where (i) the supplier's profit increases or decreases; (ii) the buyer's expected total cost increases or decreases; and (iii) more interestingly, the overall cost incurred by the supply chain may decrease (i.e., more uncertainty improves the performance of the supply chain).

Effect of Information Asymmetry

Finally, in a third game-theoretic model, we examine the effect of information asymmetry whereby the supplier does not know with certainty whether the buyer's integration factor is high (H-type buyer) or low (L-type buyer). While each type of buyer minimizes her deterministic total cost corresponding to her (known) high versus low integration factor, the supplier maximizes his expected profit given the probability he faces an H-type buyer and an L-type buyer.

Importantly, we find that the supplier pursues one of two pricing schemes. First, the supplier may set a sufficiently high price so that only the H-type buyer outsources knowledge (the L-type buyer must meet her project scope entirely from internal knowledge development). The supplier charges high price to exclude the L-type buyer from outsourcing only if the following two conditions hold simultaneously: the difference between the high versus low integration factors of the two buyer types is sufficiently large and the probability the buyer is H-type is sufficiently large. Clearly, the L-type buyer's total cost suffers because she is unable to outsource knowledge and must meet her entire project scope from internal knowledge development. The H-type buyer's cost performance is the same as that obtained in the deterministic game with full information since the supplier's price is the same. (The equilibrium solution corresponds to that of the deterministic model in which the buyer has a high integration factor.) However, the supplier's profit suffers because he forgoes all potential revenue earned from the L-type buyer.

In the second pricing scheme, the supplier sets a sufficiently low price such that both types of buyers outsource knowledge. In particular, the supplier's price is the weighted average of the equilibrium prices he would charge to a known H-type buyer and to a known L-type buyer. The L-type buyer's total cost suffers due to the supplier's higher price compared to the price he would charge if he knew she was L-type. The H-type buyer's total cost is lower because she benefits from the supplier's lower price. The supplier suffers lower profit because the additional revenue earned from the H-type buyer does not compensate for the lesser revenue earned from the L-type buyer. Overall, therefore, when the pricing scheme attracts both buyers in the game of incomplete information, only the H-type buyer wins.

With respect to the buyer, there are two implication of information asymmetry. The H-type buyer prefers to keep her integration factor as private information (thereby forcing the supplier to charge a lower price), whereas the L-type buyer prefers to inform the supplier of her type (to avoid the higher price that would be charged if the supplier were uncertain of the buyer's type).

Future Research Opportunities

In conclusion, we obtain important insights for several realistic situations in a knowledge outsourcing game between a buyer and a supplier. Moreover, we show that the equilibrium results obtained are significantly different from the classical component outsourcing literature. Nevertheless, there are considerable opportunities for future research. We do not consider the possibility that the supplier may provide technical training or improve the quality of communication to increase the buyer's integration factor. We believe important insights may be obtained in future research that allows the supplier to take actions (at a cost) to improve the buyer's absorptive capacity. In this study, we consider wholesale-price-only type of contracts. Since there may be various forms of lump-sum payments in practice, researchers may also examine how a buyer and a supplier strategically decide the optimal type of contract for knowledge outsourcing (e.g., revenue sharing, milestone-based contract, two-part tariff, exclusive contract, etc.). Driven by the need for early market entry in a new product development setting, future research may explore the situation where the supplier's price is a function of the agreed upon delivery date of the outsourced knowledge to the buyer. Lastly, beyond a buyer-supplier dyad, research opportunities exist to investigate the situation where the buyer outsources from more than one supplier, or the supplier sells his knowledge to multiple buyers.

CHAPTER 3. KNOWLEDGE OUTSOURCING FOR COMPETING BUYERS

3.1 Introduction

Knowledge is the single most valuable resource to aid the successful innovation of products and processes by firms (Grant 1996). Firms' existing repositories of internal knowledge are often not sufficient for successful innovation (Powell et al. 1996). In such cases, firms may choose to engage with external entities (Pisano 1990; Hamel 1991; Dodgson 1993) and pursue knowledge outsourcing (Quinn 1999; Gaimon et al. 2017). Empirical data shows that the level of knowledge outsourcing pursued by firms is increasing over time. According to a report by Booz&Co. and Duke University (2007), the "hot" sectors for knowledge outsourcing are: new product development and design, engineering services, R&D, and analytical knowledge services. Additionally, U.S. census data (BEA 2017) demonstrates that the GDP value produced by the knowledge-intensive service industry – which includes professional, scientific, and technical services (all of which drive product design, R&D, IT, consulting, and marketing) – has more than doubled between 1998 and 2016.

Reflecting the increasing need for professional agents in the markets for knowledge (Consoli and Elche-Hortelano 2010), external knowledge providers, such as Knowledge Intensive Business Services (KIBS)[3], have become central components of current knowledge-based economies (Muller and Zenker 2001; Howells 2006; Tether and Tajar 2008; Probert et al. 2013; Lessard 2015). KIBS specialize in knowledge development, screening, and assessment and evaluation, and they trade professional consultancy services with multiple client firms (Consoli and Elche-Hortelano 2010). The services of KIBS progress based on a contractual agreement between the knowledge source (termed "supplier") and the recipient (termed "buyer"). The contract covers the specific content (problems to be solved or experiments to be performed), form (written report, prototype, design drawing, software), and due date of the outsourced knowledge to be provided by the supplier to the buyer (Probert et al. 2013; Lee et al. 2016). For example, IDEO (2017), one of the largest suppliers of knowledge for new product development, works with several hundred different firms in over 40 industries and develops 60 to 80 products at a time, as of 1997 (Hargadon and Sutton 1997).

The unique features of such knowledge outsourcing that arise when one knowledge supplier serves multiple buyers competing in the downstream market pose many intriguing questions which have yet to be answered in the literature. In this paper, we consider the situation where two buyers (buyers 1 and 2) both outsource knowledge from a common supplier to improve their product performance (i.e., knowledge is a proxy for product performance) and attempt to answer the following questions: Under what conditions do either of the buyers pursue knowledge outsourcing from the supplier? In the situation where only one of the two buyers outsources knowledge from the supplier, how does that buyer's knowledge

[3] KIBS are firms broadly referred to as knowledge intermediaries, knowledge-intensive firms, knowledge brokers, technology brokers, or professional service firms in the literature.

outsourcing influence both buyers' decisions concerning knowledge development and their retail prices in the downstream market? Under what conditions does the supplier prefer to serve only one buyer as opposed to both buyers? Specifically, in what ways is the supplier better off serving one buyer instead of both buyers?

To answer these critical questions, we introduce a Stackelberg game of knowledge outsourcing between a common supplier and two symmetric buyers (1 and 2). During the first stage of the game, the profit-maximizing supplier (Stackelberg leader) determines a common wholesale price (per hour of effort) of knowledge to charge to both buyers based on his internal cost of developing knowledge to meet the buyers' needs. In response, profit-maximizing buyers 1 and 2 (Stackelberg followers) simultaneously determine the levels of knowledge outsourcing (hours of effort) and in-house knowledge development (hours of effort) required to improve their product performance. At the second stage, buyers 1 and 2 compete in the downstream market by simultaneously setting their retail prices.

We build on our analysis by also considering the situation where buyer 1 (she) sells her product under monopoly, where there is no second buyer. In the monopoly case, we find that buyer 1 chooses to outsource knowledge if her in-house knowledge development cost is sufficiently high, in order to reduce her total knowledge acquisition cost. In the situation where the supplier commits to serve only one of two buyers (buyer 1) under duopoly, we find a similar result; buyer 1 outsources knowledge from the supplier only if her in-house knowledge development cost is sufficiently high. This finding becomes more interesting when compared with the situation under monopoly. We find that a buyer's desire for knowledge outsourcing depends on the competition structure (i.e., monopoly or duopoly) in the downstream market. Interestingly, buyer 1 under duopoly is more inclined to outsource knowledge than under monopoly. This is because buyer 2, who does not have the option of outsourcing knowledge from the supplier in the duopoly case, makes the strategic decision to keep her level of product performance lower than that of buyer 1. This indicates that buyer 1's knowledge outsourcing effectively discourages buyer 2 from pursuing in-house knowledge development and gives buyer 1 (buyer 2, respectively) an advantage as the higher quality (lower cost, respectively) manufacturer.

Lastly, we investigate the situation where the supplier attempts to serve both buyers 1 and 2. If the buyers' in-house knowledge development costs are sufficiently low, we find that the supplier is better off charging a higher wholesale price of knowledge and serving only one of the buyers. In contrast, if the buyers' in-house knowledge development costs are sufficiently high, both buyers are responsive to the supplier's wholesale price of knowledge. Therefore, the supplier charges a lower price and serves both buyers. In addition, we identify a certain condition under which the supplier decides to serve only one buyer, even if they both pursue knowledge outsourcing.

The remainder of this paper is organized as follows: In Section 3.2, we discuss the related literature. We start our analysis by considering the monopoly case concerning the supplier and a monopolist buyer in Section 3.3. To further build on our insights, in Section 3.4 we analyze the situation where two buyers, 1 and 2, compete in the downstream market. Specifically, in Section 3.4.1, we analyze the situation where the supplier commits to serve only buyer 1, and therefore only buyer 1 has the option of outsourcing knowledge from the supplier. In Section 3.4.2, we discuss our findings on the situation where the supplier attempts to serve both buyers. We conclude with a discussion of the managerial implications in Section 3.5.

3.2 Related Literature

When firms pursue external knowledge acquisition, they generally face three external sources of knowledge: partners, competitors, and consultants (Gaimon et al. 2017). In this study, we focus on independent and non-competing knowledge suppliers such as consultancies. Using game-theoretic formulation, Iyer and Soberman (2000) study horizontal market competition between two manufacturers who acquire information from a common supplier to improve product performance. They identify conditions under which the supplier should sell his information on product modification to only one firm, as opposed to both firms. In their study, however, the buyers who compete in the downstream market are price takers. Said differently, the supplier determines the amount of knowledge embedded in product modification information (Iyer and Soberman 2000). Therefore, the buyers decide only whether to purchase the pre-packaged knowledge. In contrast, the buyers in our study decide the amount of knowledge outsourcing required to solve their specific problems and improve product performance. Then, the supplier develops and delivers customized knowledge to satisfy each buyer's knowledge needs. The aforementioned KIBS, working as consultancies, specialize in customized knowledge development to aid R&D and engineering tasks for their clients' products and services.

Researchers investigate KIBS strategies and practices to better understand their role in the successful innovation of client firms. Miles et al. (1995) first defined KIBS as businesses focusing on the supply of knowledge and contributing to their clients' own knowledge-generating activities. Therefore, while carrying out customized knowledge development projects for clients, KIBS essentially perform problem-solving activities through direct user-producer interaction (Muller and Zenker 2001; Probert et al. 2013). Using survey data collected by the US Department of Labor in 2007, Consoli and Elche-Hortelano (2010) define the sectors of KIBS and show that they have heterogeneous occupational structures and skill requirements. Based on interviews with KIBS CEOs and managers in the Cambridge area in the UK, Probert et al. (2013) show that KIBS significantly contribute to the innovation of the local client firms (also see Muller and Zenker 2001, Howells 2006, and Hsuan and Mahnke 2011 to review studies on KIBS). While contributing to a better understanding of KIBS, these empirical studies do not provide in-depth implications on the practical interactions between a knowledge supplier and a buyer, such as decisions about the supplier's wholesale price of knowledge and the buyer's level of knowledge outsourcing.

In contrast to the integration of innovative components, knowledge outsourced from a supplier needs to be utilized and embedded into a buyer's existing knowledge repository (i.e., knowledge integration). This requires additional effort and incurs integration costs (Weigelt 2009; Grimpe and Kaiser 2010; Berchicci 2013; Bianchi et al. 2016). In addition, according to Cohen and Levinthal (1990), a recipient's ability to assimilate knowledge obtained from external sources depends on their absorptive capacity. The literature shows that absorptive capacity is largely a function of a firm's level of existing knowledge (Cohen and Levinthal 1990). Considering a buyer's absorptive capacity, Lee et al. (2016) investigate how a supplier's wholesale price of knowledge and a buyer's level of knowledge outsourcing are associated with prior knowledge, uncertainty, and information asymmetry. However, Lee et al. (2016) examine only dyadic interactions between one supplier and one buyer. In contrast, we investigate how decisions on knowledge outsourcing are influenced when a common knowledge supplier serves multiple buyers who compete in the downstream market.

3.3 Monopoly Buyer

In this section, we analyze a two stage game consisting of one upstream supplier (he) and one monopolist buyer (she) in the downstream market, referred to as buyer 1. To maximize her profit in the marketplace, buyer 1 recognizes the need to increase her level of knowledge to obtain scientific, engineering, analytic and technical services to improve her final product performance (Pisano 1990; Hamel 1991; Dodgson 1993; Quinn 1999). Buyer 1 may either develop knowledge in-house or outsource knowledge from the upstream supplier. To investigate how the supplier and buyer interact, we introduce a Stackelberg game with complete and perfect information (both the supplier and buyer are aware of his/her own decisions and payoffs as well as that of the other firm).

Figure 4 below shows the sequence of decision-making. In the first stage, the supplier (Stackelberg leader) determines the wholesale price of knowledge ($w \geq 0$) to charge buyer 1 (referred to as the wholesale price). After observing the supplier's wholesale price in the second stage, buyer 1 (Stackelberg follower) determines the level of knowledge outsourcing ($S_1 \geq 0$) as well as the level of knowledge to develop in-house ($D_1 \geq 0$). Also, in the second stage, buyer 1 integrates any outsourced knowledge acquired from the supplier to improve performance of her new product. In the third stage, buyer 1 sets her retail price ($p_1 \geq 0$) and sells her product in the downstream market. The buyer's price will determine the demand for the buyer's product, which we discuss in the next section.

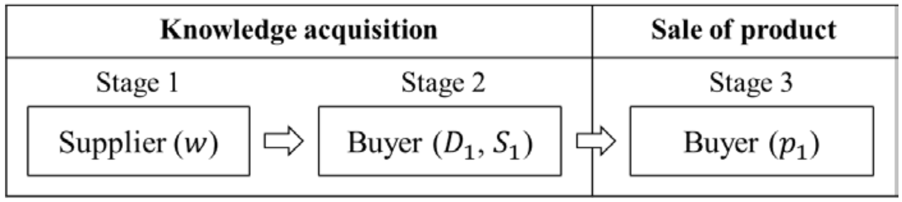


Figure 4. Sequence of decisions for the monopoly buyer.

3.3.1 Consumer Utility in the Downstream Market

Our characterization of the downstream market is based on the Hotelling model (Hotelling 1929). Consumer surplus utility is comprised of the consumer's product preference, the product's baseline utility, the increase in consumer utility (beyond the baseline value) due to performance improvement realized by buyer 1, and buyer 1's price. Figure 5 illustrates how consumers' surplus utilities and buyer 1's demand quantity are determined in the downstream market.

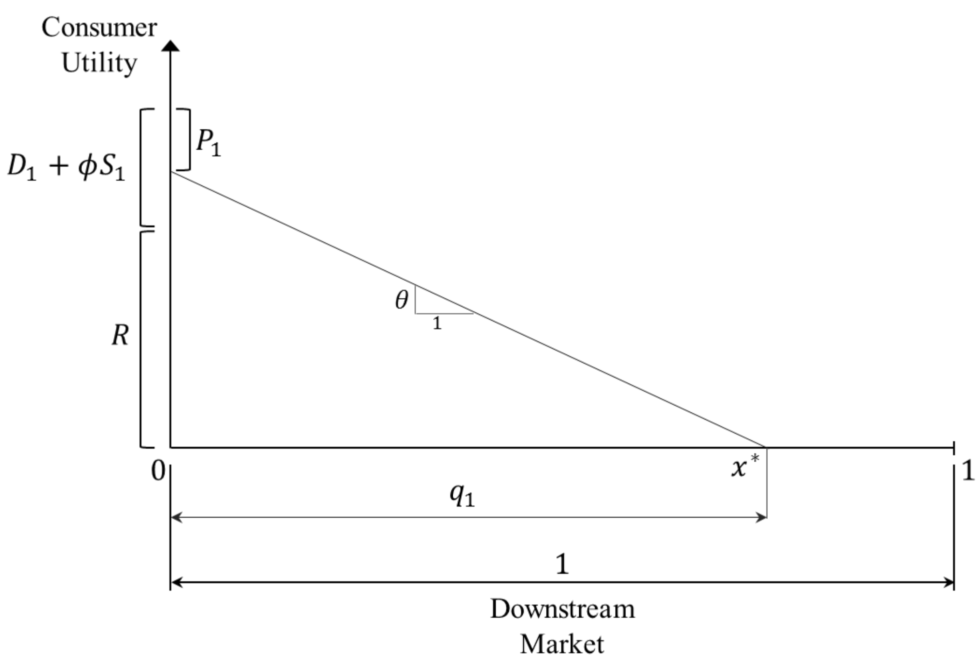


Figure 5. Hotelling market model for the monopoly buyer.

As illustrated in Figure 5, we assume a market of size 1 in the Hotelling model. Buyer 1 offers a product which is ideally positioned at the left end of the market (0) and sells her product to consumers. Each consumer's preference is denoted by x, which is uniformly distributed ($x \sim U[0,1]$) along the market between 0 and 1 (Iyer and Soberman 2000; Amaldoss and Jain 2015). Consumers incur a disutility for the mismatch between the product offered by buyer 1 and the consumers' preferences with respect to product functionality, ease of use, operating characteristics, etc. The disutility is measured by θx, where θ ($\theta > 0$) captures the intensity of the mismatch perceived by a consumer at x.

The baseline utility, denoted by $R > 0$, reflects the initial product performance without any further improvement through in-house knowledge development and/or outsourcing from the supplier (Adner and Levinthal 2001; Krishnan and Zhu 2006). If buyer 1 invests in in-house knowledge development and/or knowledge outsourcing, she improves product performance so that consumers gain additional utilities. Knowledge developed in-house by buyer 1 directly increases her product performance and thereby increases consumers' utilities by D_1. However, the level of an increase in product performance through knowledge outsourced from the supplier (S_1) depends on her absorptive capacity (Cohen and Levinthal 1990), denoted by ϕ ($0 < \phi < 1$)[4]. As such, the increase in buyer 1's product performance obtained from outsourced knowledge is given by ϕS_1. Lastly, buyer 1's retail price (p_1) reduces consumers' utilities. Summarizing the above discussion, we have Equation (12), which denotes a consumer's surplus utility at x:

$$U_1 = R + D_1 + \phi S_1 - p_1 - \theta x. \tag{12}$$

[4] Since the buyer cannot understand and apply more knowledge than the supplier delivers, absorptive capacity cannot exceed one (Cohen and Levinthal 1990).

Only those consumers having non-negative surplus purchase a product from buyer 1. Therefore, we solve Equation (13) and find buyer 1's demand quantity in the downstream market as defined in Equation (14). Naturally, buyer 1 attracts more consumers by increasing her product performance or reducing her retail price.

$$q_1 = \{x^*: U_1(x) \geq 0\}, \tag{13}$$

$$q_1 = \frac{R + D_1 + \phi S_1 - p_1}{\theta}. \tag{14}$$

Based on the elements discussed above, as demonstrated in Figure 5, if a customer has an ideal preference for buyer 1's product ($x = 0$), the customer obtains the full surplus utility ($R + D_1 + \phi S_1 - p_1$) offered by buyer 1. Otherwise, the consumer's surplus utility is reduced by θx. x^* represents a consumer's preference with which the consumer's surplus utility is zero. Therefore, consumers whose preferences are below x^* along the market between 0 and 1 obtain positive surplus utilities and buy buyer 1's product (i.e., $q_1 = x^*$).

3.3.2 Buyer's Problem

Since we solve the sequential game between the supplier and buyer 1 using backward induction, we present the buyer 1's problem first. In stage 3, buyer 1 sets the retail price p_1 and sells the quantity q_1 in the marketplace, which provides the monopoly revenue $q_1 p_1$. While we assume buyer 1's production cost is normalized to zero (Ramachandran and Krishnan 2008; Lauga and Ofek 2009), costs are incurred for in-house knowledge development and knowledge outsourcing, as follows.

In stage 2, buyer 1 incurs the cost $c_b {D_1}^2$, which is a convex increasing function of the level of in-house knowledge development with $c_b > 0$. The convex increasing cost of in-house knowledge development reflects the additional complexity, coordination, and overuse of buyer 1's limited resources used to generate knowledge (Gaimon et al. 2011; Pacheco-de-Almeida and Zemsky 2012; Ozkan-Seely et al. 2015). It is useful to note that buyer 1 (and the supplier) has capacity limitations to develop knowledge in-house. This convex increasing in-house knowledge development cost could be used to capture capacitated knowledge development without explicit capacity constraint in the model (Eliashberg and Steinberg 1991; Bhaskaran et al. 2010).

Also in stage 2, the contractual agreement between the supplier and buyer 1 specifies the content and form of knowledge (written report, engineering design drawings, physical prototypes, or software) as well as the delivery due date. Subsequently, the hours of effort committed by the supplier is determined (S_1). Once received, buyer 1 must expend effort to understand and utilize the outsourced knowledge to improve product performance. As a result, buyer 1 incurs a two-dimensional cost for knowledge outsourcing: the (external) purchase cost paid to the supplier (wS_1) and the (internal) cost to integrate (absorb) the outsourced knowledge (gS_1^2, where $g > 0$). The supplier sets the price of knowledge (w) in stage 1, as described in the next sub-section. Buyer 1's integration cost is a convex increasing function of the level of knowledge outsourcing, thereby reflecting the additional complexity, coordination, capacity limitations, and overuse of buyer 1's limited capacity to absorb the outsourced knowledge (Weigelt 2009; Gaimon et al. 2011; Pacheco-de-Almeida and Zemsky 2012; Ozkan-Seely et al. 2015).

It is useful to note that in this study buyer 1's baseline utility reflects her prior knowledge, which does not directly affect her absorptive capacity. Additionally, as described in the next sub-section, the supplier develops the knowledge required to meet buyer 1's needs in-house, without incorporating his prior knowledge. Since prior knowledge impacts the interactions between a supplier and a buyer (Lee et al. 2016), we discuss its implications in the game between a supplier and two buyers in Section 3.4.2.4.

Equations (15) and (16) mathematically summarize the above discussion. As shown in Figure 4, buyer 1 solves two sequential problems while maximizing her profit: one in stage 2 for knowledge acquisition and the other in stage 3 for the sale of her product. In stage 2, buyer 1 jointly determines her levels of in-house knowledge development and knowledge outsourcing knowing how these decisions impact her retail price. In stage 3, buyer 1 determines the retail price of her product to charge in the downstream market. Note p_1' in Equation (15) is the best response of buyer 1's retail price for a given product performance, defined by $D_1 + \phi S_1$.

$$\text{Stage 2: } \underset{S_1,\, D_1 > 0}{Max}\, \Pi_1(S_1,\, D_1) = p_1' q_1(p_1') - c_b D_1^2 - wS_1 - gS_1^2, \quad \textit{where } p_1' = arg \underset{p_1 > 0}{Max}\, \Pi_1\,(p_1), \tag{15}$$

$$\text{Stage 3: } \underset{p_1 > 0}{Max}\, \Pi_1(p_1) = p_1 q_1(p_1) - c_b D_1^2 - wS_1 - gS_1^2. \tag{16}$$

3.3.3 Supplier's Problem

In stage 1, the supplier, a Stackelberg leader in the knowledge outsourcing game between the supplier and buyer 1, sets the wholesale price per unit knowledge outsourced to buyer 1 (w) from which he obtains revenue given by wS_1. Additionally, the supplier incurs a cost to satisfy buyer 1's demand for knowledge, which is expressed as a convex increasing function of his level of internal knowledge development, denoted by $c_s S_1^2$ with $c_s > 0$. Similar to buyer 1's cost of in-house knowledge development, the supplier's convex increasing cost of internal knowledge development reflects the additional complexity, coordination, capacity limitations, and overuse of the supplier's limited resources used to meet buyer 1's demand. Equation (17) summarizes the supplier's profit maximizing objective. Note S_1' in Equation (17) is the best response of buyer 1's level of knowledge outsourcing (S_1) for a given supplier's wholesale price of knowledge. Notations used in the monopoly case are defined in Table 3.

$$\begin{gathered} \underset{w>0}{Max}\, \Pi_S = wS_1' - c_s(S_1')^2, \\ where\ S_1' = arg \underset{S_1,\, D_1>0}{Max}\, \Pi_1(S_1,\, D_1). \end{gathered} \tag{17}$$

Table 3. Terminology and notation for the monopolist model.

p_1	Retail Price charged by buyer 1 in the downstream market ($p_1 > 0$).
q_1	Quantity sold by buyer 1 in the downstream market ($0 \leq q_1 \leq 1$).
x	A consumer's preference at x, uniformly distributed along the market between 0 and 1 ($x \sim U[0, 1]$).
θ	Parameter indicating the intensity of consumers' disutility generated by the mismatch between their preferences and the product offered by buyer 1 ($\theta > 0$).
D_1	Buyer 1's level of in-house knowledge development ($D_1 \geq 0$).
S_1	Buyer 1's level of knowledge outsourcing ($S_1 \geq 0$).
ϕ	Buyer 1's absorptive capacity ($0 < \phi < 1$).
R	Consumer's baseline utility for buyer 1's product ($R > 0$).
U_1	Consumer's surplus utility for buyer 1's product.
c_b	Parameter indicating buyer 1's cost of in-house knowledge development ($c_b > 0$).
g	Parameter indicating buyer 1's cost of integrating outsourced knowledge ($g > 0$).
w	Supplier's price per unit of outsourced knowledge sold to buyer 1 ($w > 0$).
c_s	Parameter indicating the supplier's cost for in-house knowledge development ($c_s > 0$).

3.3.4 Analysis of the Monopoly Model

To build on our analysis, we must consider two situations: buyer 1 *(i)* chooses not to outsource knowledge from the supplier; and *(ii)* chooses to outsource knowledge from the supplier. Following backward induction, we obtain two equilibrium outcomes as shown in Proposition 7, below. (All proofs appear in the Appendix.)

Proposition 7. *The equilibrium decisions for the monopolist, buyer 1, are:*

(i) *If buyer 1 does not outsource knowledge from the supplier, then* $D_1^* = M_1$, $p_1^* = 2c_b\theta M_1$, *where* $M_1 = \frac{R}{4c_b\theta - 1}$;

(ii) *If buyer 1 outsources knowledge from the supplier, then* $w^* = c_b\phi\{M_1 + c_s M_2\}$, $D_1^* = \frac{1}{2}\{M_1 + M_2(c_s + 2g)\}$, $S_1^* = c_b\phi M_2$, *and* $p_1^* = c_b\theta\{M_1 + M_2(c_s + 2g)\}$, *where* $M_2 = \frac{R}{(c_s+2g)(4c_b\theta-1)-2c_b\phi^2}$.

From Proposition 7, regardless of whether or not buyer 1 outsources knowledge from the supplier, it appears that an increase in the baseline utility (R) increases all equilibrium decisions. This is because a larger R enables the buyer to benefit from further improving product performance either through in-house knowledge development or knowledge outsourcing. Similarly, our sensitivity analysis shows that if buyer 1's absorptive capacity increases, all equilibrium decisions increase due to the buyer's better ability to improve product performance by utilizing outsourced knowledge. However, we find that buyer 1's profit may decrease as her absorptive capacity increases. This happens when buyer 1's desire for knowledge outsourcing is sufficiently large (i.e., when absorptive capacity is sufficiently large). In this situation, leveraging the bargaining power, the supplier increases his wholesale price of knowledge as buyer 1's absorptive capacity increases to the extent that buyer 1's profit decreases. In response, buyer 1 accepts the supplier's high wholesale price to avoid a larger cost of in-house knowledge development required to maintain her product performance.

In the remainder of Section 3.3, we examine when the monopolist buyer benefits from pursuing knowledge outsourcing. In particular, we compare buyer 1's profit when she outsources knowledge from the supplier with the situation where she pursues only in-house knowledge development. Proposition 8 summarizes our analytical results; the discussion follows.

Proposition 8. *If the cost of in-house knowledge development (c_b) is lower than the threshold $\bar{c}_M = \frac{g}{4g\theta-\phi^2}$, ($c_b < \bar{c}_M$), then buyer 1 does not outsource knowledge from the supplier ($S_1 = 0$). Otherwise ($c_b \geq \bar{c}_M$), buyer 1 outsources knowledge from the supplier ($S_1 > 0$).*

We find a c_b threshold, denoted by $\bar{c}_M$, under which buyer 1 obtains knowledge only through in-house knowledge development, where $\bar{c}_M = \frac{g}{4g\theta-\phi^2}$. To interpret Proposition 8, suppose c_b is less than $\bar{c}_M$. Under this condition, since buyer 1 is able to improve product performance to a certain level only through in-house knowledge development, she benefits from cutting down her cost for knowledge outsourcing (costs for the purchase and integration). In contrast, if the cost of in-house knowledge development is sufficiently high ($c_b \geq \bar{c}_M$), buyer 1 improves product performance through knowledge outsourcing as well as in-house knowledge development to balance knowledge acquisition costs while maintaining her product performance to a certain level.

Further, we observe that buyer 1's absorptive capacity and integration cost also influence whether or not buyer 1 outsources knowledge from the supplier. In particular, our sensitivity analysis shows that buyer 1 is less inclined to outsource when her absorptive capacity (ϕ) is larger ($\frac{\partial \bar{c}_M}{\partial \phi} > 0$). As her absorptive capacity (ϕ) increases, buyer 1 is able to utilize and integrate more outsourced knowledge in her product, and therefore her desire for knowledge outsourcing increases. Leveraging this information, the supplier charges a higher wholesale price of knowledge. This decreases buyer 1's willingness to outsource knowledge from the supplier (i.e., $\bar{c}_M$ increases). Cost savings obtained from limiting knowledge outsourcing compensates for any loss in her revenue due to lower product performance, and therefore she earns more profit without knowledge outsourcing. It is worth noting that such an effect will not be observed in the traditional context of component outsourcing, where absorptive capacity does not play a role. Indeed, in component outsourcing, the supplier's equilibrium price and the buyer's outsourcing decision are both independent of the buyer's absorptive capacity.

Also, we find that buyer 1 is more inclined to outsource knowledge from the supplier as her integration cost increases ($\frac{\partial \bar{c}_M}{\partial g} < 0$). Similar to the logic behind the impact of ϕ above, this is because the supplier offers a low wholesale price of knowledge to attract buyer 1. If buyer 1 accepts the supplier's offer and pursues knowledge outsourcing, she is able to reduce her level of in-house knowledge development for a given level of product performance. Cost savings in buyer 1's in-house knowledge development compensates for her additional costs for the purchase and integration of outsourced knowledge, and thus she pursues knowledge outsourcing despite her higher integration cost.

The result given in Proposition 8 differs from that described in the supplier-buyer knowledge outsourcing game introduced by Lee et al. (2016) for a reason. We recognize that the buyer incurs a cost to integrate the outsourced knowledge (g) and thereby improves product performance. Basically, if g equals zero, then $\bar{c}_M$ in Proposition 8 becomes zero so that buyer 1 always pursues knowledge outsourcing, which is consistent with Lee et al. (2016). Importantly, in contrast to Lee et al. (2016), in the next section, we consider two buyers who compete in the downstream market.

3.4 Duopoly Buyer

We consider a situation where two symmetric buyers, 1 and 2, compete in the downstream market by setting their retail prices (Iyer and Soberman 2000; Lauga and Ofek 2009; Amaldoss and Jain 2015). Note we use the subscript "1" (2, respectively) to refer to "buyer 1" (buyer 2, respectively), and all other notations used in the duopoly case are defined in Table 4.

3.4.1 Two Competing Buyers but Supplier Serves One

In Section 3.4.1, we focus on examining a situation where the supplier serves only one of the two buyers (buyer 1). Figure 6 below shows the sequence of decision-making for the two competing buyers. In the second stage, after observing the supplier's wholesale price of knowledge, buyers 1 and 2 simultaneously determine their levels of knowledge developed in-house and outsourced from the supplier. Given performance improvement realized by knowledge acquisition in the second stage, the two buyers simultaneously choose their retail prices and sell their products in the third stage.

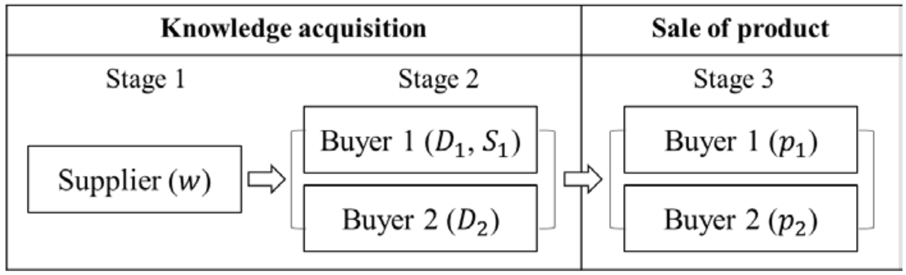


Figure 6. Sequence of decisions for two competing buyers when the supplier serves only buyer 1.

3.4.1.1 Consumers' Utilities and Buyers' Quantities

We use the Hotelling market model with two buyers in the duopoly case. As illustrated in Figure 7, buyer 1 is positioned at the left end of the Hotelling line at 0 and buyer 2 is positioned at the other end at 1. While both buyers pursue in-house knowledge development to improve their product performance (i.e., $D_1 \geq 0$ and $D_2 \geq 0$), only buyer 1 has the option to outsource knowledge from the supplier (i.e., $S_1 \geq 0$ and $S_2 = 0$).

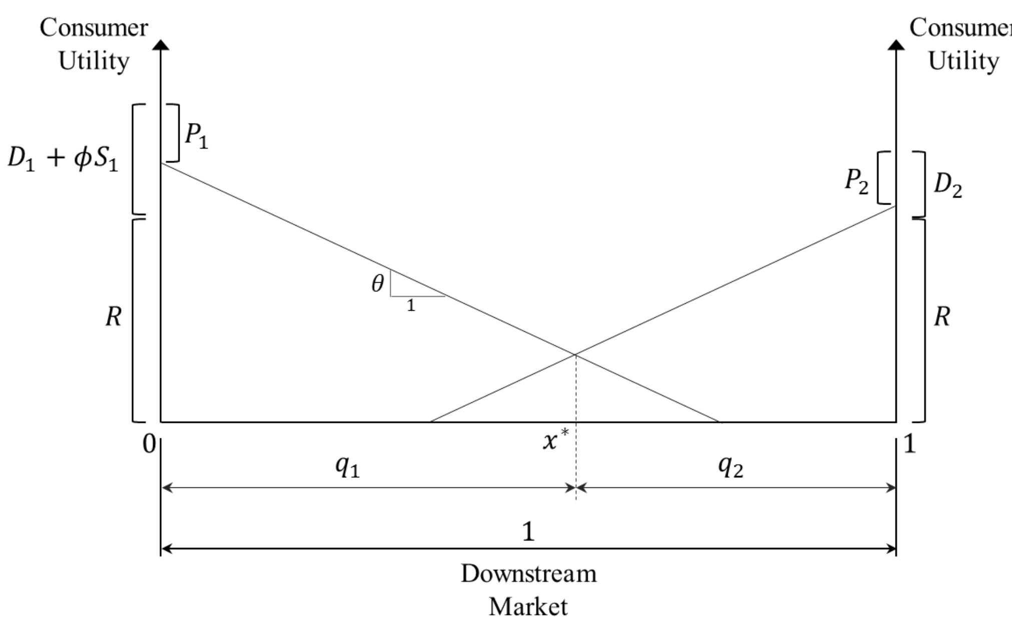


Figure 7. Hotelling market model for the duopoly case.

A consumer whose preference is x along the market between 0 and 1 incurs disutility θx ($\theta(1-x)$, respectively) by purchasing buyer 1's product (buyer 2's product, respectively). Equations (18) and (19) below denote a consumer's surplus utility at x when the consumer purchases buyer 1's product and buyer 2's product, respectively. Figure 7 also illustrates the consumers' levels of surplus utilities for different preferences.

$$U_1 = R + D_1 + \phi S_1 - p_1 - \theta x, \tag{18}$$

$$U_2 = R + D_2 - p_2 - \theta(1-x). \tag{19}$$

Given the preference (x^*) of the consumer, whose surplus utility is the same regardless of whether the consumer purchases a product from buyer 1 or 2, the buyers' quantities in the marketplace are given by:

$$q_1 = \{x^*: U_1(x) = U_2(x)\}, \tag{20}$$

$$q_2 = \{1 - x^*: U_1(x) = U_2(x)\}. \tag{21}$$

We solve Equations (20) and (21), and find the two buyers' demand quantities in the downstream market as defined in Equations (22) and (23). As in the monopoly case, each buyer increases (decreases) market demand by offering a product with superior (inferior) performance or by charging a lower (higher) retail price. In contrast, we observe that in the duopoly case a buyer loses consumers if the other buyer offers a product with better performance and/or a lower retail price due to competition. Figure 7 graphically shows how both buyers' demand quantities are obtained.

$$q_1 = \frac{D_1 - D_2 - p_1 + p_2 + \phi S_1 + \theta}{2\theta}, \tag{22}$$

$$q_2 = \frac{D_2 - D_1 - p_2 + p_1 - \phi S_1 + \theta}{2\theta}. \tag{23}$$

3.4.1.2 Problems of the Buyers and Supplier in the Duopoly Case

As shown in Figure 6, we solve two simultaneous games between buyers 1 and 2: one in stage 2 for knowledge acquisition and the other in stage 3 for the sale of their products. Each buyer in the duopoly case makes sequential decisions on the level of knowledge acquisition first and then her retail price. Therefore, we sequentially solve the two simultaneous games between the two buyers using backward induction. Given their demand quantities from Equations (22) and (23), buyers 1 and 2 who compete in the downstream market simultaneously determine their retail prices in stage 3 while maximizing their profits defined in Equations (26) and (27). In stage 2, as summarized in Equations (24) and (25), the two buyers simultaneously determine their levels of knowledge acquisition required to improve product performance. Since this section focuses on the situation where only buyer 1 has an option to outsource knowledge from the supplier, while buyer 1 jointly decides her levels of in-house knowledge development (D_1) and knowledge outsourcing (S_1), buyer 2 decides only her level of in-house knowledge development (D_2).

Stage 2 Buyer 1: $\underset{D_1, S_1 > 0}{Max}\, \Pi_1(D_1, S_1, D_2) = p_1' q_1(p_1', p_2') - c_b D_1^2 - wS_1 - gS_1^2,$ (24)

Buyer 2: $\underset{D_2 > 0}{Max}\, \Pi_2(D_1, S_1, D_2) = p_2' q_2(p_1', p_2') - c_b D_2^2,$

$where, p_1' = arg \underset{p_1 > 0}{Max}\, \Pi_1\,(p_1, p_2)\; and\; p_2' = arg \underset{p_2 > 0}{Max}\, \Pi_2\,(p_1, p_2).$ (25)

Stage 3 Buyer 1: $\underset{p_1 > 0}{Max}\, \Pi_1(p_1, p_2) = p_1 q_1(p_1, p_2) - c_b D_1^2 - wS_1 - gS_1^2,$ (26)

Buyer 2: $\underset{p_2 > 0}{Max}\, \Pi_2(p_1, p_2) = p_2 q_2(p_1, p_2) - c_b D_2^2.$ (27)

In stage 1, the supplier, a Stackelberg leader in the knowledge outsourcing game between the supplier and buyer 1, determines the wholesale price of knowledge to charge to buyer 1. In contrast to the monopoly case, since buyer 1 competes with buyer 2 in the downstream market, buyer 2's level of in-house knowledge development (D_2) indirectly influences the supplier's decision on the wholesale price of knowledge through buyer 1's response. Equation (28) summarizes the supplier's problem in the duopoly case when he serves only buyer 1. Note S_1' in Equation (28) is the best response of buyer 1's level of knowledge outsourcing for a given supplier's wholesale price of knowledge.

$$\underset{w>0}{Max}\, \Pi_S = wS_1' - c_s(S_1')^2\,, \tag{28}$$

$$where\ S_1' = arg \underset{D_1,S_1>0}{Max}\, \Pi_1(D_1, S_1, D_2).$$

Table 4. Terminology and notation for the duopoly case.

p_i	Retail price charged by buyer i in the downstream market, where $i \in \{1,2\}$ ($p_i > 0$).
q_i	Quantity sold by buyer i in the downstream market ($0 \leq q_i \leq 1$ and $q_1 + q_2 = 1$).
D_i	Buyer i's level of in-house knowledge development ($D_i \geq 0$).
S_i	Buyer i's level of knowledge outsourcing ($S_i \geq 0$).
U_i	Consumer's surplus utility for buyer i's product.

3.4.1.3 Analysis of the Duopoly Case

As in the monopoly case, we consider two situations in this duopoly case: buyer 1 *(i)* chooses not to outsource knowledge from the supplier; and *(ii)* chooses to outsource knowledge from the supplier. Following backward induction, we obtain interior solutions in each equilibrium as shown in Proposition 9 below. (All proofs appear in the Appendix.).

Proposition 9. *The equilibrium decisions when the supplier serves only buyer 1 under duopoly are:*

(i) *If buyer 1 does not outsource knowledge from the supplier, then* $D_1^* = D_2^* = \frac{1}{6c_b}$ *and* $p_1^* = p_2^* = \theta$*;*

(ii) *If buyer 1 outsources knowledge from the supplier, then* $w^* = \frac{2\phi(c_s+g)(9c_b\theta-1)-c_b\phi^3}{6M_3}$, $D_1^* = \frac{2(c_s+g)(9c_b\theta-1)-c_b\phi^2}{12c_bM_3}$, $D_2^* = \frac{2(c_s+g)(9c_b\theta-1)-3c_b\phi^2}{12c_bM_3}$, $S_1^* = \frac{\phi(9c_b\theta-1)}{6M_3}$, $p_1^* = \frac{2\theta(c_s+g)(9c_b\theta-1)-c_b\theta\phi^2}{2M_3}$, $p_2^* = \frac{2\theta(c_s+g)(9c_b\theta-1)-3c_b\theta\phi^2}{2M_3}$, *where* $M_3 = (c_s + 2g)(9c_b\theta - 1) - c_b\phi^2$*.*

From Proposition 9*(ii)*, we observe that buyer 1, who has the option to outsource knowledge from the supplier, pursues more in-house knowledge development than buyer 2 ($D_1^* > D_2^*$), who improves product performance only through in-house knowledge development. This is because buyer 1's knowledge outsourcing reduces her overall cost of improving product performance. In addition, due to superior product performance, buyer 1 charges a higher price than buyer 2 ($p_1^* > p_2^*$) in the downstream market. Buyer 1 is therefore able to pursue more in-house knowledge development. To further build on our analysis of whether or not buyer 1 outsources knowledge from the supplier in the duopoly case, in the remainder of Section 3.4.1 we examine the circumstances under which buyer 1 benefits from knowledge outsourcing. We compare buyer 1's profit when she outsources knowledge from the supplier and when she pursues only in-house knowledge development. Proposition 10 summarizes our analytical results and the discussion follows.

Proposition 10. *Consider a supplier that serves only buyer 1 under duopoly: i) If the cost of in-house knowledge development* (c_b) *is lower than the threshold* ($c_b < \bar{c}_D$)*, then buyer 1 does not outsource knowledge from the supplier. Otherwise* ($c_b \geq$

$\bar{c}_D$), *buyer 1 outsources, where* $\bar{c}_D = \frac{c_s+2g}{9(c_s+2g)\theta-\phi^2}$; *ii) Further,* $\bar{c}_D < \bar{c}_M$, *if* $\bar{c}_D < c_b < \bar{c}_M$, *buyer 1 outsources knowledge from the supplier only if there is a competitor.*

As shown in Proposition 10, we find a c_b threshold, denoted by $\bar{c}_D$, under which buyer 1's profit without knowledge outsourcing is greater than that with knowledge outsourcing. Therefore, if c_b is sufficiently small, buyer 1 under duopoly finds knowledge outsourcing not to be beneficial. Although this result seems similar to Proposition 8, since $\bar{c}_D < \bar{c}_M$, we find that the competition between buyers 1 and 2 in the marketplace makes buyer 1 more inclined to outsource knowledge than she would be under monopoly. This can be understood through the following logic. Since only buyer 1 has access to knowledge outsourcing, buyer 1's knowledge acquisition is more cost efficient than buyer 2. Therefore, if buyer 1 chooses to outsource knowledge from the supplier, buyer 2 finds it more beneficial to decrease her level of in-house knowledge development and reduce her retail price through those cost savings. This indicates that buyer 1's knowledge outsourcing discourages buyer 2 from improving product performance, which gives buyer 1 a more competitive advantage in the marketplace.

Further, it has the interesting implication that if $\bar{c}_D < c_b < \bar{c}_M$, then buyer 1 outsources knowledge from the supplier only if there is a competitor in the downstream market. If $\bar{c}_D < c_b < \bar{c}_M$, monopoly buyer 1 has no incentive to further improve her product performance through knowledge outsourcing due to her relatively low cost of in-house knowledge development. However, even with a low cost of in-house knowledge development, buyer 1 under duopoly pursues knowledge outsourcing so that her competitor (buyer 2) will reduce product performance. Therefore, the existence of competition between buyers in the marketplace provides the supplier with a higher chance of earning profit. To investigate how different parameters impact buyer 1's decision to outsource knowledge from the supplier under duopoly, we conduct a sensitivity analysis of $\bar{c}_D$ and find similar results ($\frac{\partial \bar{c}_D}{\partial g} < 0$ and $\frac{\partial \bar{c}_D}{\partial \phi} > 0$) as in the monopoly case. The details of the discussion are therefore omitted.

3.4.2 Both Buyers Outsource Knowledge

In Section 3.4.2, we consider a situation where both buyers, 1 and 2, have the option to outsource knowledge from the supplier (i.e., $S_1 \geq 0$ and $S_2 \geq 0$). To build on our insights from Sections 3.3 and 3.4.1, we examine which conditions lead both buyers to pursue knowledge outsourcing. In addition, we analyze the supplier's service strategies when he would serve only one buyer or both buyers.

3.4.2.1 Problems of the buyers and supplier in the Duopoly Case

Incorporating buyer 2's knowledge outsourcing (S_2) into the Hotelling market model from Section 3.4.1 (see Equations (18) - (21)), the demand quantities of buyers 1 and 2 in the marketplace are given as:

$$q_1 = \frac{D_1 - D_2 - p_1 + p_2 + \phi S_1 - \phi S_2 + \theta}{2\theta}, \tag{29}$$

$$q_2 = \frac{D_2 - D_1 - p_2 + p_1 + \phi S_2 - \phi S_1 + \theta}{2\theta}. \tag{30}$$

Similar to Section 3.4.1, given their demand quantities from Equations (29) and (30), buyers 1 and 2 who compete in the downstream market simultaneously determine their retail prices in stage 3 while maximizing their profits defined in Equation (32). In stage 2, as summarized in Equation (31), the two buyers simultaneously determine their levels of in-house knowledge development and knowledge outsourcing to improve product performance.

Stage 2 Buyer i: $\underset{D_i,S_i>0}{Max}\,\Pi_i(D_i,S_i,D_{-i},S_{-i}) = p_i' q_i(p_i',p_{-i}') - c_b D_i^2 - wS_i - gS_i^2,$

$$where, p_i' = arg\,\underset{p_i>0}{Max}\,\Pi_i\,(p_i,p_{-i}), i \in \{1,2\}. \tag{31}$$

Stage 3 Buyer i: $\underset{p_i>0}{Max}\,\Pi_i(p_i,p_{-i}) = p_i q_{-i}(p_i,p_{-i}) - c_b D_i^2 - wS_i - gS_i^2.$ (32)

When the supplier serves both buyers 1 and 2 simultaneously, we assume that he determines a common wholesale price, denoted by w, to charge to both buyers. The supplier gains his revenue from buyers 1 and 2 separately, but the costs of developing new knowledge to meet the needs of both buyers are pooled and denoted by $c_s(S_1+S_2)^2$. This formulation reflects a situation where undertaking two simultaneous knowledge outsourcing projects for two different buyers consumes the supplier's scarce resources, thus incurring additional coordination and opportunity costs. Equation (33) below summarizes the supplier's problem when serving both buyers 1 and 2.

$$\underset{w>0}{Max}\,\Pi_S = w(S_1+S_2) - c_s(S_1+S_2)^2. \tag{33}$$

Through backward induction we obtain optimal decisions in equilibrium, as shown in Proposition 11 below.

Proposition 11. *The equilibrium decisions when the supplier serves both buyers, 1 and 2, under duopoly:* $w^* = \frac{\phi(2c_s+g)}{6(c_s+g)}$, $D_1^* = D_2^* = \frac{1}{6c_b}$, $S_1^* = S_2^* = \frac{\phi}{12(c_s+g)}$, $p_1^* = p_2^* = \theta$.

3.4.2.2 Buyers' Decisions on Knowledge Outsourcing

A comparison of Proposition 11 and Proposition 9*(i)* produces interesting insights. The two buyers charge the same retail prices and use the same levels of in-house knowledge development regardless of whether they both together outsource knowledge from the supplier. This indicates that even if the two buyers improve their product performance through knowledge outsourcing they will in fact be worse off due to the additional costs incurred by the purchase and integration of outsourced knowledge. One might therefore expect that neither buyer would ever pursue knowledge outsourcing. However, since the game between buyers 1 and 2 is non-cooperative, we find a condition under which both buyers do pursue knowledge outsourcing. Based on an analysis of the normal-form game between buyers 1 and 2 shown in Table 5, we discuss the underlying logic behind their decisions to outsource and find it similar to the Prisoner's dilemma (Gibbons 1992).

Table 5. Normal-form game between buyers 1 and 2 under duopoly.

Outsourcing knowledge?		Buyer 2	
		Yes	No
Buyer 1	Yes	$(\underline{\Pi_1^{12}}, \underline{\Pi_2^{12}})$	(Π_1^1, Π_2^1)
	No	(Π_1^2, Π_2^2)	$(\underline{\Pi_1}, \underline{\Pi_2})$

Note that the superscripts added to the buyer's profit indicate the buyers who outsource knowledge (e.g., Π_i^{12} reflects buyer i's profit when both buyers, 1 and 2, outsource knowledge). When the supplier attempts to serve both buyers 1 and 2, under what condition do both buyers choose to pursue knowledge outsourcing? To answer this question we compare the buyers' profits in three scenarios, as shown in the normal-form game between buyers 1 and 2 in Table 5: (1) both buyers outsource (Π_i^{12}); (2) one of the two buyers outsources (Π_i^1 and Π_i^2); and (3) no one outsources (Π_i), where $i \in \{1, 2\}$. As shown in Table 5, we find two Nash equilibriums, and Proposition 12 summarizes the main results.

Proposition 12. *Consider a supplier who attempts to serve both buyers under duopoly: i) If $\bar{c}_D \leq c_b$, then both buyers, 1 and 2, pursue knowledge outsourcing from the supplier; ii) If $c_b < \bar{c}_D$, then no buyer outsources.*

In contrast to the insight obtained from the comparison of Proposition 11 and Proposition 9*(i)* above, we find that if the buyer's cost of in-house knowledge development (c_b) is higher than $\bar{c}_D$, then both buyers pursue knowledge outsourcing (i.e., ($\underline{\Pi_1^{12}}$, $\underline{\Pi_2^{12}}$)). As shown in Proposition 10, if $\bar{c}_D \leq c_b$, then we know a buyer who has the option to outsource knowledge from the supplier pursues knowledge outsourcing. Since the other buyer in Section 3.4.2 also has the option to outsource, she also pursues knowledge outsourcing in order to meet the competition in the downstream market. The interesting part of this result is that one buyer's decision to pursue knowledge outsourcing logically leads the other buyer to outsource as well, when they would in fact both be able to earn higher profits if neither of them outsourced knowledge from the supplier. If $c_b < \bar{c}_D$, however, then both buyers choose not to outsource knowledge and maintain equal ability to lower their retail prices in the downstream market.

3.4.2.3 Supplier's Service Strategy: Serving One Buyer versus Serving Both Buyers

Given the buyers' conditional desire for knowledge outsourcing in Proposition 12, we investigate further the question of whether the supplier always benefits from serving both buyers. As summarized in Proposition 13, we compare the supplier's profit in two situations: (1) the supplier chooses to serve both buyers; and (2) the supplier chooses to serve only one buyer (buyer 1).

Proposition 13. *When the supplier considers both buyers as his potential clients: i) If buyers' in-house knowledge development costs (c_b) are lower than the threshold ($c_b < \bar{c}_S$), where $\bar{c}_S = \frac{g}{9g\theta-\phi^2}$, then the supplier benefits from serving only one buyer (niche strategy); Otherwise ($\bar{c}_S \leq c_b$), the supplier serves both buyers 1 and 2 (saturation strategy); ii) Further, $\bar{c}_D < \bar{c}_S$, if $\bar{c}_D < c_b < \bar{c}_S$, even if both buyers pursue knowledge outsourcing, the supplier serves only one buyer.*

We find that if the buyers' in-house knowledge development costs (c_b) are sufficiently low ($c_b < \bar{c}_S$), then the supplier is better off serving only one buyer, where $\bar{c}_S = \frac{g}{9g\theta-\phi^2}$. The supplier's optimal service strategy in that case is a niche strategy (Erat et al. 2013). To clarify, suppose the buyers' in-house knowledge development costs are sufficiently low. The two buyers are both willing to accept a higher wholesale price of knowledge to obtain exclusive access to knowledge outsourcing. Leveraging this information, the supplier charges a premium wholesale price and provides an exclusive knowledge outsourcing service to one buyer (buyer 1). Buyer 1 can afford the supplier's high wholesale price since she then also charges a higher retail price than buyer 2 in the marketplace. The supplier also benefits because he saves on in-house knowledge development cost by reducing the need to develop knowledge for any other buyer (buyer 2).

In contrast, if $\bar{c}_S \leq c_b$, then the two buyers seek to reduce their costs of improving product performance since it is too costly. This encourages the supplier to charge a lower wholesale price of knowledge and serve both buyers. In that case, the supplier's optimal service strategy is a saturation strategy (Erat et al. 2013). Furthermore, we find that $\bar{c}_D < \bar{c}_S$. Therefore, when $\bar{c}_D < c_b < \bar{c}_S$, the supplier chooses to serve only one buyer even if both buyers pursue knowledge outsourcing.

For further analysis, we examine how exogenous parameters impact the supplier's service strategy using a sensitivity analysis of $\bar{c}_S$. First, suppose the buyers' integration costs (g) decrease. Both buyers then have an increased desire to pursue knowledge outsourcing, which increases competition pressure on their product performance in the marketplace. Both buyers are therefore more willing to accept an increase in the supplier's wholesale price. In this situation, the benefits the supplier gains from charging a higher wholesale price for providing an exclusive service to buyer 1 compensate for his loss from not serving buyer 2. Buyer 1 is willing to accept the higher wholesale price of knowledge in return for the exclusive service in order to mitigate competition pressure. As a result, the supplier is more inclined to serve only one buyer when g is lower ($\frac{\partial \bar{c}_S}{\partial g} < 0$). We also find that the supplier is more inclined to serve only one buyer ($\frac{\partial \bar{c}_S}{\partial \phi} > 0$) if the buyers' absorptive capacity (ϕ) is larger. This result can be understood through similar logic to the case of integration cost above.

Synthesizing our discussions from Sections 3.3, 3.4.1, and 3.4.2, Figure 8 below depicts the important managerial insights obtained from Propositions 8, 10, and 13 together.

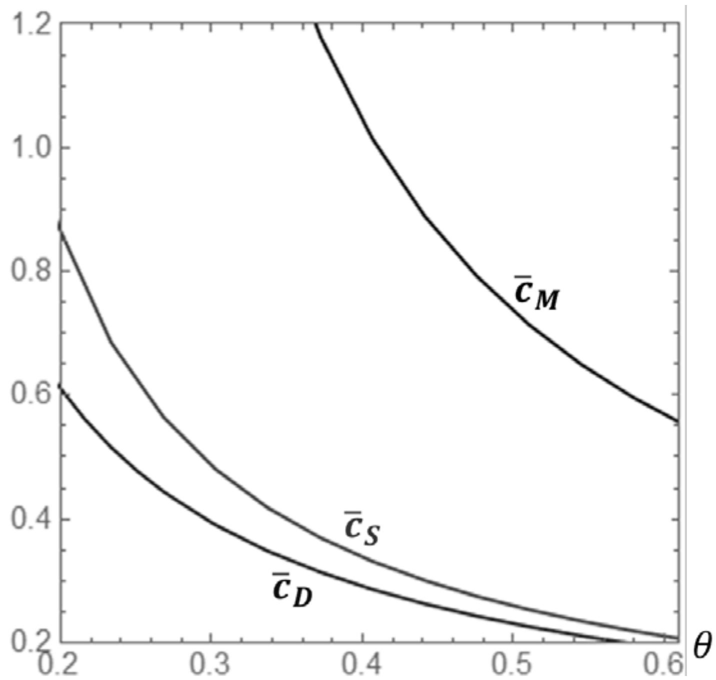


Figure 8. Collective depiction of the three thresholds. $\phi = 0.8$, $g = 1$, $c_S = 2$, $\theta \in [0.2, 0.6]$

Regardless of the competition structure in the downstream market (i.e., whether it's a monopoly or duopoly), if the buyers' in-house knowledge development costs are greater than $\bar{c}_M$ then the supplier serves both buyers. Due to the high cost of in-house knowledge development, the buyers always choose to pursue knowledge outsourcing from the supplier. In contrast, if $\bar{c}_D < c_b < \bar{c}_M$, as discussed in Proposition 10, then a buyer pursues knowledge outsourcing only if there is a competitor in the downstream market. However, if $\bar{c}_D < c_b < \bar{c}_S$ (see Proposition 13), then only one buyer is effectively served by the supplier even if both buyers pursue knowledge outsourcing because the supplier is better off providing an exclusive service to one buyer (niche strategy). In contrast, if $\bar{c}_S < c_b < \bar{c}_M$, then both buyers are sensitive to the supplier's wholesale price of knowledge, so the supplier chooses to charge a lower wholesale price and attract both buyers (saturation strategy).

3.4.2.4 Effect of Prior Knowledge

As mentioned in Section 3.3.2, in this study, the buyer's product performance does not directly reflect her prior knowledge. Since a buyer's prior knowledge influences interactions between the buyer and the supplier (Lee et al. 2016), in this section we further explore the effect of prior knowledge.

Suppose the buyer is able to utilize her prior knowledge. First, since the buyer is able to maintain a higher level of baseline performance (R), she increases her product performance through a higher level of in-house knowledge development and knowledge outsourcing in the monopoly case (see Proposition 7). Naturally, the buyer is then also able to charge a higher retail price in the marketplace. Anticipating this behavior, the supplier charges a higher wholesale price of knowledge due to the buyer's higher desire for knowledge outsourcing.

A buyer's prior knowledge also impacts whether or not the buyer pursues knowledge outsourcing under either monopoly or duopoly through her absorptive capacity, which is positively associated with prior knowledge (Lee et al. 2016). As shown in Propositions 8 and 10, if a buyer's prior knowledge increases, the buyer is less inclined to outsource knowledge from the supplier due to the supplier's higher wholesale price of knowledge ($\frac{\partial \bar{c}_M}{\partial \phi} > 0$ and $\frac{\partial \bar{c}_D}{\partial \phi} > 0$). In a duopoly case, this encourages the supplier to serve only one buyer (see Proposition 13, $\frac{\partial \bar{c}_S}{\partial \phi} > 0$). Similarly, since a higher absorptive capacity reduces integration cost (Ceccagnoli and

Jiang 2013), if a buyer utilizes her prior knowledge, the buyer is less inclined to outsource knowledge under either monopoly or duopoly ($\frac{\partial \bar{c}_M}{\partial g} < 0$ and $\frac{\partial \bar{c}_D}{\partial g} < 0$).

In addition, if the supplier is able to utilize his prior knowledge, he saves on knowledge development cost when meeting the buyer's needs. To obtain a larger amount of knowledge outsourcing, the supplier reduces the wholesale price of knowledge he charges to the buyer, thereby also encouraging the buyer to outsource knowledge. Due to the decreased pressure on his knowledge development cost, the supplier is more inclined to serve both buyers as his prior knowledge increases.

As discussed extensively above, leveraging prior knowledge, a unique feature of knowledge outsourcing, has a significant role that impacts decisions and outcomes of the buyer and the supplier for knowledge outsourcing. This is in fact because of the property of knowledge as a resource that firms can repeatedly utilize, which does not exist in component outsourcing.

3.5 Conclusion

Lee et al. (2016) first introduce knowledge outsourcing games to investigate the interactions between one supplier and one buyer. They show how absorptive capacity, uncertainty about the buyer's project scope, and information asymmetry affect the decisions and objective values of the supplier and the buyer. To further explore the implications on supplier-buyer interactions, specifically when the supplier serves multiple buyers, we introduce a Stackelberg game where a common supplier (leader) serves two buyers, 1 and 2 (followers), who compete in the downstream market. Building on the game formulation introduced by Lee et al. (2016), the supplier in this study sets the wholesale price of knowledge charged to both buyers and buyers 1 and 2 determine the extent to which they improve product performance through knowledge outsourcing and/or in-house knowledge development.

The analytic results provide important insights into the decision-making of both the supplier and buyers when one supplier serves multiple buyers. First, we find that a buyer is more inclined to outsource knowledge from the supplier when she has a competitor in the downstream market. This is because a buyer's option to outsource knowledge under duopoly leads her competitor to profit from reducing their cost of in-house knowledge development. This indicates that knowledge outsourcing influences buyers' competition strategies in the downstream market. As we show, if only buyer 1 has the option to outsource knowledge, she benefits from charging a high retail price and improving her product performance to gain advantage over buyer 2, who charges a low retail price.

Second, when the supplier serves both buyers, we find a knowledge outsourcing version of the Prisoner's dilemma. That is, there are certain conditions under which both buyers pursue knowledge outsourcing even if it results in them both being worse off. This is because if one buyer deviates from the equilibrium and does not outsource knowledge, her profit would be lower than if they both outsource knowledge and her competitor would earn an even higher profit. The non-cooperative nature of competition between the two buyers in the downstream market provides additional advantage for the supplier.

Third, leveraging the fact that one buyer who outsources knowledge under duopoly gains additional profit, the supplier can charge a higher wholesale price of knowledge and benefit from serving only one buyer, even if both buyers wish to pursue knowledge outsourcing. Specifically, we identify conditions under which the supplier is better off serving only one of the two buyers. If the buyer's in-house knowledge development cost is sufficiently low, the supplier's profit when serving only one buyer is larger than that when serving both buyers. This is because if the buyer's in-house knowledge development cost is sufficiently low, the buyer is willing to accept the supplier's high wholesale price of knowledge for a given level of knowledge outsourcing. In addition, by charging a high wholesale price and serving only one buyer, the supplier is able to eliminate the internal cost of developing new knowledge to satisfy the second buyer's needs.

Therefore, if buyers compete in classical commodity industries (i.e., the cost of in-house KD is low), firms in KIBS including IDEO can benefit from providing an exclusive services to one buyer by charging a high price. In contrast, if the buyers compete in highly technical industries (i.e., the cost of in-house KD is high), a professional service firm should reduce his price of knowledge to attract multiple buyers. This service strategy in the context of knowledge outsourcing is in parallel with Erat et al. (2013) who study issues on outsourcing for innovative components. Since buyers in their component outsourcing study are adopters of technological advancement accomplished by the supplier, supplier's capability (e.g., design capability for functionalities) plays a more significant role for his own service strategy than the buyers' internal cost of knowledge development.

Overall, building upon the dyadic case featuring one supplier and one buyer introduced by Lee et al. (2016), this study has gained important insights regarding how one common supplier and multiple buyers who compete in the downstream market can effectively manage knowledge outsourcing. However, this study does not cover the situation where multiple buyers outsource knowledge from the supplier sequentially. If one buyer waits until her competitor has first received the knowledge outsourcing services and comes to the supplier as the second client, then she may benefit from the supplier's previous experience in developing knowledge for the first buyer. In this situation, the second buyer's time to market would be delayed. Therefore, an analysis of the trade-off between a buyer's time of outsourcing and time to market would be valuable in future research.

To formulate competition between buyers in the downstream market, we use Hotelling model due to tractability, in which vertical differentiation is not fully captured. A future research may benefit from applying other market demand models such as Cournot competition to examine the impact of competition more comprehensively. In this study, we consider wholesale-price-only type of contracts. Since there may be various forms of lump-sum payments in practice, researchers may also examine the joint impact of competition and different types of contracts (e.g., revenue sharing, milestone-based contract, two-part tariff, exclusive contract, etc.) on knowledge outsourcing. Lastly, an investigation of the situation where two knowledge suppliers compete by setting their wholesale prices of knowledge to attract buyers in the market would also provide important managerial implication.

CHAPTER 4. KNOWLEDGE OUTSOURCING: A LITERATURE REVIEW AND FUTURE RESEARCH AGENDA

4.1 Introduction

Firms in a diverse range of industries, including automobiles, aerospace, computer, telecommunications, pharmaceuticals, chemicals, and software increasingly rely on external knowledge acquisition due to the increased complexity and scope of knowledge required for successful new product development (Carson 2007; Gaimon et al. 2017a; Quinn 2000). For example, under the catch-phrase, "Connect and Develop", Procter & Gamble aims to source 50% of its new products from external firms (Carson 2007). Other high-tech firms, including Dell, Hewlett-Packard, and pharmaceutical firms such as GlaxoSmithKline and Eli Lilly, are also outsourcing much of their new product research from external partners (Calantone and Stanko 2007). Reflecting the increasing importance of external knowledge acquisition, Booz&Co. and Duke University (2007) report that the "hot" sectors for business services are: knowledge/analytical services and innovation services (product development, engineering, and R&D). Additionally, U.S. census data (BEA 2017) demonstrates that the GDP value produced by the knowledge-intensive service industry – which includes professional, scientific, and technical services (all of which drive product design, R&D, IT, consulting, and marketing) – more than doubled between the years 1998 and 2016. For instance, firms such as InnoCentive have greatly expanded the role of the consulting industry (Lakhani 2008; Gaimon et al. 2017a).

As external knowledge sourcing becomes a central part of a firm's overall strategy, firms seek out knowledge from a variety of external sources including customers, competitors, suppliers, and professional knowledge providers such as consultancies (Van De Vrande 2013). In this review, we focus on firms' external knowledge acquisition from professional knowledge providers, which we refer to as 'knowledge outsourcing' (Lee et al. 2016; Gaimon et al. 2017b). It is useful to note that the term knowledge outsourcing is used interchangeably with the terms 'R&D outsourcing' (Grimpe and Kaiser 2010; Howells et al. 2008), 'design and engineering outsourcing' (Zirpoli and Becker 2011), and 'innovation outsourcing' (Cui et al. 2012; Stanko and Calantone 2011) in the current literature. Based on Grimpe and Kaiser (2010) and Howells (1999), knowledge outsourcing can be defined as a contractual agreement between a knowledge recipient (buyer) and a source (supplier), and a supplier who does not compete in the same market with the buyer performs knowledge development tasks independently on her behalf. Upon completion of his knowledge development tasks, the outcomes of the supplier's knowledge development are delivered to the buyer in pre-agreed forms (e.g., a written report, software, design drawings) with all specified exploitation rights.

While a buyer's reasons for pursuing knowledge outsourcing depend on her specific needs for technology and the market, typical motivations include: R&D cost reduction, faster new product development, lack of internal knowledge, superior technology acquisition, ease of management and control, and the reduction of uncertainty[5] and risk[6] (Cui et al. 2012; Howells et al. 2008; Stanko and Calantone 2011). However, there is some risk that knowledge outsourcing may not produce the expected outcomes because the costs of suppliers' opportunistic behavior, possible lack of ability to meet the buyer's needs, and the risk of knowledge leakage are often overlooked or underestimated when knowledge outsourcing contracts are agreed upon (Grimpe and Kaiser 2010; Raassens et al. 2012). For instance, a critical cause of the delayed launch of Boeing's 787 Dreamliner was the significant reliance on outsourcing for both design and production (Lunsford 2007). Siemens faced problems of a different nature: some of its knowledge suppliers for NPD refused to adjust technical specifications and leaked the knowledge developed for Siemens to other firms (Cui et al. 2012). Therefore, firms must understand how to better manage knowledge outsourcing in order to benefit from it.

While the operations management literature on component outsourcing has led to a deep understanding of procurement and contributed to addressing operational challenges including quality, performance, and reliability, despite its prevalence in practice, studies on knowledge outsourcing are limited (Gaimon et al. 2017a). Similarly, while the knowledge management literature extensively provides managers with important implications and insights into how to manage organizational learning processes including knowledge transfer (i.e., vicarious

[5] We consider two different types of uncertainty which jointly influence the decisions and outcomes of knowledge outsourcing: technological uncertainty and market uncertainty (Walker and Weber 1984).

[6] We consider the risk of knowledge outsourcing in two angles throughout the paper: 1) risks in obtaining desired knowledge from an external supplier and 2) risks arise in the progress of a knowledge outsourcing project.

learning) (Argote 2013; Argote and Hora 2017), although it is also a critical part of organizational learning, research on knowledge outsourcing is scant.

In this study, we review extant literature on knowledge outsourcing to document our current understanding, and provide future research agenda. In Section 4.1.1, we describe the environment in which knowledge outsourcing takes place, where various players and other factors jointly influence firms' decisions on knowledge outsourcing. In Section 4.1.2, we adopt a project management framework for knowledge outsourcing which includes five phases: Initiate, Plan, Execute, Utilize, and Check. Based on this framework, we review current studies, discuss the challenges faced during decision-making, and provide future research agendas for each phase in Sections 4.2 to 4.6. Lastly, we conclude this study with a discussion on managerial implications in Section 4.7.

4.1.1 Knowledge Outsourcing Environment

As illustrated in Figure 9, buyers obtain knowledge from various external sources in the value-chain and improve products/processes by utilizing it. Prior studies broadly identify five external pools of knowledge: customers (i.e., lead users), supplier chain (i.e., suppliers for components or materials), crowd (i.e., innovation contests), competitors (i.e., coopetition), and professional knowledge suppliers (Bellamy et al. 2014; Chen et al. 2016; Gaimon et al. 2017b; Gnyawali and Park 2011; Terwiesch and Xu 2008; Tether and Tajar 2008).

While customers (i.e., the consumers of products/services) are the target to whom a buyer (i.e., a knowledge buyer) sells her products or services, they are also a critical source of market knowledge for product innovation (Chen et al. 2016). However, since customers mainly provide a source of new ideas, the buyer still needs to develop in-depth knowledge to integrate and implement those ideas (Von Hippel 2005). Suppliers in supply networks increasingly take on broader responsibilities, including product design, due to their expertise and prior knowledge on the latest technologies and components (Bellamy et al. 2014; Du et al. 2014; Lee and Schmidt 2017). Nevertheless, as shown in the Tesla's falcon wing door case,[7] a supplier's inability to meet a buyer's requirements may result in unintended consequences such as delays in launching new products because the supplier (who develops the product design) typically produces and delivers the corresponding components (Ramsey 2016).

To save on R&D cost and expand the landscape of innovation opportunities, firms (seekers) often rely on engineers and/or scientists (solvers) in public (through intermediaries such as InnoCentive, Topcoder, and IdeaStorm.com). This is known as 'crowdsourcing' (also 'innovation contest' or 'innovation tournament') (Terwiesch and Xu 2008). Despite its potential benefits and the growing trend towards crowdsourcing, a poorly designed contest in terms of the award mechanism and participation control may reduce the quality of solvers' solutions and seekers' implementation rates (Huang et al. 2014; Terwiesch and Xu 2008). Firms in many high-tech industries, including automotive, electronics, and pharmaceuticals, often obtain knowledge from their competitors, which is formally termed as 'coopetition', because competing firms typically require similar types of knowledge and possess complementary resources (Gaimon et al. 2017b; Gnyawali and Park 2011). However, due to the simultaneous pursuit of collaboration and competition, coopetition involves a high degree of conflict between a pair of competing firms based on

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[7] The supplier's inability to meet the design specifications for vertical doors (i.e., falcon wing doors) was identified as a critical factor in the delayed launch of Tesla's Model X electric SUV.

opportunism where firms try to appropriate a greater share of the co-created value (Gnyawali and Park 2011).

Lastly, knowledge outsourcing from professional knowledge suppliers such as Knowledge Intensive Business Services (KIBS)[8] allows firms to avoid conflict with competitors as well as to leverage the specialized expertise of knowledge suppliers. However, many of the challenges involved in knowledge outsourcing, including suppliers' opportunism and knowledge leakage, are still understudied. As discussed, each source of knowledge in the knowledge outsourcing environment has its own advantages and challenges. To define the scope of this study, we focus on how to manage the knowledge outsourcing process rather than on how to choose an appropriate external source of knowledge. We include multiple research methodologies in this study such as empirical and normative modeling to synthesize the current literature. Other environmental forces such as competition and uncertainty influence firms' decisions and the outcomes of knowledge outsourcing. Therefore, we also discuss how buyers and suppliers better address those challenges and environmental forces based on the knowledge outsourcing framework, which is introduced in the next section.

[8] KIBS are firms broadly referred to as knowledge intermediaries, knowledge-intensive firms, knowledge brokers, technology brokers, or professional service firms in the literature (Howells 2006, Muller and Zenker 2001, Probert et al. 2013, Tether and Tajar 2008).

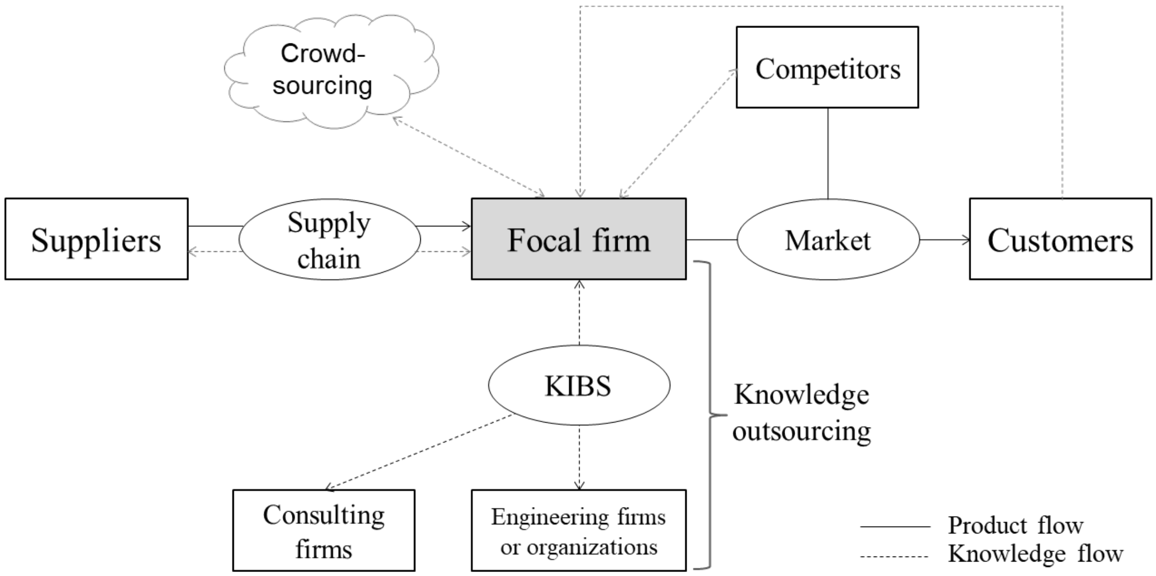

Figure 9. Knowledge outsourcing environment.

4.1.2 Knowledge Outsourcing Framework

A firm's knowledge outsourcing activities constitute processes which proceed in the form of a project (Lee et al. 2016). Therefore, it is useful to understand the life cycle of a knowledge outsourcing project in order to better manage them. Project Management Institute (PMI)[9] identifies five groups of project management processes: initiating, planning, executing, monitoring and controlling, and closing (Stackpole 2013). In the initiating phase, a project manager defines a new project or identifies improvements to be made on an existing project and obtains managerial authorization to officially start the project. After receiving budgetary approval from upper management, the project manager uses the planning phase to establish the scope of the project, refine the objectives, and define the course of action required to achieve those objectives. In the executing phase, the activities specified in the

[9] PMI is a leading non-profit organization that provides services and knowledge for project management.

planned course of action are performed to satisfy the project specifications. In the monitoring and controlling phase, the project manager tracks, reviews, and regulates the progress and performance of the project to make sure the project is successful. In addition, the project manager identifies any changes required and performs the necessary actions during this phase. In the closing phase, the project manager finalizes all activities to formally complete the project and evaluate its final performance.

A conceptual framework of a managerial initiative is considered to be an effective instrument when discussing firms' dynamic decisions, objectives, and challenges. For instance, Gaimon & Bailey (2013) propose a procedural framework based on the venture life cycle to provide entrepreneurial ventures with a guide to benefit from their knowledge management activities. Similarly, to identify future research opportunities while discussing the current literature on knowledge outsourcing, we utilize a knowledge outsourcing framework adapted from Stackpole (2013): Phase 1 – Initiate, Phase 2 – Plan, Phase 3 – Execute, Phase 4 – Utilize, Phase 5 – Check. Table 6 presents this framework, under which we discuss the processes, benefits, challenges, current studies, and future research opportunities of each phase. A detailed discussion on each phase follows.

Table 6. Knowledge outsourcing framework.

Knowledge Outsourcing Processes	Benefits	Challenges	Representative Literature	Future Research Opportunities
Phase 1: Initiate ▪ Confirm knowledge outsourcing as a sourcing mode ▪ Identify knowledge to be outsourced	▪ Saving internal resources for R&D ▪ Access to superior knowledge	▪ Uncertainty	Chatterji (1996), Swan & Allred (2003), Beneito (2006), Rothaermel & Alexandre (2009), Lee et al. (2017)	▪ Impact of uncertainty
Phase 2: Plan ▪ Select a knowledge supplier ▪ Decide the level of knowledge outsourcing ▪ Decide the timing of knowledge outsourcing ▪ Contract (payment agreement)	▪ Multiple sources available ▪ Formal contracts available	▪ Uncertainty ▪ Information asymmetry ▪ Competition ▪ Supply's optimized decision	Dyer & Singh (1998), Cassiman & Veugelers (2006), Grimpe & Kaiser (2010), Lee et al. (2016)	▪ Impact of uncertainty and information asymmetry ▪ Timing of knowledge outsourcing ▪ Impact of competition ▪ Contracting mechanisms
Phase 3: Execute ▪ Define control mechanisms ▪ Decide the locus of knowledge development	▪ Supplier's independent work ▪ Leveraging prior knowledge	▪ Knowledge leakage ▪ Supplier's opportunism ▪ Risks in fulfilling projects	Carson (2007), Buss & Peukert (2015), Yan & Kull (2015)	▪ Impact of knowledge leakage ▪ Supplier opportunism
Phase 4: Utilize ▪ Integrate outsourced knowledge ▪ Improve products/processes	▪ Knowledge codified in forms ▪ Technical assistance available	▪ Absorptive capacity ▪ NIH syndrome	Katz and Allen (1982), Cohen and Levinthal (1990), Weigelt (2009), Berchicci (2013), Lee et al. (2016)	▪ Impact of absorptive capacity ▪ Impact of NIH syndrome
Phase 5: Check ▪ Evaluate performance and interactions with the supplier ▪ Plan to reuse knowledge	▪ Clear source of knowledge ▪ Knowledge reuse	▪ Path-dependency	Hargadon and Sutton (1997), Majchrzak et al. (2004), Stanko & Calantone (2011), Lee et al. (2017)	▪ Impact of knowledge outsourcing on time to market and financial performance ▪ Impact of path-dependency ▪ Impact of knowledge reuse

4.2 Phase 1 – Initiate

When a firm first initiates a knowledge outsourcing project they must answer two critical questions: 1) Why knowledge outsourcing? And 2) Knowledge outsourcing for what? Since multiple governance modes of knowledge acquisition are available, including in-house knowledge development, the firm should understand the conditions under which they pursue knowledge outsourcing (Chatterji 1996; Nicholls-Nixon and Woo 2003; Van De Vrande 2013). The firm's reliance on knowledge outsourcing also depends on many internal and/or external factors, including their specific types of innovation (e.g., exploration versus exploitation and product innovation versus process innovation) and uncertainty (technological uncertainty and market uncertainty) (Gaimon et al.; 2017; Stanko & Calantone; 2011).

4.2.1 Why Knowledge Outsourcing?

Several studies have identified the drivers of knowledge outsourcing: familiarity of target knowledge and the market, asset specificity, appropriability, the objectives of knowledge outsourcing, and competition (Cesaroni 2004; Chatterji 1996; Gooroochurn and Hanley 2007; Narula 2001; Steensma and Corley 2000, 2001; Swan and Allred 2003; Veugelers 1997; Veugelers and Cassiman 1999). Chatterji (1996) shows that when a firm plans to either obtain unfamiliar knowledge or enter an unfamiliar market they prefer to pursue knowledge outsourcing over other external sourcing modes, including alliances (e.g., joint venture and licensing) and M&A, due to its flexibility and lower financial risk. Based on transaction cost theory (Geyskens et al. 2006), studies consistently find that when specific assets (e.g., laboratory equipment) are required to pursue knowledge outsourcing or related assets are already invested, a firm tends to internalize knowledge development activities (Cesaroni 2004; Gooroochurn and Hanley 2007; Veugelers 1997).

A firm's incentive to outsource knowledge depends on the firm's appropriability, which refers to the firm's ability to protect the outcomes of its intellectual activities and benefit from them (Cassiman and Veugelers 2006). Empirical studies have consistently shown that weak appropriability has a negative relationship with the external contracting of innovation activities due to the possibility of knowledge leakage (Gooroochurn and Hanley 2007; Steensma and Corley 2000; Veugelers and Cassiman 1999). Knowledge leakage poses a significant challenge when a firm executes a knowledge outsourcing project with a knowledge supplier. More detailed discussion follows in the section Phase 3 – Execute.

Firms' objectives to pursue knowledge outsourcing are heterogeneous. Firms may seek external knowledge either to realize their differentiation strategies or to achieve their low-cost goals. Using surveys, Swan & Allred (2003) show how firms' decisions on external knowledge acquisition are associated with their goals. With the strategic goal of differentiation, a firm needs to create and sustain a first-mover advantage. However, since external knowledge acquisition offers the most advantages to the fastest second-mover, the study shows that firms' decisions on external knowledge acquisition are negatively associated with their differentiation goals. Similarly, other studies using surveys and case-based methodologies suggest that firms tend to obtain knowledge from their internal resources to fully exploit opportunities if technological innovation is their competitive advantage (Narula 2001; Steensma and Corley 2001). Consequently, a firm's desire to imitate competitors is positively associated with external knowledge acquisition (Chatterji

1996). On the other hand, external knowledge acquisition often incurs additional costs due to loss of control, knowledge leakage, or the supplier's opportunistic behavior. Based on these arguments, empirical studies show that firms rely less on knowledge outsourcing if cost is their dominant concern (Swan and Allred 2003; Veugelers and Cassiman 1999).

While there have been a good deal of empirical studies, research using analytical modeling is scant. Using a game-theoretical formulation between a common knowledge supplier and two buyers who compete in the downstream market, Lee et al. (2017) study how the interactions between the supplier and the two buyers is associated with competition between the buyers. They analytically find that a buyer pursues knowledge outsourcing only if the buyer's in-house knowledge development cost is sufficiently high. More interestingly, they show that if a buyer has a competitor in the downstream market, the buyer is more inclined to pursue knowledge outsourcing because the buyer's knowledge outsourcing discourages the competitor from investing in quality improvement.

4.2.2 What Type of Knowledge to Be Outsourced?

To allocate resources efficiently and utilize innovation outcomes effectively, firms apply different managerial schemes to their knowledge acquisition projects depending on project type (Chandrasekaran et al. 2015). First, firms often categorize their knowledge acquisition projects based on the innovativeness of outputs (i.e., radical versus incremental innovation[10]) and use different knowledge sourcing modes.

[10] Ettlie et al. (1984, p. 683) state that "If a technology is new to the adopting unit and new to the referent group of organizations, or if it requires both throughput (process) as well as output (production or service) change, perhaps the magnitude or cost of change required by the organization is sufficient to warrant the designation of a rare of radical, as opposed to incremental, innovation."

Projects with targets to achieve radical innovation deal with more complex and firm-specific knowledge, which requires frequent information exchange between the related functions (Mowery and Rosenberg 1989). This interaction between a source of information and a recipient occurs more easily if it happens within the boundaries of a firm. Driven by this argument, Beneito (2006) empirically shows that radical innovation tends to be conducted by in-house R&D, whereas incremental innovation is pursued more frequently by contracted R&D. In fact, firms simultaneously manage internal and external R&D projects to obtain both existing and new knowledge. Based on this practical observation, Rothaermel & Alexandre (2009) study how a firm's mixture of technology sourcing (internal sourcing and external sourcing) and the type of technology sourced (known or new technologies) jointly impact the performance of a knowledge acquisition project (innovativeness and financial performance). Their study suggests that a firm's performance is improved if exploitation (exploration, respectively)[11] for the known (new, respectively) technologies is pursued by internal (external, respectively) R&D, which provides an opposing result argument to Beneito (2006).

The discrepancy above calls for a more comprehensive study to understand how the innovativeness of knowledge outsourcing projects is associated with firms' decisions about their knowledge sourcing modes (Gaimon et al. 2017b). As Carrillo & Gaimon (2004) argue in their analytical study, a radical innovation to obtain new knowledge entails a high degree of uncertainty (technological uncertainty). In the context of knowledge outsourcing, Lee et al. (2016) study how a buyer's project scope

[11] Levinthal & March (1993) have defined exploration as "the pursuit of new knowledge, of things that might come to be known," and exploitation as "the use and development of things already known."

uncertainty impacts the interactions between the buyer and a supplier. They analytically find that the question of whether the buyer increases or decreases her level of knowledge outsourcing as her project scope uncertainty increases depends on her cost of obtaining knowledge from other sources. Specifically, if the buyer's cost of obtaining additional knowledge elsewhere is relatively high (low, respectively), then the buyer relies more (less, respectively) on knowledge outsourcing as her project scope uncertainty increases. Since the buyer naturally compares the supplier's price with the cost of outside sourcing options, this result suggests that the relative advantage of possible external knowledge sourcing options is one of the driving forces in decisions about which knowledge sourcing mode to use for radical knowledge sourcing projects.

While current studies are actively investigating the relationship between knowledge sourcing mode and the level of innovativeness, most studies focus on knowledge acquisition for product innovation. Given the importance of a firm's process innovation as a competitive weapon (Pisano 1997), Krzeminska & Eckert (2016) study how the different characteristics of knowledge involved in process innovation, as opposed to product innovation, influence firms' knowledge sourcing modes (internal versus external R&D). Using cross-sectional firm-level data, they find that firms benefit less from knowledge outsourcing for process innovation than for product innovation since there is more tacit knowledge involved in process innovation. The limited benefits gained from using knowledge outsourcing for process innovation are shown to be reduced when upstream suppliers are selected as external knowledge sources (Antonelli and Fassio 2016). Since selecting the best suitable knowledge supplier is a key decision for buyers, we discuss it in more detail in Section 4.3 on the second phase (Plan).

4.2.3 Future Research Opportunities

Managers in the initiate phase invariably deal with uncertainty (technological uncertainty and market uncertainty) when making their knowledge outsourcing decisions. Resulting from technological uncertainty, there are two opposing forces which influence a firm's desire for knowledge outsourcing reversely: flexibility and complexity (Stanko and Calantone 2011). As technological uncertainty increases, firms need more flexibility to hedge against investment risk, which encourages them to obtain knowledge from external sources. On the other hand, the composition of knowledge involved in a knowledge acquisition project becomes more complicated as technological uncertainty increases, which makes it difficult to describe the requirements in a knowledge outsourcing contract. Reflecting these trade-offs, current empirical studies produce mixed results on the relationship between the level of technological uncertainty and a firm's propensity toward knowledge outsourcing (positive association: Swan & Allred (2003), negative association: Nakamura & Odagiri (2005)). Clearly, further research is needed to better understand the conditions under which the advantages of flexibility obtained from knowledge outsourcing offset the disadvantages caused by increased complexity as technological uncertainty increases.

Since the current literature on knowledge outsourcing is relatively quiet on the impact of market uncertainty on a firm's knowledge outsourcing decisions, there are a myriad of opportunities for impactful research. While empirical studies may have limitations when measuring the level of market uncertainty, studies using analytical models or lab experiments are better able to fill this gap in the literature. In addition, further research is required to investigate how the two types of uncertainty jointly influence a firm's knowledge outsourcing decisions, in order to obtain a more comprehensive view of the impact of uncertainty on knowledge outsourcing.

4.3 Phase 2 – Plan

After receiving official authorization to pursue a knowledge outsourcing project in the initiating phase, the buyer determines the most suitable knowledge supplier and the level of knowledge outsourcing required in the planning phase. Subsequently, the buyer and the selected supplier make a contractual agreement on the specific content of the knowledge to be outsourced (solutions for problems to be solved or results of experiments to be performed), the form of knowledge to be outsourced as deliverables (written report, engineering design drawings, physical prototypes, or software), the price of knowledge, the level of knowledge outsourcing (hours of effort from the supplier), and the due date (Lee et al. 2016). The buyer may find these decisions challenging due to uncertainty and information asymmetry between the buyer and the supplier. Moreover, since the supplier also optimizes his decision such as the unit price of knowledge, the buyer's decision-making process becomes even more complicated. In this section, we review current studies on the decisions corresponding to the planning phase and provide suggestions for future research to address the current challenges.

4.3.1 Selection of a Knowledge Supplier

When a buyer seeks a supplier for knowledge to solve a specific problem, some firm-specific information about the supplier, such as the amount of existing knowledge he possesses which is relevant to the buyer's problem, may remain private. This is an issue of information asymmetry. In such situations, the buyer faces the risk that the supplier might in fact be incapable of meeting her needs. Therefore, the buyer evaluates whether the supplier is capable of understanding the problem and developing effective solutions. A supplier's research and technical capability is an important criterion for the buyer's selection. It has been empirically shown that buyers tend to select outsourcing partners who possess superior technological resources (Howells et al. 2008). If the supplier has lower capabilities, the buyer may consider a supplier with the right complementary resources to leverage the supplier's prior knowledge (Miotti and Sachwald 2003). Lee et al. (2016) analytically show that the supplier charges a reduced price for knowledge if his level of prior knowledge is larger, which means the buyer's total cost is lower. This finding suggests that a buyer benefits from selecting a supplier with knowledge proximity.

Given that the recombination of different technological domains can produce more creative knowledge (Fleming 2001), geographical distance in knowledge outsourcing projects may provide this advantage to buyers. In particular, offshore knowledge outsourcing[12] facilitates knowledge creation through the recombination of heterogeneous inputs due to greater cognitive distance[13] (Bertrand and Mol 2013; Nooteboom 2009). Offshore knowledge outsourcing has further practical advantages, including highly qualified knowledge workers available at lower costs abroad (Eppinger & Chitkara 2006; Liu et al. 2017). Therefore, Bertrand & Mol (2013) empirically show that while knowledge outsourcing from a domestic supplier can be used as a substitute for internal knowledge development, knowledge outsourcing from

[12] Offshore knowledge outsourcing refers to the procurement of knowledge intensive activities from independent suppliers located abroad (Bertrand & Mol, 2013).
[13] Cognitive distance refers to the phenomenon that "a people who have developed their cognition along different life trajectories, in different environments, will see, interpret, understand and evaluate the world differently." (Nooteboom, 2009, p. 95)

a foreign supplier may be used to complement and strengthen internal knowledge development (especially for product innovation as opposed to process innovation). In addition, interactions with a foreign knowledge supplier may also provide a buyer with access to new markets and argument sales. In their empirical research, Rodríguez & Nieto (2016) show that offshore knowledge outsourcing directly and positively affects the sales growth of SMEs (small and medium-sized enterprises) who actively seek new revenue sources.

Relational factors, including trustworthiness and familiarity, are also key criteria for a buyer's supplier selection (Howells et al. 2008; Levin and Cross 2004). Since repeated interactions, which build trust and familiarity, may augment the supplier's relationship-specific investments and facilitate active information exchange, a buyer may benefit from selecting a supplier with whom they have previously worked (Dyer & Singh 1998; Martinez-Noya et al. 2013). Some geographical regions may have more frequent social interactions, which facilitates the transmission of information and creates trust. In their empirical study, Laursen et al. (2012) show that operating a knowledge outsourcing project with a supplier in a region with high levels of social interaction improves the outcomes of knowledge outsourcing. Since relational factors also influence the effectiveness of a buyer's knowledge integration, we discuss them further in the section Phase 4 – Utilize.

4.3.2 Decision on the Level of Knowledge Outsourcing

Once a supplier has been selected, the buyer determines her level of reliance on knowledge outsourcing before agreeing on a contract. While knowledge outsourcing may provide buyers with benefits in terms of R&D cost saving, flexibility, and innovative outputs, relying heavily on knowledge outsourcing may also bring about new organizational challenges. From the transaction cost of economics (TCE) perspective, finding a suitable supplier and coordinating a knowledge outsourcing project across the boundaries of organizations may require more resources than in-house knowledge development and thus incur additional cost (Dyer and Singh 1998). The resource-based view (RBV) of buyers also suggests that heavy reliance on knowledge outsourcing may restrict a buyer's building of path-dependent knowledge stocks due to a reduction in learning-by-doing (Bettis et al. 1992). Reflecting these conflicting views, several empirical studies find an inverted-U shaped relationship between the level of knowledge outsourcing and buyers' innovation performance, showing that there is an optimal level of knowledge outsourcing (Berchicci 2013; Grimpe and Kaiser 2010). It is also empirically shown that the optimal level of reliance on knowledge outsourcing is associated with a buyer's level of internal knowledge development (i.e., complementarity), knowledge protection mechanisms, and absorptive capacity (Beneito 2006; Cassiman and Veugelers 2006; Krzeminska and Eckert 2016; Spithoven and Teirlinck 2015; Weigelt and Sarkar 2012).

These empirical studies, however, generally neglect to study a supplier's optimizing behavior. Incorporating the empirical findings above into their game-theoretical formulation, Lee et al. (2016) employ a Stackelberg game between a supplier and a buyer, in which the buyer determines her optimal level of knowledge outsourcing after observing the supplier's decision on the unit price of knowledge. In a key result, Lee et al. (2016) show that if the buyer's absorptive capacity is larger the buyer's level of knowledge outsourcing may be greater despite the supplier's higher price of knowledge. Moreover, their study identifies conditions whereby knowledge outsourcing and in-house knowledge development become complements or substitutes in relation to the buyer's absorptive capacity and project scope uncertainty. Using a similar game-theoretical formulation, Lee et al. (2017) analytically investigate how competition between two buyers in the downstream market impacts the supplier's decision on his price of knowledge. They show that the supplier's optimizing behavior might cause unintended negative consequences for the buyers. That is, even if both buyers pursue knowledge outsourcing, the supplier may serve only one buyer and charge a premium price of knowledge. The supplier's rejection of a knowledge outsourcing partnership may lead a buyer to incur more cost because they must use in-house knowledge development and potentially lose market competitiveness in the downstream market.

4.3.3 Future Research Opportunities

Another important decision that the buyer should make in the planning phase is the timing of knowledge outsourcing. While a knowledge supplier serves multiple buyers simultaneously (Lee et al. 2017), buyers who compete in the downstream market often work with a common supplier sequentially (Hargadon and Sutton 1997). Many questions regarding decisions on the timing of knowledge outsourcing remain unanswered. For example, should a buyer outsource knowledge earlier than her competitors? If the buyer outsources knowledge from the supplier early, the supplier may charge a higher price of knowledge because the related knowledge has not yet matured. On the other hand, the buyer may be able to benefit from a faster time to market. Further, while a superior buyer may have a greater fear of knowledge leakage than inferior buyers when they have different technological capabilities, the superior buyer can more effectively understand and utilize the outsourced knowledge from the supplier. In this situation, who should the supplier serve first? How can the supplier charge optimal prices of knowledge depending on the buyers' technological capabilities and the timing of knowledge outsourcing? Future research can investigate factors that impact buyers' decisions on timing and the supplier's service strategy.

Both buyers and suppliers face uncertainty when making decisions in the planning phase. A buyer deals with market demand uncertainty and technological uncertainty when selecting a supplier and determining the level of knowledge outsourcing. Future research investigating how a buyer addresses uncertainty when making decisions in the planning phase would be valuable. The supplier may also deal with uncertainty regarding his technological capability to complete the knowledge outsourcing project and satisfy the buyer's needs within the deadline specified by the contract. The question of how a supplier's uncertainty regarding his technological capability impacts his interactions with a buyer remains unanswered. If the supplier undervalues his technological capabilities and requests a long deadline, the buyer may terminate the contract and find another supplier. In contrast, if the supplier overvalues his technological capabilities and shortens the length of the knowledge outsourcing project, he faces a higher chance of missing the deadline and damaging his reputation. Since these trade-offs exist, future research may investigate how both a supplier and a buyer can better respond to the supplier's uncertainty regarding his technological capabilities.

A more challenging factor influencing decisions in the planning phase is information asymmetry, which remains understudied in the knowledge outsourcing literature. The buyer cannot discern whether the supplier has the required knowledge at the time of supplier selection. Reversely, the buyer has a better understanding of her specific problems than the supplier. Is the buyer better off providing the supplier with a less structured description of her problem, which may allow the supplier to explore more freely and find better solutions? To answer this question, Rahmani and Ramachandran (2016) consider a knowledge outsourcing contract in which a supplier performs a specialized search for a buyer's innovation in technology. They find that the solution flexibility allowed by flexible problem specifications may negatively influence the quality of solutions due to the buyer's over-expectations, which may lead the supplier to procrastinate. This suggests that a buyer should reduce the level of information asymmetry regarding the nature of her problems to be solved by the supplier.

In fact, most firm-specific information may remain private knowledge: the cost of knowledge development, the level of prior knowledge, a supplier's technological ability to meet the deadline (adverse selection problem), absorptive capacity, etc. Considering information asymmetry about the buyer's absorptive capacity, Lee et al. (2016) analytically show that both the buyer and the supplier may suffer because of information asymmetry. Especially, if the buyer keeps her absorptive capacity private, the supplier is not able to charge the optimal price in relation to the buyer's absorptive capacity. Consequently, while the question of whether the buyer benefits from information asymmetry depends on her level of absorptive capacity, the supplier's profit is always reduced because the buyer requests either too much or too little knowledge outsourcing. In addition, the buyer's inability to recognize if the supplier possesses the required knowledge (i.e., information asymmetry on the amount of the supplier's existing knowledge) to accomplish knowledge outsourcing tasks may also impact the decisions and performance of knowledge outsourcing. Further research is needed to advance our understanding on how asymmetric information about various factors impacts the decisions and profits of both the buyer and the supplier.

Once a buyer and a supplier agree to the contents of knowledge, the form of knowledge as deliverables, the price of knowledge, the level of knowledge outsourcing, and the due date, they sign the contract and the supplier commences independent knowledge development activities (Lee et al. 2016). The literature on the impact of different contracts between supply chain partners is well developed (Cachon 2003). Studies in the literature of knowledge coproduction (i.e., joint knowledge development), which is close to the knowledge outsourcing literature, examine how different types of contract impact profit, cost, and product quality (Bhaskaran and Krishnan 2009; MacCormack and Mishra 2015; Xue and Field 2008). In the knowledge outsourcing literature, Lai et al. (2009) consider two specific types of contract: revenue sharing and lump-sum payment. Based on a principal-agent framework, they analytically identify conditions under which either revenue-sharing or lump-sum payment is the principal's optimal choice. However, since their study does not take into consideration any of the critical factors related to knowledge outsourcing (e.g., prior knowledge, absorptive capacity, the price of knowledge, and uncertainty), further research is required to better understand how knowledge outsourcing contracts are influenced by other parameters (Gaimon et al. 2017b).

As Lee et al. (2017) consider competition between two buyers in the downstream market (both buyers outsource knowledge from a common supplier), future research is also needed to examine how competition between knowledge suppliers in the market for knowledge (i.e., knowledge-intensive business service industry) (Beltencourt et al. 2002) impacts the decisions and profits of the buyers and suppliers. Further, while Lee et al. (2016) and Lee et al. (2017) provide important analytical insights for managerial decisions in knowledge outsourcing, firms often deviate from theoretical guidance due to behavioral aspects (Loch 2017). Future research opportunities exist to explore how behavioral or psychological aspects, including bounded rationality (Gurnani et al. 2014), complexity aversion (Ramachandran et al. 2018), risk aversion and loss aversion (Bendoly et al. 2010; Kahneman & Tversky 1979), fairness concerns (Katok et al. 2014), and not-invented here syndrome (Katz and Allen 1982; Menon and Pfeffer 2003) impact buyers' and suppliers' decisions on knowledge outsourcing.

4.4 Phase 3 – Execute

In the executing phase, the supplier undertakes knowledge development to meet the buyer's needs based on the specifics agreed upon in the contract between the buyer and the supplier. Unlike collaborative innovation, where firms jointly develop knowledge (e.g., alliances and joint ventures), the supplier develops knowledge independently and with discretion under a knowledge outsourcing contract. The buyer therefore employs controlling mechanisms to manage the quality of the supplier's work and prevent potential opportunistic behavior from the supplier. The buyer often needs to share her existing knowledge with the supplier to facilitate knowledge development. Since the supplier may work for multiple buyers, this can cause an unintended flow of knowledge from the supplier to the buyer's competitors. Therefore, the buyer should carefully determine how to communicate with the supplier in the executing phase.

After completing knowledge development, the supplier delivers knowledge in the format specified by the contract to the buyer. Similar to the generic processes of project management (i.e., Closing process[14]), the buyer evaluates the quality of the supplier's outputs compared to the initial specifications in contract, proceeds the formal acceptance of all deliverables, and closes out the contact with the supplier at the end of the executing phase (Stackpole 2013). In this section, we discuss previous research studying buyers' decisions in the executing phase and provide an agenda for future research.

4.4.1 Controlling the Execution of Knowledge Outsourcing

A supplier must be highly creative to develop knowledge to meet a buyer's needs. Since the creative process is delicate and vulnerable to various disruptions, controlling behavior from the buyer may negatively influence the supplier's task performance if the knowledge outsourcing project requires a high degree of creativity (Andrews and Smith 1996). Carson (2007) empirically investigates the relationship between buyer control and supplier performance in creative knowledge development when buyers outsource knowledge for new product development. Using Likert-type perceptual measures, the study operationalizes control in two ways and reports divergent results: ex ante control (control specifications described in the contractual agreement) and ex post control (ongoing control activities imposed during the execution of the project).

Carson (2007) shows that low levels of ex ante control in highly creative knowledge outsourcing tasks results in reduced supplier performance due to the

[14] The generic closing processes in project management consist of those processes performed to finalize all activities and formally close the project. Those processes commonly include activities such as: obtaining formal acceptance of all deliverables, comparing the final results to the initial objectives (e.g., product requirements, the scope, schedule, and cost baselines), transitioning the final results (product or service) to the customer or operations, and closing out all contracts (Stackpole 2013).

ambiguity of the buyer's needs. This suggests that highly innovative knowledge outsourcing projects are more successful when the buyer establishes more control over the supplier's knowledge development process before they start enter the execution phase. However, it is also known that control from outside sources may limit the supplier's ability to perform creative tasks. Especially, control during the execution stage may limit the supplier's discretion and ability to apply his expertise in creative problem solving (Andrews and Smith 1996). Carson (2007) shows that the relationship between ex post control and supplier performance is negatively moderated by the level of creativity required by the knowledge outsourcing project. This suggests that the buyer should impose less ex post control to improve supplier performance on highly innovative knowledge outsourcing projects.

4.4.2 Future Research Opportunities

Since creative tasks such as knowledge development require substantial levels of motivation (Andrews & Smith 1996; Ko et al. 2005), different types of contract between a buyer and a supplier may provide the supplier with different levels of motivation in the context of knowledge outsourcing. The supplier's obligation, based on contractual agreement with the buyer, is to provide an acceptable solution for the problem specified in the contract; it does not have to be the best solution. Carson (2007) suggests that a buyer should reduce her level of control while the supplier focuses on the execution of knowledge development, so which specific type of contract allows the buyer to most effectively motivate the supplier to develop the best possible solution? Future studies may investigate how contract types and control mechanisms jointly impact the quality of a supplier's knowledge development.

Another important decision that a buyer needs to make during the executing phase is the location where the knowledge development will be carried out. Since geographical proximity increases the frequency and improves the quality of communication between the buyer and the supplier, the buyer may encourage the supplier to work in-house (Narula and Santangelo 2009). While enhanced communication may shorten the completion time of a project, improve the supplier's performance, and/or aid the buyer's knowledge integration (discussed in the utilizing phase), it does also raise concerns about knowledge leakage (Baccara 2007; Lai et al. 2009). Despite the contractual terms specifying intellectual property rights, Buss & Peukert (2015) empirically show that there is a positive link between knowledge outsourcing and intellectual property infringement due to the absence of perfect contracting (Lai et al. 2009). They also show that larger companies and more knowledge-intensive firms have a higher risk of intellectual property infringement. Using primary data, Martínez-Noya & García-Canal (2016) show that sharing a knowledge supplier with competitors increases a buyer's fear of knowledge leakage (especially for non-standardized knowledge services), which leads to decreased knowledge transfer and thus reduced supplier performance.

The impact of knowledge leakage on buyer profit and innovation performance is currently understudied. Does knowledge leakage always reduce a buyer's profit? Regardless of whether knowledge leakage occurs directly or indirectly, the common supplier is able to refine his capabilities and reduce knowledge development cost by serving multiple buyers. The reduced price of knowledge offered by the common supplier may also lead the buyer to benefit from knowledge leakage. Future research is required to investigate if there is any situation where the advantages of knowledge leakage outweigh the disadvantages. Furthermore, future studies may examine whether the existence of a common knowledge supplier who serves incumbents might lower the barrier of market entrance when an entrant pursues knowledge outsourcing to join a preexisting downstream market.

One practical challenge that buyers face in the executing phase is supplier opportunism, which is defined as self-interest seeking with guile (Jap and Anderson 2003). A supplier's opportunistic behavior may include shirking responsibilities, hiding information or providing false information, and making hollow promises or window-dressing efforts, which results in low motivation to perform (i.e., moral hazard problem) (Yan and Kull 2015). Factors such as agreed incentive structures in the contract, the buyer's controlling mechanisms, and the supplier's concerns about reputation and long-term relationship may reduce the extent of the supplier's opportunism. Nevertheless, some degree of opportunism always remains once the execution of the supplier's knowledge development to meet the buyer's needs is in progress (Jap and Anderson 2003).

Using primary data collected from the U.S. and China, Yan & Kull (2015) show that when supplier opportunism is observed by buyers, it negatively influences the performance of knowledge outsourcing. Likewise, supplier opportunism may also impact the time spent to finish a knowledge outsourcing project. How should a buyer deal with a supplier's uncertain ability to meet the deadline? When making decisions on knowledge outsourcing, the buyer should consider the possibility that the supplier may finish the project earlier or later than the deadline specified in the contract. Even more challenging is the fact that the level of supplier opportunism is closely related to buyer uncertainty (market uncertainty and technological uncertainty) (Yan and Kull 2015). Future research may explore incentive mechanisms through which buyers can encourage trustworthy behavior from suppliers during knowledge outsourcing projects.

4.5 Phase 4 – Utilize

Regardless of the source, any knowledge obtained from outside must be integrated and transformed into physical innovations (e.g., new products or processes) to add value to the firm (Roper and Arvanitis 2012). The integration of external knowledge is remarkably different from the assembly of physical components. When the buyer assembles a component delivered by a supplier into her product, the buyer does not have to fully understand the knowledge embedded in the outsourced component. In contrast, to integrate the outsourced knowledge into her knowledge repository and make use of it (the transformation of knowledge into physical innovations – new products or processes) the buyer should have a complete understanding of the knowledge, which may incur additional knowledge integration cost (Berchicci 2013; Bianchi et al. 2016; Grimpe & Kaiser 2010; Weigelt 2009). It is known that while a buyer's absorptive capacity[15] improves the performance of value extraction from outsourced knowledge, behavioral biases such as NIH syndrome[16] may hamper knowledge integration. In this section on the utilizing phase, we discuss current studies on buyers' absorptive capacity and suggest future research opportunities regarding NIH syndrome and other influencing factors.

[15] Cohen & Levinthal (1990)refer to "absorptive capacity" as "the ability of a firm to recognize the value of new external information, assimilate it, and apply it to commercial ends."
[16] NIH (Not-Invented-Here) syndrome is defined as "the tendency of a project group of stable composition to believe it possess a monopoly of knowledge of its field, which leads it to reject new ideas from outsiders to the likely detriment of its performance (Katz and Allen 1982)."

4.5.1 Absorptive Capacity

The literature shows that absorptive capacity is largely a function of a firm's level of existing knowledge (Cohen and Levinthal 1990). It has been empirically shown that a buyer with large amounts of existing knowledge is better able to understand and apply the outsourced knowledge received from a supplier, subject to diminishing returns (Cohen and Levinthal 1989). Specifically, empirical studies consistently show that a firm's internal R&D capability enhances the positive impact of knowledge outsourcing on their innovation performance (Berchicci 2013; Cassiman and Veugelers 2006; Grimpe and Kaiser 2010). In addition, relational factors such as trust, familiarity, and the quality of communication also affect the performance of a buyer's integration of outsourced knowledge (Howells et al. 2008; Levin and Cross 2004). For example, benefits are realized if the buyer and supplier have established methods of communication (such as shared terminology) and trust based on past experience working together (Levin and Cross 2004).

Considering the two drivers of a buyer's absorptive capacity (existing knowledge and relational factors), Lee et al. (2016) investigate how those two drivers influence interactions between the buyer and the supplier differently. Using a game-theoretic formulation, they show that while the buyer always benefits from higher absorptive capacity regardless of what drives it, the supplier's profit may be reduced when the buyer has high level of existing knowledge because the buyer has a lower desire to pursue knowledge outsourcing.

4.5.2 Future Research

Lee et al. (2016) consider dyadic interactions between one supplier and one buyer to show how the supplier may increase the price of knowledge as the buyer's absorptive capacity increases. Is a supplier still be able to increase the price of knowledge when the buyer competes with other buyers in the downstream market? When a buyer competes with other firms in the downstream market, the increased price of knowledge leads to a higher cost to obtain knowledge, therefore reducing the buyer's competitiveness. Future research may investigate how buyers' absorptive capacity and downstream market competition between buyers jointly influence interactions between buyers and a supplier.

If a buyer is highly motivated to accept the outsourced knowledge, then she is better able to understand and apply it (Ko et al. 2005; Osterloh and Frey 2000). There are opportunities to study how both buyers and suppliers can incentivize their knowledge workers to improve the performance of knowledge outsourcing projects. Further, lab experiments can be used to investigate how NIH syndrome influences the decisions and profits of both buyers and suppliers. Naturally, levels of motivation and NIH are associated with a firm's management policy and regime. Therefore, firms need to define product architecture (e.g., modularity) and the structure of R&D organization in such a way that they facilitate the integration of outsourced knowledge for innovations (Bianchi et al. 2016; Kamuriwo and Baden-Fuller 2016; Sanchez and Mahoney 1996; Vickery et al. 2016). Future studies may investigate how a firm's product architecture (e.g., modularity) and the structure of R&D organization, including incentive mechanisms, impact knowledge outsourcing.

4.6 Phase 5 – Check

In the final checking phase, buyers evaluate the outcomes of knowledge outsourcing projects and plan to further utilize the outsourced knowledge for future knowledge development projects. While the generic project management guideline evaluates the quality of outputs (i.e., deliverables) compared to the specifications in the initial plan (Stackpole 2013), the checking phase in the knowledge outsourcing framework goes beyond assuring the quality of outsourced knowledge and includes checking activities for the performance of utilizing outsourced knowledge. Buyers often analyze how their knowledge outsourcing projects improve their innovativeness and/or financial performance (Cui et al. 2012; Howells et al. 2008; Stanko & Calantone 2011).

Since relational factors impact the performance of knowledge outsourcing, buyers also analyze the effectiveness of their interactions with suppliers, which may include suppliers' responsiveness to their requests, the quality of communication, the quality of deliverables, ex post technical support, and the levels of knowledge leakage and opportunism. Likewise, a buyer's internal performance of knowledge integration should be also evaluated in the checking phase. However, continuous reliance on external sources of knowledge produces concerns that a buyer may lose the ability to solve problems independently. In this section, we discuss current studies on the outcomes of knowledge outsourcing and knowledge reuse, and explore future research opportunities in relation to the path-dependent nature of knowledge development.

4.6.1 Outcomes of Knowledge Outsourcing

Buyers should evaluate the performance of each individual knowledge outsourcing project. We provide guidance for such evaluations by reviewing the current literature on the overall performance of knowledge outsourcing. Several studies investigate the impact of knowledge outsourcing on different outcomes, including innovativeness, product quality, time to market, cost, and financial performance. We observe that the current studies are not only scant but conflicting in their findings. A detailed discussion is provided as follows.

Innovativeness. Using survey and archival data from the U.S. pharmaceutical industry, Nicholls-Nixon & Woo (2003) show that having R&D contracts (i.e., knowledge outsourcing) in a mixture of knowledge sourcing modes (e.g., licenses, joint ventures, acquisitions, etc.) increases the number of new products. This is because different linkages between different knowledge sourcing modes facilitate the development of different types of knowledge. However, other empirical studies find an inverted U-shape relationship between the degree of knowledge outsourcing and innovation performance, which demonstrates that heavy reliance on knowledge outsourcing may reduce innovation performance due to knowledge leakage, the dilution of firm specificity, the risk of integration failure, and the additional managerial resources required to coordinate and monitor (Berchicci 2013; Bianchi et al. 2016; Cassiman and Veugelers 2006; Grimpe and Kaiser 2010).

Product quality. Using survey data on the NPD make/buy choices of automobile firms in the U.S., Kalaignanam et al. (2017) show that while NPD outsourcing more positively influences the short-term quality of new products than NPD insourcing, it leads to a reduction in long-term quality. This is because a buyer can benefit from a supplier's greater expertise with respect to a particular technology at the time of product launch. However, after product launch, disadvantages such as lack of control, adaptation failure, and insufficient learning benefits from NPD outsourcing lower the quality of new products over time. In addition, they show that the positive impact of NPD outsourcing on the short-term quality of new products is larger if either the technological complexity of NPD or the buyer's technological capability is higher.

Time to market. Despite the importance of a quick time to market, little is known about whether knowledge outsourcing accelerates a buyer's innovation on new products and processes. Based on case-based research, studies argue that knowledge outsourcing reduces the time required to develop new products (Chatterji 1996; Quinn 2000). In contrast, by surveying new product development projects from large US-based companies, Kessler et al. (2000) show that heavy reliance on knowledge outsourcing for developing new products increases the time it takes to complete those projects.

Cost reduction. With regard to cost reduction, Kessler et al. (2000) find no relationship between knowledge outsourcing and reduced cost of developing new product innovations from their survey results. Using a similar survey method, Huang et al. (2009) show that knowledge outsourcing reduces the development cost of NPD projects only for incremental innovations (i.e., standardized technology, which is relatively easy to codify). Case-based studies, however, consistently argue that knowledge outsourcing has the advantage of reducing R&D cost. In their game-theoretic formulation, Lee et al. (2016) employ cost minimization problems for a buyer to choose optimal levels of in-house knowledge development and knowledge outsourcing while satisfying a pre-determined project scope. They find that the buyer will always pursue a certain level of knowledge outsourcing to compensate for costly in-house knowledge development.

Financial performance. Does knowledge outsourcing ultimately improve financial performance? Even though profitability is one of the biggest motivations for knowledge outsourcing, there are a surprisingly small number of studies investigating it. Using the survey method, Huang et al. (2009) show that knowledge outsourcing generates more profit than in-house knowledge development only for incremental innovations. Using event study methodology, Raassens et al. (2012) examine the effect of knowledge outsourcing for NPD on shareholder value (i.e., stock price) and find that the announcement of knowledge outsourcing increases stock returns by 0.20% on average. In their game-theoretic formulation, Lee et al. (2017) investigate how competition between two buyers in the downstream market impacts their decisions and profits when both buyers outsource knowledge from a common supplier to improve product quality. To build insights, they first consider the profit maximization problem for a monopolist buyer and find that knowledge outsourcing increases the buyer's profit only if the buyer's cost of in-house knowledge development is sufficiently high. More interestingly, they show that under certain conditions, a buyer under duopoly outsources knowledge even at the expense of lower profit because they cannot reasonably assume that the other buyer will not outsource knowledge (i.e., the Prisoner's dilemma).

As there are currently an insufficient amount of studies, all with wide discrepancies, there are a myriad of opportunities for impactful future research on the outcomes of knowledge outsourcing. This will be discussed in the future research section.

4.6.2 Knowledge Reuse

One important outcome of knowledge development, which is remarkably different from the production of physical components, is knowledge reuse, and knowledge outsourced from a supplier is no exception. Pre-existing knowledge stocks are well recognized as important sources for continuous innovations from the literature (Cefis and Orsenigo 2001; Helfat and Leonard-Barton 1994; Roper and Hewitt-Dundas 2008). Once the knowledge outsourced from the supplier is integrated into a buyer's knowledge stock, the buyer can plan to reuse the knowledge for future knowledge development projects. As discussed in the section on absorptive capacity, knowledge assimilated from knowledge outsourcing projects can be used to facilitate a buyer's understanding and utilization of additional outsourced knowledge in the future.

Beyond the impact of knowledge reuse on a buyer's absorptive capacity, the supplier also reuses knowledge developed to satisfy the needs of buyers in future knowledge development projects (Hansen et al. 1999). Despite concerns about knowledge leakage, the supplier in fact learns and builds his stock of knowledge through experience serving buyers (Hargadon and Sutton 1997). In particular, a supplier may repeatedly leverage his stock of knowledge without incurring additional development cost (Alavi & Leidner 2001; Haefliger et al. 2008).

According to Majchrzak et al. (2004), there are two modes of leveraging existing knowledge. "Replication" occurs when a firm transfers existing knowledge between related research programs, whereas "leveraging existing knowledge for innovation" refers to a recombinative integration of prior knowledge. In their empirical case studies, Haefliger et al. (2008) find that leveraging existing knowledge in the form of computer code is common in software development projects and mitigates development cost. To our knowledge, Lee et al. (2016) is the only study that examines the impact of knowledge reuse in the context of knowledge outsourcing. They show that high rates of knowledge reuse by a supplier is mutually beneficial to both the buyer and the supplier.

4.6.3 Future Research

To deepen our understanding of the outcomes of knowledge outsourcing, future studies may investigate: 1) under which circumstances firms can improve the quality of products and processes, increase profits, save R&D cost, and reduce time to market, 2) what the main factors that influence those outcomes are and how they function. For instance, as there are conflicting findings on the impact of knowledge outsourcing on time to market, more comprehensive studies are required to better understand whether (or under which conditions) knowledge outsourcing reduces time to market. Researchers can also investigate how the impact of knowledge outsourcing on time to market is associated with the type of knowledge sourced (known or new knowledge), the complexity of problems, and incentive structures (or contracting mechanisms), etc. Furthermore, researchers have opportunities to contribute to the practice by establishing applicable methods to work on those factors to increase the positive outcomes of knowledge outsourcing. In this regard, empirical studies can identify applicable measures to evaluate the outcomes and influencing factors of knowledge outsourcing.

Despite the importance of feedback on suppliers' performance for future projects, studies evaluating the effectiveness of interactions with suppliers for knowledge outsourcing are scant. Researchers can establish applicable metrics to analyze suppliers' responsiveness to buyers' requests, the quality of communication, the quality of deliverables, ex post technical support, and levels of knowledge leakage and opportunism.

While previous studies show knowledge reuse to be beneficial to both buyers and suppliers, there are still questions which remain unanswered. For example, how can firms dynamically develop workers' knowledge (Carrillo and Gaimon 2004). This question can be narrowed down to a job allocation problem: how to deploy knowledge workers to maximize the benefits gained from reusing knowledge embedded in workers' individual knowledge stocks for both the buyer and the supplier. In two extreme cases, firms can allocate their knowledge workers permanently to either very similar knowledge development projects or very different projects. Which allocation mechanism is better under which circumstances? Since knowledge development and the integration of outsourced knowledge require very different skill sets, buyers may permanently allocate their knowledge workers to either in-house knowledge development or knowledge outsourcing, or let them continue to alternate between the two. If a balancing point exits, what are the factors that influence it? Future studies may address these questions.

Despite the importance of internal knowledge flow (in-house knowledge development) which contributes to innovation outputs (Roper and Hewitt-Dundas 2015), firms also recognize the potential for its negative innovation effects through path-dependency (Thrane et al. 2010). As a result, firms tends to obtain knowledge more from external sources (Howells et al. 2008). This, however, incurs the cost of losing opportunities of learning-by-doing with which firms build their core capabilities (Bettis et al. 1992). With these trade-offs in mind, future studies may investigate how a firm can develop a dynamic path of knowledge sourcing modes (i.e., insourcing and outsourcing) to obtain different types of knowledge (i.e., known vs. unknown and products vs. processes) while maximizing innovativeness and/or profit.

4.7 Conclusion

While synthesizing the current literature on knowledge outsourcing, we clarify what is currently known and unknown in each phase of the knowledge outsourcing framework introduced in this study. In phase 1 (Initiate), a buyer needs to be able to clearly identify her purpose and targets for knowledge outsourcing. Current studies consistently report that knowledge outsourcing is more suitable to incremental innovation, with its relatively low risk of knowledge leakage.

In phase 2 (Plan), during which the buyer selects a supplier and makes a contractual agreement, the buyer faces the risk that the supplier may not possess sufficient technical capabilities to satisfy her knowledge needs. Current studies show that choosing a highly capable supplier or a known supplier with whom the buyer has previously worked may alleviate this risk. Further studies to identify incentive mechanisms or contract types through which the buyer can effectively ensure cooperative behavior from the supplier are required. Since both the buyer and the supplier make their decisions under uncertainty and with asymmetric information in these two phases, future studies may investigate how information structure impacts decisions and the outcomes of knowledge outsourcing.

In phase 3 (Execute), the supplier independently undertakes knowledge development tasks based on the signed contract. The buyer needs to utilize balanced controlling mechanisms to ensure the quality of the supplier's knowledge outcomes and to promote the supplier's creativity. As knowledge leakage is known to be a risk to the buyer, it will be interesting to see whether the buyer can ever benefit from knowledge leakage in relation to the timing of her knowledge outsourcing. In addition, the supplier's opportunistic behavior is a critical challenge that the buyer faces in the executing phase and future research can investigate how the buyer can effectively ensure trustworthy behavior from the supplier.

In phase 4 (Utilize), the buyer integrates and utilizes the knowledge outsourced from the supplier to generate value. Current studies consistently report that higher absorptive capacity leads to higher performance of the buyer's knowledge integration. However, certain behavioral factors of the buyer including NIH syndrome may reduce the effectiveness of the buyer's internal knowledge integration process. Future studies should investigate how the buyer can incentivize her internal knowledge workers to improve the performance of knowledge integration.

In the final phase (Check), the buyer evaluates the performance of the knowledge outsourcing project and plans ways to reuse the knowledge developed by the supplier in future projects. For most performance measures, including time to market, R&D cost, and financial performance, the current literature has not reached a consensus. Therefore, further research may investigate under which conditions pursuing knowledge outsourcing improves each measure of performance.

As most of the current studies on knowledge outsourcing use empirical methodologies, more diverse research approaches including normative modeling and lab experiments are required to examine the various aspects of knowledge outsourcing more comprehensively. In addition, most current studies focus on the buyer's perspective. Exceptions include Lee et al. (2016), Lee et al. (2017), and Iyer et al. (2000). As the industry scale of knowledge-intensive business services keeps increasing, future research can contribute to the expanding landscape of knowledge outsourcing literature by investigating the supply side of knowledge outsourcing.

APPENDIX A. PROOFS OF CHAPTER 2

A.1 Proof of Proposition 1

We substitute $D_b = J - K_b - \phi S$ into the buyer's objective function (Equation (2)). Solving the first order condition $\frac{\partial TC}{\partial S} = 0$ yields the buyer's best response: $BR(S) = \frac{2c_b\phi(J - K_b) - p}{2c_b\phi^2}$. Since $\frac{\partial^2 TC}{\partial^2 S} > 0$, we know that there is an S satisfying $\frac{\partial TC}{\partial S} = 0$ minimizes the buyer's total cost. The supplier's problem has an additional constraint, $p \le 2c_b\phi(J - K_b)$, due to $BR(S) \ge 0$. By substituting $BR(S)$ into Equation (4) and having $\frac{\partial^2 \Pi}{\partial^2 p} < 0$, we know that there is a p maximizes the buyer's profit. Solving the supplier's constrained optimization problem with respect to p yields the two solutions shown in Proposition 1 for $D_s = 0$ and $D_s > 0$ with conditions $0 < J - K_b \le 2K_s\phi$ and $J - K_b > 2K_s\phi$, respectively. Since this paper focuses on the case with $D_s > 0$, $J - K_b > 2K_s\phi$ holds for our analytical results in Section 2.3. *Q.E.D.*

A.2 Proof of Corollary 1

Given the closed-form solutions, we take the partial derivative of the equilibrium outcomes in Proposition 1 with respect to K_s and obtain:

$\frac{\partial p^*}{\partial K_s} = -\frac{2c_bc_s\phi^2}{c_s + 2c_b\phi^2}$, $\frac{\partial D_s^*}{\partial K_s} = -\frac{2c_b\phi^2}{c_s + 2c_b\phi^2}$, $\frac{\partial D_b^*}{\partial K_s} = -\frac{c_s\phi}{c_s + 2c_b\phi^2}$, $\frac{\partial S^*}{\partial K_s} = \frac{c_s}{c_s + 2c_b\phi^2}$,

$\frac{\partial \Pi^*}{\partial K_s} = \frac{2c_bc_s\phi(J - K_b - 2K_s\phi)}{c_s + 2\phi^2c_b}$, $\frac{\partial TC^*}{\partial K_s} = -\frac{2c_bc_s\phi^2\left(c_b\phi(J - K_b) + c_sK_s\right)}{\left(c_s + 2c_b\phi^2\right)^2}$. By the condition for

$D_s > 0$ ($J - K_b > 2K_s\phi$), we observe $\frac{\partial p^*}{\partial K_s} < 0$, $\frac{\partial D_s^*}{\partial K_s} < 0$, $\frac{\partial D_b^*}{\partial K_s} < 0$, $\frac{\partial S^*}{\partial K_s} > 0$, $\frac{\partial TC^*}{\partial K_s} < 0$, and $\frac{\partial \Pi^*}{\partial K_s} > 0$, which give us Corollary 1. *Q.E.D.*

A.3 Proof of Corollary 2

Given the closed-form solutions, we take the partial derivative of the equilibrium outcomes in Proposition 1 with respect to δ and obtain:

$$\frac{\partial D_b^*}{\partial \delta} = \frac{-\left\{c_s^2 K_s \phi + 2c_b c_s \phi^2 \left(J - K_b - \phi K_s\right)\right\}}{\delta\left(c_s + 2c_b\phi^2\right)^2}, \quad \frac{\partial p^*}{\partial \delta} = \frac{2c_b\phi\left(J - K_b\right)\left(c_s^2 + c_b c_s \phi^2 + 2c_b^2\phi^4\right) - 4c_b c_s^2 \phi^2 K_s}{d\left(c_s + 2c_b\phi^2\right)^2},$$

$$\frac{\partial \Pi^*}{\partial \delta} = \frac{2c_b c_s \phi\left(J - K_b - 2\phi K_s\right)\left\{c_s K_s + c_b\phi\left(J - K_b\right)\right\}}{\delta\left(c_s + 2c_b\phi^2\right)^2}, \quad \frac{\partial TC^*}{\partial \delta} = -\frac{2c_b c_s \phi^2 \left\{c_s K_s + c_b\phi\left(J - K_b\right)\right\}\left\{c_s K_s + 2c_b\phi\left(J - K_b - \phi K_s\right)\right\}}{\delta\left(c_s + 2c_b\phi^2\right)^3},$$

$$\frac{\partial S^*}{\partial \delta} = \frac{c_b\phi\left(J - K_b\right)\left(c_s - 2c_b\phi^2\right) - 4c_b c_s \phi^2 K_s}{\delta\left(c_s + 2c_b\phi^2\right)^2}.$$

By the condition for $D_s > 0$ ($J - K_b > 2K_s\phi$) and the non-negativity of equilibrium solutions, we observe the signs of $\frac{\partial p^*}{\partial \delta}$, $\frac{\partial D_b^*}{\partial \delta}$, $\frac{\partial S^*}{\partial \delta}$, $\frac{\partial TC^*}{\partial \delta}$, and $\frac{\partial \Pi^*}{\partial \delta}$, which give us the conditions in Corollary 2. Since $\frac{\partial D_s^*}{\partial \delta} = \frac{\partial S^*}{\partial \delta}$, its derivation is omitted. *Q.E.D.*

A.4 Proof of Corollary 3

Given the closed-form solutions, we take the partial derivative of the equilibrium outcomes in Proposition 1 with respect to K_b and obtain:

$$\frac{\partial p^*}{\partial K_b} = \frac{\delta c_b \left\{2c_b^2\phi^4\left(J - 3K_b\right) + c_b c_s \phi^2\left(J - 7K_b\right) + c_s^2\left(J - 3K_b - 2K_s\phi\right)\right\}}{\sqrt{K_b}\left(c_s + 2c_b\phi^2\right)^2}, \quad \frac{\partial S^*}{\partial K_b} = -\frac{\delta c_b \left\{2c_b\phi^2\left(J + K_b\right) - c_s\left(J - 3K_b - 4K_s\phi\right)\right\}}{2\sqrt{K_b}\left(c_s + 2c_b\phi^2\right)^2},$$

$$\frac{\partial D_b^*}{\partial K_b} = \frac{c_s K_s \delta\left(2c_b\phi^2 - c_s\right) - 2\sqrt{K_b}\left\{c_b c_s \delta^2\left(J + 2K_b\right) + 2c_b^2\phi^4 + c_s^2\right\}}{2\sqrt{K_b}\left(c_s + 2c_b\phi^2\right)^2}, \quad \frac{\partial \Pi^*}{\partial K_b} = \frac{\delta c_b \left\{c_b\phi\left(J - K_b\right) + c_s K_s\right\}\left\{c_s\left(J - 3K_b - 2K_s\phi\right) - 4c_b K_b \phi\right\}}{\sqrt{K_b}\left(c_s + 2c_b\phi^2\right)^2},$$

$$\frac{\partial TC^*}{\partial K_b} = \frac{c_b\left[c_b c_s K_s \delta^2 \phi\left\{2c_b\phi^2\left(J+K_b\right)-c_s\left(3J-5K_b\right)\right\}-2\left(J-K_b\right)\left\{c_b^2 c_s \delta^2 \phi^2\left(10K_b+J\right)+6c_b^3\phi^6+6c_b c_s^2\phi^2+c_s^3\right\}+c_s^2\delta^2 K_s^2\left(2c_b\phi^2-c_s\right)\right]}{\left(c_s+2c_b\phi^2\right)^3}.$$

Similar to the proof of Corollary 2 above, by the condition for $D_s > 0$ $\left(J - K_b > 2K_s\phi\right)$ and the non-negativity of equilibrium solutions, we observe the signs of $\frac{\partial p^*}{\partial K_b}$, $\frac{\partial D_b^*}{\partial K_b}$, $\frac{\partial S^*}{\partial K_b}$, $\frac{\partial TC^*}{\partial K_b}$, and $\frac{\partial \Pi^*}{\partial K_b}$, which give us the conditions in Corollary 3. Since $\frac{\partial D_s^*}{\partial K_b} = \frac{\partial S^*}{\partial K_b}$, its derivation is omitted. *Q.E.D.*

A.5 Proof of Proposition 2

Table 7. Additional terminology and notation for the stochastic model.

$\hat{J}$	Mean value of the buyer's project scope distributed uniformly, $\hat{J} > 0$.
J	Buyer's true project scope, which is uncertain and uniformly distributed from $\hat{J} - t$ to $\hat{J} + t$, where $t \in \left[0, \hat{J}\right]$.
J_A	Planned project scope the buyer pursues by determining D_b and S, where $J_A = K_b + D_b + \phi S$.
$J_A - \hat{J}$	Extent of the buyer's planned surplus ($J_A - \hat{J} > 0$) or shortage ($J_A - \hat{J} < 0$), indicating the difference between the buyer's planned project scope and the mean of the true project scope.
c_e	Buyer's cost per unit expedited knowledge purchased from an external source (other than the original supplier) to meet her knowledge shortage after the true project scope is realized.
v	Buyer's future unit value of surplus knowledge observed after the true project scope is realized.

To solve the buyer's problem in Equation (5), we define Hessian matrix $\mathbf{H} = \begin{bmatrix} 2c_b + \frac{c_e - v}{2t} & \frac{\phi\left(c_e - v\right)}{2t} \\ \frac{\phi\left(c_e - v\right)}{2t} & \frac{\phi^2\left(c_e - v\right)}{2t} \end{bmatrix}$. To focus on non-trivial situations, we assume $c_e > v$ with which we have $\frac{\partial^2 E\left[TC\right]}{\partial^2 D_b} = 2c_b + \frac{c_e - v}{2t} > 0$ and $\left|\mathbf{H}\right| = \frac{c_b \phi^2 \left(c_e - v\right)}{t} > 0$. Therefore, D_b and S jointly minimize $E\left[TC\right]$. The buyer's first order conditions are:

$f1 = \frac{\partial E\left[TC\right]}{\partial D_b} = 2c_b D_b + \frac{\left(c_e - v\right)\left(K_b + D_b + \phi S - \hat{J}\right) - t\left(c_e + v\right)}{2t} = 0$ and $f2 = \frac{\partial E\left[TC\right]}{\partial S} = p + \frac{\phi\left(c_e - v\right)\left(K_b + D_b + \phi S - \hat{J}\right) - t\left(c_e + v\right)}{2t} = 0$.

Simultaneously solving $f1$ and $f2$ for D_b and S gives us $D_b^t = \frac{p}{2\phi c_b}$ and

$S^t = \frac{2\phi c_b \left\{\left(c_e - v\right)\left(\hat{J} - K_b\right) + t\left(c_e + v\right)\right\} - p\left(c_e - v\right) - 4c_b tp}{2c_b \phi^2 \left(c_e - v\right)}$. Substituting D_b^t and S^t into

$J_A^t = K_b + D_b^t + \phi S^t$ yields $J_A^t = \hat{J} + \frac{t\left\{\phi\left(c_e + v\right) - 2p\right\}}{\phi\left(c_e - v\right)}$. Since $c_e > v$, $J_A^t \geq \hat{J}$ only if $c_e + v \geq \frac{2p}{\phi}$.

Otherwise, $J_A^t < \hat{J}$. *Q.E.D.*

A.6 Proof of Proposition 3

To prove this result, we first characterize the equilibrium decisions in Lemma 1.

Lemma 1. *The equilibrium decisions when the project scope is uncertain are given by:*

(i) The supplier's price $p^* = \frac{2c_b \phi \left\{c_s \Omega_1 \Omega_2 + c_b \phi^2 \Omega_1 \left(c_e - v\right) - c_s K_s \phi \Omega_2 \left(c_e - v\right)\right\}}{\Omega_2 \left\{c_s \Omega_2 + 2c_b \phi^2 \left(c_e - v\right)\right\}}$;

(ii) The buyer's internal knowledge production is $D_b^* = \frac{c_s \Omega_1 \Omega_2 + c_b \phi^2 \Omega_1 \left(c_e - v\right) - c_s K_s \phi \Omega_2 \left(c_e - v\right)}{\Omega_2 \left\{c_s \Omega_2 + 2c_b \phi^2 \left(c_e - v\right)\right\}}$

and the amount of outsourcing is $S^* = \frac{c_b \phi \Omega_1 + c_s K_s \Omega_2}{c_s \Omega_2 + 2c_b \phi^2 \left(c_e - v\right)}$;

(iii) The amount of new knowledge produced by the supplier is $D_s^* = \frac{c_b \phi \left\{\Omega_1 - 2K_s \phi \left(c_e - v\right)\right\}}{c_s \Omega_2 + 2c_b \phi^2 \left(c_e - v\right)}$,

where $\Omega_1 = c_e\left(\hat{J} - K_b + t\right) - v\left(\hat{J} - K_b - t\right)$, $\Omega_2 = c_e + 4c_b t - v$.

Proof: Substituting D_b^t and S^t from the proof of Proposition 2 above into the supplier's problem and taking its second order differentiation with respect to

p yields: $\frac{\partial^2 \Pi}{\partial^2 p} = -\frac{\left(c_e - v + 4c_b t\right)\left\{c_s\left(c_e - v + 4c_b t\right) + 2c_b\phi^2\left(c_e - v\right)\right\}}{2c_b^2\phi^4(c_e - v)^2}$. Since $\frac{\partial^2 \Pi}{\partial^2 p} < 0$ due to $c_e > v$, there is p that maximizes the supplier's profit. We find the supplier's first order condition:

$\frac{\partial \Pi}{\partial p} = \frac{2c_b^2\phi^3\Omega_1\left(c_e - v\right) + 2c_b\phi\Omega_2\left\{c_s\Omega_1 - \phi\left(c_e - v\right)\left(c_s K_s + p\right)\right\} - c_s\Omega_2^2 p}{2c_b^2\phi^4(c_e - v)^2} = 0$. By solving the supplier's first order condition, we obtain the supplier's equilibrium price:

$p^* = \frac{2c_b\phi\left\{c_s\Omega_1\Omega_2 + c_b\phi^2\Omega_1\left(c_e - v\right) - c_s K_s\phi\Omega_2\left(c_e - v\right)\right\}}{\Omega_2\left\{c_s\Omega_2 + 2c_b\phi^2\left(c_e - v\right)\right\}}$. Substituting p^* into the buyer's best responses (D_b^t and S^t) yields the equilibrium decisions as shown in Lemma 1. *Q.E.D.*

Now we return to the Proof of Proposition 3 using the expressions above.

(i) By the Envelope Theorem, we have $\left.\frac{dE[TC]}{dt}\right|_* = \frac{\partial E[TC]}{\partial t} + \frac{\partial E[TC]}{\partial p}\frac{\partial p}{\partial t}$. Since $\frac{\partial E\left[TC^*\right]}{\partial p} = S^*$ and $\frac{\partial E\left[TC^*\right]}{\partial t} = \frac{-\left(c_e - v\right)\left(K_b + D_b^* + \phi S^* - \hat{J} - t\right)\left(K_b + D_b^* + \phi S^* - \hat{J} + t\right)}{4t^2}$, we obtain $\frac{\partial E\left[TC^*\right]}{\partial t} = S^*\frac{\partial p^*}{\partial t} - \frac{\left(c_e - v\right)\left(K_b + D_b^* + \phi S^* - \hat{J} - t\right)\left(K_b + D_b^* + \phi S^* - \hat{J} + t\right)}{4t^2}$. This gives us $\frac{\partial E\left[TC^*\right]}{\partial t} \le 0$ if $S^*\frac{\partial p^*}{\partial t} + \frac{\left(c_e - v\right)\left\{t^2 - \left(J_A^* - \hat{J}\right)^2\right\}}{4t^2} \le 0$, where $J_A^* = K_b + D_b^* + \phi S^*$; otherwise $\frac{\partial E\left[TC^*\right]}{\partial t} > 0$.

(ii) Similarly, by the Envelope Theorem, we have $\left.\frac{d\Pi}{dt}\right|_* = \frac{\partial \Pi}{\partial S}\left(\frac{\partial S}{\partial p}\frac{\partial p}{\partial t} + \frac{\partial S}{\partial t}\right)$. Since $\left.\frac{\partial \Pi}{\partial p}\right|_* = \frac{\partial \Pi}{\partial S}\frac{\partial S}{\partial p}$, we know $\left.\frac{d\Pi}{dt}\right|_* = \frac{\partial \Pi}{\partial p}\frac{\partial p}{\partial t} + \frac{\partial \Pi}{\partial S}\frac{\partial S}{\partial t}$. Recall $\Pi = pS - c_s\left(S - K_s\right)^2$ from Equation (4). This gives us $\frac{\partial \Pi}{\partial p} = S$ and $\frac{\partial \Pi}{\partial S} = p - 2c_s\left(S - K_s\right)$. This yields

$\frac{d\Pi^*}{dt} = S^* \frac{\partial p^*}{\partial t} + \left\{ p^* - 2c_s \left(S^* - K_s \right) \right\} \frac{\partial S^*}{\partial t}$. Therefore, $\frac{\partial \Pi^*}{\partial t} \geq 0$ if $S^* \frac{\partial p^*}{\partial t} + \left\{ p^* - 2c_s \left(S^* - K_s \right) \right\} \frac{\partial S^*}{\partial t} \geq 0$; otherwise $\frac{\partial \Pi^*}{\partial t} < 0$.

Further, taking the total derivative of the two first order conditions for the buyer's problem given by $f1$ and $f2$ in the proof of Proposition 2 with respect to t and writing them in a matrix form yields:

$$\begin{bmatrix} 2c_b + \frac{c_e - v}{2t} & \frac{\phi\left(c_e - v\right)}{2t} \\ \frac{\phi\left(c_e - v\right)}{2t} & \frac{\phi^2\left(c_e - v\right)}{2t} \end{bmatrix} \begin{bmatrix} \frac{dD_b}{dt} \\ \frac{dS}{dt} \end{bmatrix} = \begin{bmatrix} \frac{\left(c_e - v\right)\left(K_b + D_b + \phi S - \hat{J}\right)}{2t^2} \\ \frac{\phi\left(c_e - v\right)\left(K_b + D_b + \phi S - \hat{J}\right)}{2t^2} - \frac{\partial p}{\partial t} \end{bmatrix}$$

. Using Cramer's rule, we have

$\frac{dD_b}{dt} = \frac{1}{2c_b\phi} \frac{\partial p}{\partial t}$ and $\frac{dS}{dt} = \frac{K_b + D_b + \phi S - \hat{J}}{t\phi} - \frac{4tc_b + c_e - v}{2\phi^2 c_b \left(c_e - v\right)} \frac{\partial p}{\partial t}$. The supplier's first order condition is $f3 = \frac{\partial \Pi}{\partial p} = S' + p\frac{\partial S'}{\partial p} + 2c_s\left(S' - K_s\right)\frac{\partial S'}{\partial p} = 0$. From the proof of Proposition 2, we know that $\frac{\partial S^t}{\partial p} = -\frac{4c_b t + c_e - v}{2c_b \phi^2 \left(c_e - v\right)}$, $\frac{\partial^2 S^t}{\partial^2 p} = 0$, $\frac{\partial S^t}{\partial t} = \frac{K_b + D_b^t + \phi S^t - \hat{J}}{t\phi}$, and $\frac{\partial^2 S^t}{\partial p \partial t} = -\frac{2}{\phi^2\left(c_e - v\right)}$. Also, using the Implicit Function Theorem, we obtain

$$\frac{\partial p}{\partial t} = -\frac{\frac{\partial f3}{\partial t}}{\frac{\partial f3}{\partial p}} = \frac{2\phi c_b\left(c_e - v\right)\left[\left(K_b + D_b + \phi S - \hat{J}\right)\left\{4c_b c_s t + \left(c_e - v\right)\left(c_s + \phi^2 c_b\right)\right\} - 2\phi c_b t\left\{p - 2c_s\left(S - K_s\right)\right\}\right]}{t\left(4tc_b + c_e - v\right)\left\{4tc_b c_s + \left(c_e - v\right)\left(2\phi^2 c_b + c_s\right)\right\}}$$

so that

$\frac{\partial p^*}{\partial t} \geq 0$ if $J_A^* - \hat{J} \geq T$, where $J_A^* = K_b + D_b^* + \phi S^*$ and $T = \frac{2c_b t\phi\left\{p^* - 2c_s\left(S^* - K_s\right)\right\}}{4c_b c_s t + \left(c_e - v\right)\left(c_s + c_b\phi^2\right)}$;

otherwise, $\frac{\partial p^*}{\partial t} < 0$. *Q.E.D.*

A.7 Proof of Propositions 4 and 5

To obtain equilibrium solutions for the information asymmetry model, we derive the best responses for the H and L-type buyers from Equation (10) as:

$BR(S_H)=\frac{2c_b\phi_H(J-K_b)-p}{2c_b\phi_H^2}$ and $BR(S_L)=\frac{2c_b\phi_L(J-K_b)-p}{2c_b\phi_L^2}$. Substituting the best responses into the supplier's problem (Equations (7), (8), and (9)) yields the constrained optimization problem, where $\mathcal{L}$ denotes the Lagrangian $\mathcal{L}$: $\max_{p\geq 0}\mathcal{L}=E[\Pi_A]+\lambda_1 BR(S_H)+\lambda_2 BR(S_L)$. The Kuhn-Tucker conditions are: $\frac{\partial\mathcal{L}}{\partial p}\leq 0$, $p\geq 0$, $p\frac{\partial\mathcal{L}}{\partial p}=0$, $BR(S_H)\geq 0$, $\lambda_1\geq 0$, $\lambda_1 BR(S_H)=0$, $BR(S_L)\geq 0$, $\lambda_2\geq 0$, and $\lambda_2 BR(S_L)=0$ from which we obtain one interior solution and one binding solution whereby $BR(S_L)=0$ as shown in Table 8.

Table 8. The equilibrium outcomes in the asymmetric information model.

	Serving both types of buyers ($\psi\leq 0$)	Serving only the H-type buyer ($\psi>0$)
p_A^*	$\left(\frac{\Lambda_H}{\Lambda_H+\Lambda_L}\right)p_H^*+\left(\frac{\Lambda_L}{\Lambda_H+\Lambda_L}\right)p_L^*$	$p_H^*=\frac{2c_b\phi_H\left\{(J-K_b)(\phi_H^2c_b+c_s)-c_s\phi_H K_s\right\}}{2c_b\phi_H^2+c_s}$
D_{sAi}^*	$S_{Ai}^*-K_s$	$D_{sH}^*=S_H^*-K_s$, $D_{sL}^*=0$
S_{Ai}^*	$\frac{J-K_b}{\phi_i}-\frac{p_A^*}{2c_b\phi_i^2}$	$S_H^*=\frac{J-K_b}{\phi_H}-\frac{p_H^*}{2c_b\phi_H^2}$, $S_L^*=0$
D_{bAi}^*	$J-K_b-\phi_i S_{Ai}^*$	$D_{bH}^*=J-K_b-\phi_H S_H^*$, $D_{bL}^*=J-K_b$
$E[\Pi_A^*]$	$\theta\{p_A^*S_{AH}^*-c_s(S_{AH}^*-K_s)^2\}+(1-\theta)\{p_A^*S_{AL}^*-c_s(S_{AL}^*-K_s)^2\}$	$E[\Pi_H^*]=\theta\{p_H^*S_H^*-c_s(S_H^*-K_s)^2\}$
TC_{Ai}^*	$c_b\left(D_{bAi}^*\right)^2+p_A^*S_{Ai}^*$	$TC_H^*=c_b\left(D_{bH}^*\right)^2+p_H^*S_H^*$, $TC_L^*=c_b\left(D_{bL}^*\right)^2$

Note $\psi=\frac{c_b\phi_H^2\phi_L(J-K_b)\left\{\theta\phi_H\phi_L-(\theta-1)\phi_H^2-2\theta\phi_L^2\right\}+c_s\left[\theta\phi_L^2(J-K_b)(\phi_H-\phi_L)-\phi_H^2K_s\left\{(\theta-1)\phi_H^2+\theta\phi_L^2\right\}\right]}{c_b\phi_H^4\phi_L^2}$.

If $\lambda_1^*=\lambda_2^*=0$, then we have the interior solution in which a price to serve both types of buyers is optimal. Letting $\Lambda_H=\theta\phi_L^4(c_s+2c_b\phi_H^2)$ and $\Lambda_L=(1-\theta)\phi_H^4(c_s+2c_b\phi_L^2)$, and rearranging terms in the equilibrium price yields $p_A^*=\left(\frac{\Lambda_H}{\Lambda_H+\Lambda_L}\right)p_H^*+\left(\frac{\Lambda_L}{\Lambda_H+\Lambda_L}\right)p_L^*$, where p_H^* and p_L^* are the equilibrium prices for H-type and L-type buyer in the base model (Proposition 1). Substituting p_A^* into the buyer's best responses ($BR(S_H)$ and $BR(S_L)$), D_{sAi}, D_{bAi}, and objective functions, where $i \in \{H, L\}$, gives us the left column of Table 8. In contrast, if $\lambda_2^* > 0$ while $\lambda_1^* = 0$, then $BR(S_L) = 0$ so the L-type buyer is out of the information asymmetry game. Therefore, we form a separate problem in which the supplier serves only the H-type buyer. Solving the problem in a similar way to Proposition 1 gives us the equilibrium outcomes as shown in the right column of Table 8. *Q.E.D.*

A.8 Proof of Proposition 6

If the supplier serves both types of buyers, his price maximizes expected profit $E\left[\Pi_A^*\right] = \theta \Pi_{AH}^*\left(p_A^*\right) + \left(1-\theta\right)\Pi_{AL}^*\left(p_A^*\right)$. However, if the supplier serves only the H-type buyer, his price maximizes the expected profit $E\left[\Pi_H^*\right] = \theta \Pi_H^*\left(p_H^*\right)$. Solving the inequality $\theta \Pi_{AH}^*\left(p_A^*\right) + \left(1-\theta\right)\Pi_{AL}^*\left(p_A^*\right) \geq \theta \Pi_H^*\left(p_H^*\right)$ for θ gives us $E\left[\Pi_A^*\right] \geq E\left[\Pi_H^*\right]$ only if $0 < \theta \leq \dfrac{\Pi_{AL}^*\left(p_A^*\right)}{\Pi_{AL}^*\left(p_A^*\right) + \Pi_H^*\left(p_H^*\right) - \Pi_{AH}^*\left(p_A^*\right)}$ holds. *Q.E.D.*

APPENDIX B. PROOFS OF CHAPTER 3

B.1 Proof of Proposition 7

Let the superscript added on objective functions indicate the buyer who outsources knowledge from the supplier hereinafter. Therefore, Π_1^{1*} (Π_1^*, respectively) reflects buyer 1's profit with (without, respectively) knowledge outsourcing. First, consider the situation where buyer 1 outsources knowledge from the supplier as a monopolist. Given the location of the consumer who has a positive surplus, buyer 1's quantity in the downstream market is given by $q_1 = \frac{R + D_1 + \phi S_1 - p_1}{\theta}$. Following backward induction, we substitute q_1 into buyer 1's problem (Π_1^1) and find $\frac{\partial^2 \Pi_1^1}{\partial^2 p_1} = -\frac{2}{\theta} < 0$, and therefore there is a p_1 that maximizes Π_1^1. Solving the first order condition, $\frac{\partial \Pi_1^1}{\partial p_1} = 0$, we obtain buyer 1's best response of the consumer price of her product: $BR(p_1) = \frac{R + D_1 + \phi S_1}{2}$. Here, buyer 1 simultaneously determines both levels of in-house knowledge development (D_1) and knowledge outsourcing (S_1). Therefore, we define Hessian matrix $\mathbf{H} = \begin{bmatrix} -2c_b + \frac{1}{2\theta} & \frac{\phi}{2\theta} \\ \frac{\phi}{2\theta} & -2g + \frac{\phi^2}{2\theta} \end{bmatrix}$ in the buyer's problem and find $|\mathbf{H}| = \frac{4c_b g\theta - g - c_b\phi^2}{\theta}$. To focus on non-trivial solutions, we further assume:

$$-2g + \frac{\phi^2}{2\theta} < 0 \tag{B1}$$

$$\frac{4c_b g\theta - g - c_b\phi^2}{\theta} > 0 \tag{B2}$$

Under these assumption, D_1 and S_1 jointly maximize buyer 1's profit. We find that if assumption (B2) holds, the other assumption (B1) also holds, therefore the optimal condition is given: $\frac{4c_b g\theta - g - c_b\phi^2}{\theta} > 0$. We substitute buyer 1's $BR(D_1) = \frac{\phi w - 2gR}{2\left(g - 4cg\theta + c\phi^2\right)}$ and $BR(S_1) = \frac{\phi w - 2gR}{2\left(g - 4cg\theta + c\phi^2\right)}$ in the supplier's problem and find $\frac{\partial^2 \Pi_S^A}{\partial^2 w} = \frac{(1-4c\theta)\left\{(c_s+2g)(4c\theta-1)-2c\phi^2\right\}}{2\left(g-4cg\theta+c\phi^2\right)^2} < 0$ due to $\frac{4c_b g\theta - g - c_b\phi^2}{\theta} > 0$. Since there is w that maximizes the supplier's profit, solving the first order condition yields the supplier's optimal wholesale price of knowledge: $w^* = c_b R\phi\left\{\frac{c_s}{(c_s+2g)(4c_b\theta-1)-2c_b\phi^2} + \frac{1}{4c_b\theta-1}\right\}$. By substituting w^* in the best responses and objective functions, we obtain equilibrium outcomes when buyer 1 outsources knowledge from the supplier under monopoly: $w^* = c_b\phi\left\{M_1 + c_s M_2\right\}$, $S_1^* = c_b\phi M_2$, $D_1^* = \frac{1}{2}\left\{M_1 + M_2(c_s+2g)\right\}$, $p_1^* = c_b\theta\left\{M_1 + M_2(c_s+2g)\right\}$, $\Pi_S^{A*} = c_b^2\phi^2 M_1 M_2$, and $\Pi_1^{A*} = \frac{c_b M_1 M_2^2}{R}\left\{(c_s+2g)^2(1-4c_b\theta)^2 - c_b\phi^2(4c_s+7g)(4c_b\theta-1)+3c_b^2\phi^4\right\}$, where $M_1 = \frac{R}{4c_b\theta-1}$ and $M_2 = \frac{R}{(c_s+2g)(4c_b\theta-1)-2c_b\phi^2}$. *Q.E.D.*

B.2 Proof of Proposition 8

We compare buyer 1's profits in the two situations with and without knowledge outsourcing. Consider the monopoly situation without knowledge outsourcing. Given the location of the consumer who has a non-negative surplus, monopolist buyer A's quantity in the downstream market is given by $q_1 = \frac{R + D_1 - p_1}{\theta}$. Similar to the situation where buyer 1 outsources knowledge in Appendix B.1, we substitute q_1 into buyer 1's problem (Π_1) and find $\frac{\partial^2 \Pi_1}{\partial^2 p_1} = -\frac{2}{\theta} < 0$, and therefore there is p_1 that maximizes Π_1. Solving the first order condition, $\frac{\partial \Pi_1}{\partial p_1} = 0$, we obtain buyer 1's best response of the consumer price of her product: $BR(p_1) = \frac{R + D_1}{2}$. To obtain buyer 1's best response of the level of in-house knowledge development (D_1), we substitute $BR(p_1)$ into Π_1, and find $\frac{\partial^2 \Pi_1(BR(p_1))}{\partial^2 D_1} = -2c_b + \frac{1}{2\theta}$. To focus on non-trivial solutions, we assume:

$$-2c_b + \frac{1}{2\theta} < 0 \tag{B3}$$

Solving the first order condition, $\frac{\partial \Pi_1(BR(p_1))}{\partial D_1} = 0$, yields buyer 1's optimal level of in-house knowledge development: $D_1^* = \frac{R}{4c_b\theta - 1}$. Now, we substitute D_1^* into buyer 1's best response and objective function, and obtain equilibrium outcomes: $p_1^* = 2c_b\theta M_1$, $q_1^* = 2c_b M_1$, $D_1^* = M_1$, and $\Pi_1^* = c_b R M_1$. Using the equilibrium outcomes in the proofs B1 and B2, we have $\Pi_1^{1*} - \Pi_1^* = \frac{c_b^2\phi^2 M_1 M_2^2 \left(g - 4c_b g\theta + c_b\phi^2\right)}{R}$. By the conditions for the optimality and non-negativity of the equilibrium outcomes, we obtain $\Pi_1^{1*} - \Pi_1^* = \begin{cases} < 0 & if \;\; 0 < c_b < \bar{c}_M \\ \geq 0 & otherwise \end{cases}$, where $\bar{c}_M = \frac{g}{4g\theta - \phi^2}$. *Q.E.D.* Since Propositions 9-13 can be similarly proved, their derivations are omitted.

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