Quality Risk in Outsourcing: Noncontractible Product Quality and Private Quality Cost Information

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Received 4 April 2008; revised 9 June 2009; accepted 14 June 2009
DOI 10.1002/nav.20372
Published online 27 July 2009 in Wiley InterScience (www.interscience.wiley.com).

Abstract: This article addresses the concept of quality risk in outsourcing. Recent trends in outsourcing extend a contract manufacturer’s (CM’s) responsibility to several functional areas, such as research and development and design in addition to manufacturing. This trend enables an original equipment manufacturer (OEM) to focus on sales and pricing of its product. However, increasing CM responsibilities also suggest that the OEM’s product quality is mainly determined by its CM. We identify two factors that cause quality risk in this outsourcing relationship. First, the CM and the OEM may not be able to contract on quality; second, the OEM may not know the cost of quality to the CM. We characterize the effects of these two quality risk factors on the firms’ profits and on the resulting product quality. We determine how the OEM’s pricing strategy affects quality risk. We show, for example, that the effect of noncontractible quality is higher than the effect of private quality cost information when the OEM sets the sales price after observing the product’s quality. We also show that committing to a sales price mitigates the adverse effect of quality risk. To obtain these results, we develop and analyze a three-stage decision model. This model is also used to understand the impact of recent information technologies on profits and product quality. For example, we provide a decision tree that an OEM can use in deciding whether to invest in an enterprise-wide quality management system that enables accounting of quality-related activities across the supply chain. © 2009 Wiley Periodicals, Inc. Naval Research Logistics 56: 669–685, 2009

Keywords: outsourcing; quality risk; quality effort; quality management; supply chain management

1. INTRODUCTION

Recent trends in outsourcing have extended contract manufacturers’ (CM’s) responsibility to new areas, such as sourcing, design, and even research and development [5]. For example, Flextronics, an electronics contract manufacturer, has been offering procurement and logistic services to its OEM customers (www.flextronics.com). Celestica, another CM, has been designing products for customers, including IBM, Sun, and Cisco [6]. Several CMs in the pharmaceuticals industry have been undertaking research and development, creating a $30 billion drug-development and manufacturing market [12]. Because of these increasing responsibilities, the CM essentially determines the OEM’s product quality, which exposes the OEM to what we refer to as the quality risk. We define quality as product attributes for which consumers prefer more to less. We define quality risk as lower OEM profit and product quality in the OEM-CM channel relative to a vertically integrated firm. We identify two factors that cause quality risk. First, the firms may not contract on quality. Second, the OEM may not know the CM’s cost to achieve quality. Our objective is to characterize the effects of each quality risk factor and to design contracts that maximize the OEM’s profit by mitigating quality risk. We also study how the OEM’s product-pricing strategy affects the quality risk factors.

The first factor of quality risk is that the OEM and the CM may not contract on quality, although consumers and the OEM may observe quality. Our objective is to characterize the effects of each quality risk factor and to design contracts that maximize the OEM’s profit by mitigating quality risk. We also study how the OEM’s product-pricing strategy affects the quality risk factors.

The first factor of quality risk is that the OEM and the CM may not contract on quality, although consumers and the OEM may observe quality. The firms may not contract on quality mainly for three reasons. First, quality is difficult to measure and verify for a third party such as a court. If a court cannot articulate the product’s quality level, quality is unverifiable. Hence, firms cannot contract upon it. Second, the firms cannot identify every possible contingency in advance. Thus, they cannot write a complete contract that defines what to do in every possible contingency. Third, the OEM faces time-to-market pressure. The OEM may prefer to proceed with a not-so-perfect product rather than be late to

1 Tirole [35] provides additional discussion on observability and verifiability, and incomplete contracts.

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the market. Note that the OEM and the CM can contract on measurable aspects of quality, such as the product’s physical dimensions, tolerances, and specifications. In this article, our focus is on noncontractible quality aspects.

As a generic example for noncontractible but observable quality, consider a hard-drive OEM that uses a CM for a new model. After the OEM markets the hard-drive, the consumers, as well as the OEM, observe that the hard-drive makes an occasional clicking noise because of head-positioning, but otherwise functions perfectly. The CM could have eliminated this problem by exerting more effort to improve quality. Because of noise sensitive consumers, this defect affects the market demand for the hard-drive. The OEM might not have foreseen this possibility and, hence, may not mention it in the contract (incomplete contract). Also, proving in court that this noise is excessive may not be possible (unverifiable quality factor). Alternatively, the OEM might have anticipated the problem but chose to introduce this noisy hard-drive rather than being late to the market (time-to-market).

The second factor of quality risk is the CM’s private quality cost. We refer to the CM’s cost to achieve a desired quality level as the CM’s quality cost. The CM’s quality cost includes, for example, his investments in R&D, production technology, human resources, product design, and relationships with sub-tier suppliers. Differences in technical capabilities, efficiency, experience, connections with other firms, and organizational structure lead to different CM quality costs. The OEM may not know the CM’s quality cost because the quality cost components are difficult for outsiders to assess. For example, Sun and GM have teams to learn their suppliers’ cost structures [19]. Companies such as Technology Forecasters Inc. offer workshops to educate OEMs on CMs’ cost structures. Workshop director Charlie Barnhart mentions a gap between OEMs’ common beliefs and the CMs’ actual cost structures (http://www.techforecasters.com).

Note that it is not clear which of the two quality risk factors affects the system more. When does one quality risk factor play a more important role than the other? When should an OEM pay more attention to these quality risk factors? The outsourcing trend enables the OEM to focus on brand management and pricing, whereas the CM is responsible for manufacturing and setting the quality level of the final product. In this outsourcing relationship, what is the impact of the OEM’s pricing strategy on the resulting quality and profits? Intuitively, the CM’s return on his costly effort to achieve a desired quality level is less than a vertically integrated firm’s return. When the OEM sets the sales price for the product, she can perhaps reap the benefit of the CM’s quality investment. As a result, the CM would be reluctant to exert quality effort. This creates a tension between the CM and the OEM because the OEM cannot enforce her desired quality level. Private CM quality cost further aggravates this tension because the cost uncertainty makes it difficult for the OEM to provide incentives to induce high quality. Hence, outsourcing may result in poor product quality and low channel profit. In this article, in addition to identifying the quality risk factors, we also quantify their impact on profits and product quality. We identify the market characteristics under which these two factors are most relevant and design contracts to mitigate their adverse effects.

The software development industry is one example that entails significant quality risk due to outsourcing. Most software outsourcing projects are custom. Quality is generally unverifiable in a court because software is often perceived as a service rather than a good [37]. Quality-related costs, such as the cost to hire better engineers, the cost to test the product, and the cost of time allocated to the project are hard to observe by outside parties. If the software developer does not provide good quality, software bugs that are not observable in tests may cause trouble later during the execution of the software. Another example illustrating how an OEM depends on her CM for quality is from the pharmaceutical industry. Pan Pharmaceuticals was the world’s fifth largest CM of vitamins and health supplements. The Australian government suspended the firm’s license to produce medicines for 6 months because of a quality failure [14]. As a result, OEMs that outsourced production to Pan Pharmaceuticals faced costly consequences due to product recalls [1]. In this article, we provide a framework that can help quantify how the two quality risk factors may have affected these companies.

We also use our model and analysis to understand the impact of new information technologies on profits and product quality. For example, outsourcing necessitates OEMs to use cross-border enterprise management systems. Realizing the importance of quality management within and across the company borders, management information system providers, such as MetricStream, started to develop enterprise quality and compliance management systems. Gunjan Sinha, the chairman of MetricStream, envisions enterprise quality management systems to be as common as the ERP systems, such as SAP and Oracle, of the 90s (www.metricstream.com). A quality management system enables the OEM to collect, track, and account for quality related costs and activities, also revealing CM-specific quality costs. Documenting quality-related activities and developing necessary accounting ledgers may enable the OEM and the CM to contract on quality. On the basis of our analysis, we provide some insights on the value of such quality management systems.

Finally, we study how the OEM’s product-pricing strategy affects profits and product quality. In our correspondence with executives from the semiconductor and telecommunications industries, we observed two opposing product-pricing strategies. The semiconductor executive advocated setting the sales price for the product after receiving the products from...
the CM. The telecom executive advocated setting the sales price before the CM actually started to produce, that is, he commits to a final sales price in his contract terms with the CM. We compare the effects of these two pricing strategies on quality risk. To do so, we first study the supply chain in which the OEM sets the sales price for her product after observing the product’s quality. Next, we conduct a parallel study in which the OEM commits to the sales price in the contract with the CM before observing the product’s quality. We compare the effects of the quality risk factors under these two pricing strategies. Table 2 summarizes our findings.

2. LITERATURE REVIEW

Quality and quality cost both have various definitions. Our definition of quality is “the product attributes for which consumers prefer more to less”. This definition is similar to the user-based definition in Garvin’s [16] classification. According to this definition, quality is related to customer satisfaction and fitness for intended use. Our CM quality cost definition includes the prevention costs (those incurred to prevent quality problems, such as training and preventive maintenance costs) and the appraisal costs (monitoring and inspection costs) in Crosby’s [11] classification. Because the CM in our model provides design and sourcing services, our quality cost definition also includes costs associated with performance quality [15]. Performance quality is related to the functioning and physical characteristics of the product to satisfy customer expectations.

Majority of quality and supply chain management related research focuses on the interaction between a supplier’s quality provision effort and a buyer’s inspection effort. Examples include Reyniers and Tapiero [28, 29], Tagaras and Lee [33], Baiman et al. [4], Lim [24], and Sheopuri and Zemel (manuscript in preparation). These authors consider a manufacturing-based quality definition. They define a high probability of producing nondefective items as good quality. They consider a variety of schemes to induce high manufacturing-based quality. Our focus is on quality aspects that affect the consumer demand in the market, such as satisfaction and fitness for intended use. We consider a consumer demand function that is increasing in the quality level and decreasing in the sales price. The aforementioned authors do not consider market demand functions. Hence, they do not capture how the supply chain partners’ interaction affect the resulting product quality and price both of which affect consumer demand and profits.

Another group of researchers study outsourcing relationships between OEMs and CMs. For example, Gray, Roth and Tomlin (manuscript, in preparation) provide empirical evidence that unobservability of quality risk causes the CM to shirk on quality. The authors develop a metric of quality risk based on data from the drug industry. Amaral et al. [2] discuss the risks involved in outsourcing strategic functions to CMs. The authors propose strategies for outsourcing the procurement function to CMs. Plambeck and Taylor [27] study the trade-off between pooling and the incentive to innovate when manufacturing takes place at the CM and innovation takes place at the OEM. See also Ulkii et al. [36] Gray et al. [13] and the references therein.

Our article also complements research related to sales-effort models in which the downstream firm exerts effort to increase demand. Examples include Taylor [34], Krishnan et al. [20], and Chen [8]. In sales-effort models, the agent is located downstream in the chain and the principal cannot observe the agent’s effort; hence, she cannot act on it. In our model, the upstream firm, i.e., the CM, exerts demand-enhancing quality effort. The OEM can observe the agent CM’s quality provision and can determine the sales price accordingly. This sequence differentiates the quality-effort concept from the sales-effort models. To highlight this difference, one can refer to this class of models as quality-effort models.

The article also contributes to the principal-agent literature by considering the interactions between three factors in an OEM-CM relationship regarding quality: (1) noncontractible quality (moral hazard), (2) CM’s private quality cost (asymmetric information), (3) OEM’s end-product pricing strategy. The first two factors result in quality risk. A group of researchers study the effect of private production cost information on firms’ profits. Examples include Ha [18] and Corbett et al. [10]. Chen [7] provides a comprehensive review of this research stream from the operations management literature. Another group of researchers study combinations of the aforementioned factors, albeit not all three together [9, 17, 21, 23, 30]. By modeling and studying the three factors simultaneously, we quantify their joint effects on profits and resulting product quality. We also determine when one factor affects profits and quality more than the others. Doing so enables us to recommend effective policies to mitigate quality risk, and to provide insight on the value of recent quality management systems. Given today’s global supply chains, our hope is that these results will also contribute to the general understanding of the effect of outsourcing and thereby bring us one step closer to building more efficient supply chains.

The rest of this article is organized as follows. In Section 3, we describe the model and solve two benchmark scenarios. In Section 4, we study a scenario in which the OEM does not commit to a sales price in the contract with the CM. We consider symmetric information (in Section 4.1) and asymmetric information cases (in Section 4.2) with respect to the CM’s quality cost information. In Section 5, we study a scenario in which the OEM commits to a sales price in the contract. In Section 6, we compare the results in the no-commitment
3. THE MODEL

We consider an OEM (she) that outsources functional areas, such as design, procurement, and manufacturing to a CM (he). We use the following linear demand function \[ q = a - bp + e + \epsilon \] to model the market demand for the product:

The demand parameters \( a > 0 \) and \( b > 0 \) are common knowledge. Behind this assumption is the notion that both the OEM and the CM obtain the demand forecast from a third party market research firm, such as Gartner/Dataquest. The OEM sets the sales price \( p \), whereas the CM determines the quality level \( e \) for the product. Because of general demand uncertainty, demand experiences a market shock \( \epsilon \) with zero mean. We denote the expected market demand as \( \bar{q} \equiv E[q] \).

Note that quality is modeled as an attribute that increases demand at every sales price. The quality level \( e \) captures the product quality that is determined by the CM and that is noncontractible.

We consider two scenarios depending on whether the OEM commits to a sales price in her contract. Figure 1 summarizes the sequence of events for the first scenario, which we refer to as the no-commitment scenario. Under this scenario, the OEM offers a two-part tariff with a per unit payment \( w \) and a lump-sum transfer payment \( t \). The CM accepts the offer if his expected profit is higher than his outside opportunities, i.e., his reservation profit. Next, the CM determines the product’s quality level \( e \) by exerting costly quality effort. The OEM observes the quality level, determines the sales price \( p \) to maximize her expected profit, and introduces the product to the market. The market shock \( \epsilon \) is realized, and the firms observe market demand. The CM produces to satisfy the market demand.

The sequence of events for the second scenario, which we refer to as the commitment scenario, is similar. The main difference from the no-commitment scenario is that at stage 1, in addition to \( w \) and \( t \) the OEM determines a sales price \( p \) before observing the quality level, and commits to sell the product to consumers at this price.

Note that the OEM cannot link the compensation of the CM to the quality level because quality is noncontractible. In addition, because of the existence of the market shock \( \epsilon \), the OEM cannot verify the quality level \( e \) through the realized demand. Industries such as semiconductor equipment manufacturing and electrical generator manufacturing follow this outsourcing, make-to-order sequence [32].

The expected profits are given as follows

\[
\Pi^{\text{OEM}} = (p - w)E[q] - t, \quad (2)
\]

\[
\Pi^{\text{CM}} = (w - c)E[q] - \frac{ke^2}{4} + t, \quad (3)
\]

where \( c \) is the CM’s unit production cost. The term \( \frac{ke^2}{4} \) is the quality cost, i.e., the cost of providing quality level \( e \) and \( k \) is the quality cost parameter. The quadratic form implies increasing marginal cost of quality level. Division by 4 is for notational ease in subsequent analysis. This approach is similar to Chen [8] who uses \( e^2/2 \) to model the cost of effort. The focus of this study is on industries where quality costs are of a lump-sum variety. For example, in the software and pharmaceutical industries, costs related to providing a high quality software or medicine are mainly incurred during the research and development phase. In such industries, the effect of product quality on the unit production cost is relatively small and well known.

3.1. The Road Map

Figure 2 summarizes all cases and comparisons considered in this article. First, we study two benchmarks—integrated firm and contractible quality. The first benchmark results are obtained by studying the integrated firm that owns both the OEM and the CM. The second benchmark results are obtained by studying the OEM and the CM as two distinct firms that can contract on quality. Next, we consider two broad scenarios. The first one is the no-commitment scenario in which the OEM sets the sales price after observing
the CM’s quality provision. The second one is the commitment scenario in which the OEM commits to the sales price before observing the CM’s quality provision. Within both of these broad scenarios, we consider two cases depending on whether the OEM knows the CM’s quality cost information: the symmetric and asymmetric quality cost information cases. We study and compare the outcomes of all these scenarios to quantify the impact of outsourcing on product quality and profits; i.e., the effects of the two quality risk factors—noncontractible quality and private quality cost information. We also determine how committing to a sales price affects the two quality risk factors.

3.2. Integrated Firm

The integrated firm case can be interpreted as the OEM’s alternative of in-house production. The integrated firm determines the product quality and the sales price. Then, the market shock $\epsilon$ is realized, and the firm produces to meet demand. The objective is

$$\Pi_I = \max_{e,p} (p - c)E[q] - \frac{ke^2}{4}. \quad (4)$$

This function is jointly concave in quality level and sales price. Thus, the firm may determine quality level and sales price in any order. The following lemma summarizes the results, where subscript $I$ denotes the optimal values for the integrated firm. We defer all proofs and auxiliary results to the appendix and present the main results here.

**LEMMA 1:** The results for the integrated firm’s problem are as follows: (a) Sales price $p_I = \frac{ak}{bk - 1}$; (b) Quality level $e_I = \frac{c - bc}{ak}$; (c) Expected market demand $q_I = \frac{bk(a - bc)}{2(bk - 1)}$; (d) Expected firm profit $\Pi_I = \frac{ka - bc}{4(bk - 1)}$.

The rest of this article discusses outsourcing scenarios with an independent CM and OEM.

3.3. Contractible Quality

If the OEM can specify a quality level in the contract and enforce it, then her objective is

$$\max_{e,p,t,w} (p - w)E[q] - t$$

subject to $$(w - c)E[q] - \frac{ke^2}{4} + t \geq \Pi_{CM}^R. \quad (6)$$

The constraint assures that the CM’s expected profit is at least his reservation profit $\Pi_{CM}^R$.

**PROPOSITION 1:** If the quality level $e$ is contractible, then the OEM can achieve the integrated firm results given in Lemma 1 by offering a per-unit payment $w$ and a corresponding lump-sum payment $t = \Pi_{CM}^R + \frac{(w - c)bk(a - bc)}{2(bk - 1)} + \frac{ka - bc}{4(bk - 1)}$ to the CM in exchange for the quality level $e_I$ of Lemma 1(b). The CM’s expected profit is $\Pi_{CM}^R$ and the OEM’s expected profit is $\Pi_I - \Pi_{CM}^R$.

Proposition 1 characterizes the optimal contract terms and shows that when quality level is contractible, the channel does not lose efficiency due to outsourcing. The OEM is effectively the only decision maker. Hence, she can squeeze out all channel profits and leave the CM with just enough profit to ensure
his participation. We remark that when quality is contractible, whether the OEM commits to a sales price or not is irrelevant because the CM does not make any decision. We also note that we will not study the asymmetric cost information when the quality is contractible. This case is similar to the classical mechanism design problem and does not yield additional insights. Our focus is on the noncontractible quality scenario, for which Section 3.3 serves as a benchmark.

4. NO COMMITMENT TO SALES PRICE

In this section, we consider an OEM that does not commit to a sales price in her contract with the CM. Instead, the OEM sets the sales price after observing the CM’s quality provision. First, we analyze the symmetric quality cost information case in which the OEM knows the CM’s quality cost followed by the asymmetric information case.

4.1. Symmetric Quality Cost Information

Recall from Fig. 1 that we model the relationship between the OEM and the CM as a three-stage game. The following proposition characterizes the OEM’s optimal lump-sum payment to adjust the division of total channel profit.

Having solved stages 3 and 2, we consider stage 1 at which the OEM determines the contract parameters \( w \) and \( t \) by solving:

\[
\begin{align*}
\max_{w,t} \quad & (p - w)\bar{q} - t \\
\text{subject to} \quad & (w - c)\bar{q} - \frac{ke^2}{4} + t \geq \Pi_{CM}^R \\
& (CM’s \ participation \ constraint).
\end{align*}
\]

The following proposition characterizes the OEM’s optimal two-part contract and provides the resulting optimal values as functions of the quality cost parameter \( k \).

PROPOSITION 3: When the OEM does not commit to a sales price in the contract, the OEM’s optimal two-part contract \( (w^*, t^*) \) under symmetric information is such that

\[
\begin{align*}
(a) & \quad w^* = \frac{ak + (b - c)k - 1}{k} \quad \text{decreasing in } k; \\
(b) & \quad t^* = \Pi_{CM}^R - \frac{k(a - bc - k^2)}{4M^2} \quad \text{increasing in } k, \text{where } M = b^2k^2 + bk - 1. \\
\end{align*}
\]

The CM accepts the contract. The resulting optimal values are (c) \( e^* = \frac{a - bc}{w^*} > 0 \), decreasing in \( k \); (d) \( p^* = \frac{ak(bk + 2c - c^2)}{2M} \), decreasing in \( k \); (e) \( \bar{q}^* = \frac{b^2k^2(a - bc)}{3M} \), decreasing in \( k \); for \( 1 < bk < 2 \) and increasing in \( k \) for \( bk > 2 \); (f) The OEM’s optimal profit \( \Pi_{OEM}^R = \frac{ka^2(bk + 2c - c^2)}{4M^2} - \Pi_{CM}^R \) is decreasing in \( k \); (g) The CM’s optimal profit \( \Pi_{CM}^R = \Pi_{CM}^R \).

The proposition characterizes the optimal contract terms, the resulting profits and product quality. In summary, a high quality cost decreases the OEM’s profit and causes the end consumers to receive a lower quality product. This is primarily because the OEM optimally offers a low per-unit payment to the CM knowing that the return on quality will be low. Specifically, when the cost of quality is high, the CM sets a lower quality level for the same per-unit payment. Not surprisingly, product quality, sales price, expected market demand, and the OEM’s expected profit are reduced with high quality cost. Despite the decrease in both the per-unit payment and the expected market demand, the CM’s expected profit remains at \( \Pi_{CM}^R \) because the OEM offers a larger lump-sum payment to ensure the CM’s participation.

More importantly, the proposition enables us to quantify the impact of quality cost. Note that in practice the CM can reduce his quality cost by investing in new technologies. He can, for example, differentiate himself as a design house and attract talent at a lower cost. Alternatively, the OEM can help

\[\text{LEMMA 2: When the OEM does not commit to a sales price in the contract, the optimal values as functions of the per-unit payment } w \text{ are (a) } e^*(w) = \frac{w - c}{w (1 - b)}; \quad (b) \quad \bar{q}^*(w) = \frac{1}{2}(a - \frac{c}{w} + w(1 - b)); \quad (c) \quad p^*(w) = \frac{1}{2b}(a - \frac{c}{w} + w(1 + b)); \quad (d) \quad \Pi_{OEM}^R(w) = \frac{1}{2b}(a - \frac{c}{w} + w(1 - b))^2 - t; \quad (e) \quad \Pi_{CM}^R(w) = \frac{1}{2}(a - \frac{c}{w} + w(1 - b))(w - c) - \frac{(w - c)^2}{4k} + t.
\]

We note the pivotal role of the per-unit payment \( w \). The OEM can increase the per-unit payment as an incentive to the CM to set a high quality level. In contrast, she uses the
the CM establish quality management programs. The proposition can be used to quantify how such activities impact resulting profit and product quality when the cost of quality is known to both parties.

Next, we characterize the effects of the first quality risk factor, noncontractible quality, by comparing Propositions 1 and 3. From Proposition 1, we know that contractible quality benchmark results are the same as the integrated firm benchmark results given in Lemma 1. Thus, to find the effects of noncontractible quality, we compare Lemma 1 with Proposition 3. This comparison reveals that inability to contract on quality leads to lower product quality, expected total channel profit, expected profit for the OEM, sales price, and expected market demand.

The reason for the inefficiency is an incentive misalignment due to the OEM’s timing of the pricing decision. Essentially, the OEM charges a sales price that is higher than the per-unit payment to the CM when she sets the market price after observing the CM’s quality effort. In particular, the CM considers only his own profit margin while setting the quality level, and the OEM considers only her own margin while setting the sales price. The CM knows that he will not be able to capture the full benefit of his quality investment, because the OEM will set the sales price to maximize her own profit after observing the quality level. Thus, the CM sets a lower quality level than the channel optimal, resulting in lower OEM profit.

In some cases, the firms may partially contract on quality at the cost of writing a comprehensive contract, conducting extensive testing and losing valuable time. The following proposition provides an upper bound on the value of such activities. The proposition also quantifies the effect of contractibility on product quality can be obtained similarly.

PROPOSITION 4: When the OEM does not commit to a sales price in the contract, the value of being able to contract on the quality level to the OEM is $(\Pi_{CM}^R - \Pi_{CM}^M) = \Pi_{OM}^M = \frac{(a-c)k^2}{4bk-1} > 0$. This value is decreasing in $k$.

4.2. Asymmetric Quality Cost Information

Here, we address the inefficiency due to private CM quality cost, the second factor of quality risk. To do so, we study the case in which quality is noncontractible and quality cost is the CM’s private information. Consider a CM that can be of two types with respect to quality cost: a low-quality-cost CM with quality cost parameter $k_L$ and a high-quality-cost CM with parameter $k_H > k_L$. The belief is such that the CM has high quality cost with probability $\pi$ and low quality cost with $1 - \pi$.

We define a new function to facilitate the analysis. Using Lemma 2(e), we write the CM’s expected profit as functions of the contract parameters, i.e., $\Pi_{CM}^R = v(w, k) + t$ where

$$v(w, k) = \begin{cases} \Pi_{CM}^R, & w = 0 \text{ if the CM rejects} \\ \frac{1}{2} \left( a - c + w \left( \frac{1}{k} - b \right) \right) (w - \epsilon) - \frac{w^2 - \epsilon^2}{4c}, & w > \epsilon \text{ if the CM accepts}. \end{cases}$$

The function $v(w, k)$ summarizes the effects of the per-unit payment $w$ and the quality cost parameter $k$ on the CM’s profit at stages 2 and 3. The following lemma describes an important property of the $v(w, k)$ function that we use in the analysis.

LEMMA 3: The function $v(w, k)$ has decreasing differences in $k$, that is, $v(w_1, k) - v(w_2, k)$ is strictly decreasing in $k$ for all $w_1 > w_2 > c$. Thus, a low-quality-cost CM values an increase in the per-unit payment $w$ more than a high quality cost CM does.

Before offering a contract, the OEM can presumably ask the CM to report his quality cost and next she can offer the contract characterized in the previous section. However, if the OEM asks the CM for his quality cost report, a low-quality-cost CM has an incentive to report high quality cost. Therefore, the information would not be considered credible. Hence, the OEM needs to design a mechanism to credibly obtain the quality cost information while maximizing her profit. Specifically, the OEM can maximize her profit by designing a menu of contracts. According to the revelation principle [26], to find the optimal menu of contracts $\langle (w_L^0, t_L^0), (w_H^0, t_H^0) \rangle$, the OEM can restrict her attention to the class of truth-telling mechanisms. The OEM solves the following problem.

$^6$ To observe this outcome, note that Lemma 3 implies $v(w_L^0, k_L) > v(0, k_L) > v(w_H^0, k_L) = v(0, k_H)$. Adding $t_H^0$ to both sides, we obtain $v(w_L^0, k_L) + t_H^0 > v(w_H^0, k_L) + t_H^0 = 0$. The right-hand side of this inequality is a high-quality-cost CM’s rent under symmetric quality cost information, which is equal to zero from Proposition 3(g). The left-hand side is the rent of a low-quality-cost CM who reports high quality cost. Because this rent is positive, a low-quality-cost CM has an incentive to exaggerate his quality cost.
The individual rationality constraints $IR_L$ and $IR_H$ ensure that both CM types participate in trade. The incentive compatibility constraints $IC_{LH}$ and $IC_{HL}$ ensure that the CM chooses the contract intended for his type. Note that the function $v(w, k)$ allows us to cast the problem in the well-known mechanism design format by embedding the effects of stages 2 and 3 on the CM’s profit. This function significantly improves the tractability of the three-stage model.

When choosing a contract at stage 1, the CM considers the quality level he will set at stage 2 and the sales price of the OEM will set at stage 3. Hence, the contract menu the OEM prepares at stage 1 determines the solution of all three stages. The proposition below presents the OEM’s optimal contract menu and the resulting optimal values at stages 2 and 3. The proposition also compares the results in this asymmetric information scenario with the results in the symmetric information scenario from Proposition 3.

**PROPOSITION 5:** When the OEM does not commit to a sales price in the contract, under asymmetric quality cost information, a low-quality-cost CM optimally chooses the contract $(w_{L}^{q}, t_{L}^{q})$ where the per-unit payment is not distorted (that is, $w_{L}^{q} = w_{H}^{q}$). A high-quality-cost CM optimally chooses the contract $(w_{H}^{q}, t_{H}^{q})$ where the per-unit payment is distorted downward (that is, $w_{H}^{q} < w_{H}^{q}$). The contract parameters satisfy

$$w_{L}^{q} = \frac{a_1 k_{L} + c (b_{2} k_{L}^2 - 1)}{b_{2} k_{L}^2 + b_{L} - 1};$$

$$w_{H}^{q} = \frac{(a_{H} - b_{2} c_{H} k_{L}) + c A}{(b_{2} k_{L}^2 + b_{H} - 1) + A};$$

$$t_{L}^{q} = \frac{(a + b_{2} c_{H} k_{L} - b_{2} k_{L}^2 - 1)}{4 (b_{2} k_{L}^2 + b_{L} - 1)^2} + \frac{k_{H} (a - b_{2} c_{H})^2}{4 (b_{2} k_{L}^2 + b_{H} - 1 + A)^2} \left(\frac{k_{H} - k_{L}}{k_{L}}\right);$$

$$t_{H}^{q} = \frac{(a - b_{2} c_{H} k_{L} - b_{2} k_{L}^2 + 2 A - 1)}{4 (b_{2} k_{L}^2 + b_{H} - 1 + A)^2},$$

where $A = \left(\frac{1 - \pi}{2}\right) b_{L} k_{L} (k_{L} - 1)$. The results at stages 2 and 3, and their comparisons with the symmetric quality cost information results are as follows.

**Proposition 5** summarizes the effects of private CM quality cost, the second factor of quality risk. The results are consistent with the classical mechanism design results. When the CM has low quality cost, the only difference from the symmetric information scenario results is the information rent that the CM obtains. To reduce this rent, the OEM distorts the high-quality-cost CM’s per-unit payment $w_{H}^{q}$ downward. The high-quality-cost CM responds with a lower quality product, causing a reduction in the OEM’s expected profit.

Note that the OEM sacrifices a rent to a low-quality-cost CM just because she considers doing business with a high-quality-cost CM as well. One may question whether the OEM should always aim to conduct business with both CM types. In fact, the OEM is better off by not doing business with a high-quality-cost CM when $(1 - \pi) \Pi_{L}^{CM} > \Pi_{H}^{OEM}$ holds. The term $(1 - \pi) \Pi_{L}^{CM}$ denotes the OEM’s expected profit when she offers a single contract that only a low-quality-cost CM accepts. In other words, the OEM resolves information asymmetry by not doing business with a high-quality-cost CM.

**COROLLARY 1:** When the OEM does not commit to a sales price in the contract, if the CM’s reservation profit level $\Pi_{R}^{CM}$ is above a threshold $\Pi_{R}^{CM} > 0$, then the OEM is better off by not doing business with a high-quality-cost CM.

In some cases, the OEM may acquire information on the CM’s quality cost by conducting costly activities, such as auditing or receiving expert help. The following proposition provides an upper bound on the value of such activities. The proposition quantifies the effect of the second quality risk factor on the OEM’s profit for the no-commitment scenarios.

**PROPOSITION 6:** When the OEM does not commit to a sales price in the contract, the value of information on the CM’s quality cost to the OEM is $\Pi_{L}^{OEM} - \Pi_{H}^{OEM} = \frac{(a_{H} - b_{2} c_{H})^2 k_{H} (a_{H} - k_{L}) (1 - \pi)}{4 (b_{2} k_{L}^2 + b_{H} - 1)^3} \left(\frac{k_{H} - k_{L}}{k_{L}}\right) > 0$.

4.3. **Comparing the Effects of the Quality Risk Factors**

Next, we compare the effects of the two quality risk factors. To this end, we compare the value of contracting on
quality (Proposition 4), with the value of information on the CM’s quality cost (Proposition 6). Figures 3a and 3b illustrate the comparison as functions of $k_L$ and $\pi$, respectively. We observe that the value of contracting is significantly greater than the value of information (note the scale difference between the left and right y axes). Table 1 illustrates the ratio $(\Pi_{OEM}^f - \Pi_{OEM}^s)/(\Pi_{OEM}^f - \Pi_{OEM}^p)$ with other parameter combinations. The reason behind the relatively low value of information is the mitigating effect of the OEM’s pricing power. The OEM can adjust the sales price at stage 3 after observing the CM’s quality provision. As a result, not knowing the CM’s quality cost does not cause a large reduction in the OEM’s profit. Thus, the first factor of quality risk (noncontractible quality) is significantly more important than the second factor (private CM quality cost) when the OEM sets the price of the product after observing quality.

5. COMMITMENT TO SALES PRICE

In this section, we consider an OEM that commits to a sales price in her contract before the CM sets product quality. Under this price commitment scenario, we study both the symmetric and asymmetric quality cost information cases. We compare the results to quantify the effects of the two quality risk factors when the OEM commits to a sales price. We also compare the results to those with the no-commitment scenario to explore how the OEM’s price commitment strategy interacts with the effects of the quality risk factors. Intuitively, pricing the product after observing the CM’s quality provision (i.e., no-commitment) should be an advantage for the OEM. This is because the OEM can then better stimulate demand by adjusting the sales price in accordance with the quality level she observes. However, as we will show, this intuition turns out to be wrong under both symmetric and asymmetric quality cost information.

5.1. Symmetric Quality Cost Information

First, we solve the OEM’s problem given a sales price that she commits to.

PROPOSITION 7: When the OEM commits to an exogenously given sales price $p$ in the contract, the OEM’s optimal two-part contract $(w^P, t^P)$ under symmetric information is
such that (a) \( w^p = p \); (b) \( r^p = \Pi_{CM}^R - (a - bp)(p - c) - \frac{(p-c)^2}{k} \). The CM accepts the contract. The resulting optimal values are (c) \( e^p = \frac{2(p-c)}{k} \); (d) \( q^p = a - bp + \frac{2(p-c)}{k} \); (e) \( \Pi_{OEM}^p = (a-bp)(p-c) - \frac{(p-c)^2}{k} - \Pi_{CM}^R \); (f) \( \Pi_{R}^{CM} = \Pi_{R}^{CM} \).

This proposition provides the solution for a supply chain in which the sales price is exogenously given as \( p \), rather than determined by the OEM. This situation may arise for a commodity product, for which the sales price is set by the market. Our primary focus is a supply chain in which the OEM sets the sales price. This scenario may arise for a custom product sold exclusively by the OEM. Next, we determine the OEM’s optimal sales price and profit.

PROPOSITION 8: When the OEM sets her optimal sales price under symmetric information, she commits to the integrated firm’s optimal sales price; that is, \( p^{ac} = p^I = \frac{ak+1+bk-2c}{4(k+1)} \). The OEM also sets \( w^{ac} = p^{ac} \). The CM’s expected profit is \( \Pi_{CM}^R \). The OEM’s expected profit is \( \Pi_{OEM}^p = \Pi^I - \Pi_{CM}^R = \frac{(a-bc)^2}{4(6k-1)} - \Pi_{CM}^R \). The profit values satisfy \( \Pi_{OEM}^p > \Pi_{OEM}^I \), where \( \Pi_{OEM}^I \) is the OEM’s profit in the no-commitment scenario.

This result is counterintuitive at first, because the OEM appears to give away the advantage of adjusting the sales price \( p \) after observing the quality level that the CM provides. However, when the OEM knows the CM’s quality cost, she can foresee the CM’s quality level selection as \( e = \frac{w^{ac}}{p} \) [from Proposition 2(b)]. She does not need to observe the quality level. By setting the per-unit payment equal to the sales price in the market (i.e., \( w^{ac} = p^{ac} \)), the OEM leaves the whole profit margin to the CM. The lump-sum payment in this case is negative, i.e., it is from the CM to the OEM. Hence, the OEM is selling the business to the CM. Alternatively, the OEM is selling the license, which is the right to produce and sell the OEM’s product, to the CM. The CM uses the OEM’s brand, but otherwise owns the business. When the OEM offers the CM the full profit margin, the CM acts as the integrated firm, eliminating the incentive misalignment problem. Thus, noncontractual quality, the first factor of quality risk, does not cause inefficiency when the OEM commits to a sales price in the contract. The following proposition formalizes this result.

PROPOSITION 9: When the OEM commits to the optimal sales price in the contract, the value of being able to contract on the quality level to the OEM is \( (\Pi^I - \Pi_{CM}^R) - \Pi_{OEM}^p = 0 \).

It is well known in principal-agent theory that a principal can obtain the first-best outcome by leaving the whole profit margin to a risk neutral agent. Hence, the result in this section is somewhat expected. The real question is whether commitment to a sales price increases the OEM’s profit when the OEM does not know the CM’s quality cost. This question has not been addressed in the literature before and we explore it next.

5.2. Asymmetric Quality Cost Information

First, we solve the OEM’s problem given a sales price \( p \) under asymmetric quality cost information, a low-quality-cost CM optimally chooses the contract \( (w_{L}^{ap}, r_{L}^{ap}) \) where the per-unit payment is not distorted (that is, \( w_{L}^{ap} = w_{L}^{sp} \)). A high-quality-cost CM optimally chooses the contract \( (w_{H}^{ap}, r_{H}^{ap}) \) where the per-unit payment is distorted downward (that is, \( w_{H}^{ap} < w_{H}^{sp} \)). The contract parameters satisfy

\[
\begin{align*}
w_{L}^{ap} &= p; \quad w_{H}^{ap} = \frac{\pi k_L p + c(1 - \pi)(k_H - k_L)}{\pi k_L + (1 - \pi)(k_H - k_L)}; \\
\end{align*}
\]

\[
\begin{align*}
t_{L}^{ap} &= \frac{\pi k_L}{k_H} \frac{(p - c)^2 - \pi^2 k_L^2 (k_H - k_L)}{k_H (\pi k_L + (1 - \pi)(k_H - k_L))^2}; \\
\end{align*}
\]

\[
\begin{align*}
t_{H}^{ap} &= \frac{\pi k_L}{k_H} \frac{(p - c)^2 - \pi^2 k_L^2 (k_H - k_L)}{k_H (\pi k_L + (1 - \pi)(k_H - k_L))^2}.
\end{align*}
\]

The results at stages 2 and 3, and their comparisons with the symmetric quality cost information results are as follows.

<table>
<thead>
<tr>
<th>Low-quality-cost CM</th>
<th>High-quality-cost CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (L1) ) ( e_{L}^{ap} = e_{L}^{sp} )</td>
<td>( (H1) ) ( e_{H}^{ap} &lt; e_{H}^{sp} )</td>
</tr>
<tr>
<td>( (L2) ) ( \Pi_{CM}^{L} = \Pi_{CM}^{sp} )</td>
<td>( (H2) ) ( \Pi_{CM}^{H} = \Pi_{CM}^{sp} )</td>
</tr>
<tr>
<td>( \Pi_{CM}^{L} + (w_{L}^{sp} - c)^2 \left( \frac{1}{k_L} - \frac{1}{k_H} \right) )</td>
<td>( \Pi_{CM}^{H} = \Pi_{CM}^{sp} )</td>
</tr>
<tr>
<td>( (L3) ) ( \Pi_{OEM}^{L} = \Pi_{OEM}^{sp} )</td>
<td>( (H3) ) ( \Pi_{OEM}^{H} &lt; \Pi_{OEM}^{sp} )</td>
</tr>
<tr>
<td>( \Pi_{OEM}^{L} + (w_{L}^{sp} - c)^2 \left( \frac{1}{k_L} - \frac{1}{k_H} \right) )</td>
<td>( \Pi_{OEM}^{H} = \Pi_{OEM}^{sp} )</td>
</tr>
<tr>
<td>( (L4) ) ( q_{L}^{ap} = q_{L}^{sp} )</td>
<td>( (H4) ) ( q_{H}^{ap} &lt; q_{H}^{sp} )</td>
</tr>
</tbody>
</table>

Next, using Proposition 10 we determine the optimal sales price for the OEM to commit to. We also compare the OEM’s expected profit with and without price commitment.

PROPOSITION 11: When the OEM sets her optimal sales price and commits to it under asymmetric information, she optimally commits to \( p^{ac} = \frac{a+bc-2\theta}{2(b-\theta)} \), where

\[
\begin{align*}
\theta = \frac{\pi k_L + (1 - \pi)(k_H - k_L) + (1 - \pi)(k_H - k_L)}{k_H k_L + \pi k_L + (1 - \pi)(k_H - k_L)}. \\
\end{align*}
\]

The OEM’s expected profit with this sales price is \( \Pi_{OEM}^{sp} = \frac{(a-bc)}{2(b-\theta)} - \Pi_{CM}^R \). We have
Figure 4. The values of contracting and information in commitment scenarios when \( a = 10 \), \( b = 2 \), \( c = 1 \), \( k_H = 2k_L \), and \( \Pi_H^{CM} = 5 \). (a) As a function of \( k_L \), when \( \pi = 0.3 \). (b) As a function of \( \pi \), when \( k_L = 1 \). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

\[
\Pi_{OEM}^{*} > \Pi_{OEM}^{*}, \text{ where } \Pi_{OEM}^{*} \text{ is the OEM’s profit in the no-commitment scenario.}
\]

6. CAN PRICE COMMITMENT MITIGATE QUALITY RISK?

Here, we compare the effects of the quality risk factors with and without price commitment. Table 2 summarizes the comparison between the results. The results are based on analytical comparisons, which are also illustrated numerically in Figures 3 and 4.

Recall that the value of contracting is zero when the OEM commits to a sales price (Proposition 9). The OEM can achieve the contractible-quality scenario results by aligning the CM’s incentives with the integrated firm incentives in the commitment scenario. Hence, the value of contracting is higher when the OEM does not commit to sales price than when she does. Conversely, we have the following result regarding the value of information.

**Proposition 13:** The value of information, (i.e., value of knowing the CM’s quality cost) is higher for the OEM when she commits to a sales price in her contract than when she does not.

Table 2 also shows that the combined effect of the quality risk factors under the commitment scenario,
The results in this section also show that the OEM is more likely to commit to a sales price when noncontractible quality is the dominant quality risk factor. This may explain why the telecom executive preferred commitment (in the example we provide in the introduction); whereas, the semiconductor executive preferred pricing after observing quality (i.e., no-commitment). Perhaps, the telecom OEM is knowledgeable about her CM’s cost structure due to the close OEM-CM relations in this industry. Hence, private CM quality cost factor is less significant than the noncontractible quality factor, making commitment strategy more attractive.

Note that not committing to a sales price might allow the OEM to better react to changes in market conditions. For example, the OEM may receive better information about market demand by delaying the pricing decision. Our model ignores such advantages. If such information is available, our results could be considered as a possible upper bound on the value of commitment. Also, the OEM in our model commits to a single sales price before observing the quality level. One might consider an alternative in which the OEM commits to two separate sales prices, such that one price will be used if the CM is a high-quality-cost type and the other is to be used if the CM is a low-quality-cost type, which the OEM can tell from the quality level she observes. However, this alternative requires the quality level to be contractible. In addition, this alternative would preclude the OEM from making a price commitment to end consumers before the introduction of the product. Apple, for example, announced the price of its 4GB iPhone in January 2007 as $499, well before the introduction of the product in the US consumer market in June 2007 (http://www.apple.com/pr/library/2007/01/09iphone.html).

7. CONCLUSIONS

This article combines the moral hazard, information asymmetry, and product pricing dimensions of the quality problem in an OEM-CM relationship. Often, the literature assumes that an OEM and a CM can contract on quality. However,
as a CM undertakes more advanced responsibilities such as design and strategic sourcing, contracting on quality and knowing the cost of quality become difficult for an OEM. We determine the adverse effects of these two quality risk factors on profits and product quality. The way quality is defined, the issue of contracting on quality, and the three decision stages modeled are relevant for contemporary OEM-CM relations. Hence, the results of this article can be used to understand the impact of outsourcing. They may also help to understand the value of information technologies to better manage outsourcing relationships. Consider, for example, the recent enterprise-wide quality management systems (QMS) that enable the OEM to track quality-related activities across the supply chain. What is the value of such a system for an OEM?

The decision tree in Fig. 5 summarizes our recommendations to an OEM regarding QMS investment, based on the results of this article. In her decision, the OEM should consider whether quality is contractible, whether she knows the CM’s quality cost, whether she can price the product in the consumer market, and whether she can commit to a sales price in the contract (when she can price the product). For example, the OEM does not need to invest in such a system when (i) the market determines the price of the product, or the OEM can commit to a sales price in the contract (when she can price the product). For example, the OEM does not need to invest in such a system when (i) the market determines the price of the product, or the OEM can commit to a sales price in the contract (when she can price the product). For example, the OEM does not need to invest in such a system when (i) the market determines the price of the product, or the OEM can commit to a sales price in the contract (when she can price the product). For example, the OEM does not need to invest in such a system when (i) the market determines the price of the product, or the OEM can commit to a sales price in the contract (when she can price the product). For example, the OEM does not need to invest in such a system when (i) the market determines the price of the product, or the OEM can commit to a sales price in the contract (when she can price the product). For example, the OEM does not need to invest in such a system when (i) the market determines the price of the product, or the OEM can commit to a sales price in the contract (when she can price the product).

These two conditions are likely to be satisfied for a commodity (standard) product. If, however, the OEM is outsourcing a custom product for which she can set the sales price (and for which she cannot commit to a sales price in the contract), she cannot eliminate quality risk. Instead, the OEM should probably invest in a quality management system.

Quality risk in OEM-CM relationships offers a fertile avenue for future research. For example, some of our assumptions, such as the specific form of quadratic quality cost, can be generalized at the expense of losing some of the closed-form solutions. These assumptions are common in the literature and enable us to derive closed-form results while solving the three-stage model with backward induction. A more interesting research direction, however, is to investigate the impact of different contract forms, such as quantity discounts and rebates on the quality risk factors. Another one is to study the impact of CMs’ growing power in certain industries. To model this change, one may analyze a relationship in which the CM offers the contract. Also, a CM may pool production for several OEMs. Studying a scenario in which (possibly) competing OEMs use the same CM would be promising. Finally, empirical investigation of the quality risk factors discussed in this article is also a promising research direction. Given the outsourcing trend in today’s global supply chains, we predict that the quality risk concept will become increasingly important and will require additional research in related issues.
ACKNOWLEDGMENTS

The authors thank the anonymous associate editor, the referees, and the participants of the May 2004 CORS/INFORMS Joint International Meeting in Banff session TA07, October 2004 INFORMS Annual Meeting in Denver session MD39, June 2005 MSOM Conference in Chicago session TA6, the seminars at Stanford University, University of Michigan-Ann Arbor, HP Laboratories for their helpful comments and suggestions. They also thank Francis Courreges, SVP of Operations at Cypress Semiconductor Corp, and Gunjan Sinha, the Chairman of MetricStream, for discussions on issues related to quality management.

APPENDIX: PROOFS

For ease of reference, we state two assumptions:

ASSUMPTION 1: \( a - bc > 0 \) holds.

The expected market demand \( \bar{q} = a - bp \) is positive only when \( a - bc > 0 \), because \( p > c \).

ASSUMPTION 2: \( bk > 1 \) holds.

The assumption ensures that when price sensitivity \( b \) is low, the cost of quality should be high enough (high \( k \)) to prevent the firm from setting an infinite quality level \( e \) and making infinite profit.

PROOF OF LEMMA 1: The Hessian of the objective function in (4) is

\[
\begin{pmatrix}
-k/2 & 1 \\
1 & -2b
\end{pmatrix}
\]

The Hessian is negative definite (because the leading principal minors satisfy \(-k/2 < 0\) and \(bk - 1 > 0\) from Assumption 2), and thus, the objective function is jointly concave in \( p \) and \( e \). Simultaneous maximization gives \( \bar{p}_1 = \frac{a + (bk - 1)}{2bk - 1} \) and \( \bar{e}_1 = \frac{k - \bar{q}}{bk} \). We find \( \bar{q} \) and \( \Pi_t \) by substituting \( p_1 \) and \( e_1 \) into Eqs. (1) and (4).

PROOF OF PROPOSITION 1: The OEM can increase her expected profit given in the objective function (5) by decreasing \( t \) until constraint in (6) holds. Thus, she sets

\[
t = \Pi_t^{CM} + \bar{q}(w - c) + \frac{ke^2}{4} \tag{A1}
\]

Substituting \( t \), the objective function becomes \( \max_{c,e} \bar{q}(p-c)-\frac{ke^2}{4} - \Pi_t^{CM} \). The objective is equivalent to the objective of the integrated firm problem in (4). Thus, the OEM achieves the integrated firm solution. Note that \( w \) vanishes from the objective. For any \( w \) the OEM chooses, there is a corresponding \( t \) given in Eq. (A1). We find \( t \) by substituting \( \bar{e}_1 \) and \( \bar{q} \) from Lemma 1 into Eq. (A1). From the binding constraint in (6), the CM’s profit is \( \Pi_t^{CM} \), whereas the OEM obtains the rest of the integrated firm profit \( \Pi_t = \Pi_t^{CM} \).

PROOF OF PROPOSITION 2: At stage 3, the OEM chooses a sales price \( p^* \) to maximize her expected profit \( \Pi_t^{OEM} = (p-w)(a-bp+e) - t \). This function is concave in \( p \) and it is maximized at \( p^* = \frac{aw+be-\bar{q}^2}{2aw} \), for which we find \( \bar{q}^2 = \frac{aw+be-\Pi_t^{CM}}{aw} \) from Eq. (1). At stage 2, the CM anticipates \( p^* \) and \( \bar{q}^2 \) values of stage 3. Given the contract parameters \( w \) and \( t \), he chooses \( e^* \) to maximize his expected profit \( \Pi_t^{CM} = (w-c)\bar{q}^2 - \frac{ke^2}{4} + t = (w-c)\bar{q}^2 - \frac{ke^2}{4} \). This function is concave in \( e \) and it is maximized at \( e^* = \frac{aw}{bk} \).

PROOF OF LEMMA 2: Parts (a), (b), and (c) follow from substituting \( e' = \frac{aw}{bk} \) from Proposition 2 into the \( q' \) and \( p' \) expressions in Proposition 2. Parts (d) and (e) follow from substituting \( e', q', \) and \( p' \) expressions into the objective functions in (2) and (3).

PROOF OF PROPOSITION 3: The OEM can increase her expected profit by decreasing the lump-sum payment \( t \) until the CM’s participation constraint in (8) binds. The OEM sets this constraint as binding, proving Part (g). We have

\[
t' = \Pi_t^{CM} - \bar{q}'(w' - c) + \frac{ke'^2}{4} \tag{A2}
\]

Substituting the above \( t' \), as well as \( p' \) and \( q' \) from Lemma 2, the OEM’s objective function in (7) becomes

\[
\Pi_t^{OEM} = \frac{1}{4b} \left( (a - \frac{c}{k} + \frac{w}{k})^2 - w^2b^2 \right) - \frac{c}{2} \left( a - \frac{c}{k} + w \left( \frac{1}{k} - b \right) \right) - \frac{(w - c)^2}{4k} - \Pi_t^{CM}. \tag{A3}
\]

The function \( \Pi_t^{OEM} \) is concave in \( w \) for \( \left( \frac{1-k^2+4k}{2bk} \right) < 0 \). This condition requires \( bk > 0.62 \), which is a relaxation of Assumption 2. Recall that we need \( bk > 1 \) to have a solution to the integrated firm problem. The inefficiency in the decentralized channel allows a wider range of quality cost parameter \( k \) values for a given \( b \) value. For \( bk > 0.62 \), \( \Pi_t^{OEM} \) is maximized at \( w' = \frac{ak+bc(bk^2-1)}{2bk^2} \), which proves Part (a). Under Assumption 1, \( u' \) is decreasing in \( k \). Part (b) follows from substituting \( u', \bar{q}' \), \( e' \) into Eq. (A2). The lump-sum payment \( t' \) increases in \( k \) for \( 0 < 2b^2k^3 - 2b^2k^2 + 3bk^2 - bk - 1 \), which holds due to Assumption 2. Parts (c), (d), and (e) follow from Assumptions 1 and (f) and substituting \( u' \) into the expressions in Proposition 2 (a), (b), and (c). In Part (c), \( e^0 > 0 \) due to Assumption 1. Part (f) follows from substituting \( u' \) from Part (a) into Eq. (A3). The function \( \Pi_t^{OEM} \) is decreasing in \( k \) for \( 0 < 2b^2k^3 + 3bk^2 - bk - 1 \), which holds due to Assumption 2.

PROOF OF PROPOSITION 4: The proof follows from substituting \( \Pi_t \) from Lemma 1(d) and \( \Pi_t^{CM} \) and \( \Pi_t^{OEM} \) from Proposition 3(f) and (g).

PROOF OF LEMMA 3: From Eq. (9), we have \( v(w_1,k) - v(w_2,k) = \frac{1}{2}(w_1-c)^2 - (w_2-c)^2 \) + \( \frac{1}{2}[(a-bw_1)(w_1-c) - (a-bw_2)(w_2-c)] \). Thus, \( \frac{v(w_1)(w_1-c)}{aw_1} = \frac{v(w_2)(w_2-c)}{aw_2} = -\frac{1}{2b^2}(w_1-c)^2 - (w_2-c)^2 < 0 \), because \( w_1 > w_2 > c \).

PROOF OF PROPOSITION 5: We first prove a lemma that provides the contract parameters in the optimal menu. Then, we compare the results with the symmetric quality cost information results.

LEMMMA 4: In the solution to the OEM’s problem in (10), the optimal menu’s contract parameters are as follows (a) \( r_1^L = v(0,k_l) - v(w_1^L,k_l) + v(w_1^H,k_l) - v(w_1^H,k_H) \); (b) \( r_1^R = v(0,k_H) - v(w_1^H,k_H) \); (c) \( w_2^L = w_1^L = \frac{ak_l+bc(bk_l^2-1)}{2bk_l^2+bk_l+1} \); (d) \( w_2^R = bc+ak_H+bc(bk_H^2-1)+A \) < \( w_H \), where \( A = (1 - \frac{w}{b})bk_H(\frac{bk_H}{k_H} - 1) \).

PROOF OF LEMMA 4: First, observe that the constraint \( IR_t \) is redundant at optimality. This follows from \( v(w_1^L,k_l) + r_1^L - v(0,k_l) \geq v(w_1^H,k_l) + r_1^L - v(0,k_l) \) > \( v(w_1^H,k_H) + r_1^R - v(0,k_H) \geq 0 \). The three inequalities are due to \( IC_{H,H} \), decreasing differences property from Lemma 3, and \( IR_{H,H} \), respectively. For Part (b), note that \( IR_{H,H} \) is binding at optimality. Otherwise, decreasing both \( k_l \) and \( IH \) by the same amount would increase the OEM’s
expected profit while preserving IC\textsubscript{L}, and not affecting IC\textsubscript{H}. To prove Part (a), first note that IC\textsubscript{L} must be binding. Otherwise, decreasing \( t_k \) by a small amount would preserve IC\textsubscript{L}, relax IC\textsubscript{H}, and increase the OEM’s expected profit. We use binding IC\textsubscript{L}, and substitute \( \tau^*_L \) from Part (b) to obtain \( \tau^*_H = v(0, k_L) - v(w_H, k_L) = v(w_H, k_L) - v(u_H, k_L) \), proving Part (a). Here, \( v(0, k_L) - v(w_H, k_L) \) is the payment required to give the low-quality-cost CM his reservation profit; whereas, \( v(w_H, k_L) - v(u_H, k_L) \) is his rent in the optimal contract. From Eq. (9), the rent is

\[
v(w_H, k_L) - v(u_H, k_L) = \frac{(w_H - c)^2}{4} \left( k_L - 1 \right) H > 0.
\] (A4)

Next, we observe that the constraint IC\textsubscript{L} is redundant at optimality. Substituting \( \tau^*_L \) and \( \tau^*_H \), and using \( v(0, k_H) = v(0, k_L) \), the constraint IC\textsubscript{H} becomes \( v(w_H^2, k_L) - v(w_H^2, k_H) \geq v(w_H^2, k_L) - v(w_H^2, k_H) \). This constraint is satisfied as a strict inequality due to Lemma 3.

Substituting \( \tau^*_L \) and \( \tau^*_H \), OEM’s objective becomes \( \max \pi \tilde{q}_H (p_H - \tilde{w}_H) + v(u_H, k_H), \) subject to IC\textsubscript{H}, Eq. (9) and the rent \( v(w_H, k_H) \). We ignore the constants \( v(0, k_H), \) and \( v(w_H, k_H) \). This function is additively separable in \( u_H \) and \( w_H \):

**Section L:** \( \max_{u_H} \pi \tilde{q}_H (p_H - \tilde{w}_H) + v(u_H, k_H) \)

**Section H:** \( \max_{w_H} \pi \tilde{q}_H (p_H - \tilde{w}_H) + v(u_H, k_H) \)

To prove Parts (c) and (d), we solve the two sections separately.

**Section L:** Substituting \( v(u_H, k_H) \) from Eq. (9) as \( \tilde{q}_H (u_H, c) - \tilde{w}_H - \tilde{w}_H \), we obtain \( \max_{u_H} \pi \tilde{q}_H (p_H - \tilde{w}_H) + \tilde{q}_H (u_H, c) - \tilde{w}_H - \tilde{w}_H \). Substituting \( \tilde{q}_H \) and \( p_H \) from Lemma 2, we have \( \max_{u_H} \frac{1}{2} \left( \frac{a - \theta + \frac{\theta^2}{2}}{\theta} \right)^2 - \theta^2 + \frac{a - \theta^2}{\theta} + \tilde{w}_H - \tilde{w}_H \), which is maximized at \( u_H^* = \frac{ak_L - (b + c)^2}{b - \theta (b + c)^2} - \frac{1}{\theta} \). Note that \( u_H^* = u^*_H \) from Proposition 3.

**Section H:** Substituting \( v(u_H, k_H) \) from Eq. (9) and the rent \( v(u_H, k_H) - v(w_H, k_H) \) from Eq. (A4), we have \( \max_{w_H} \pi \tilde{q}_H (p_H - \tilde{w}_H) + \tilde{q}_H (u_H, c) - \tilde{w}_H - \tilde{w}_H \) \( (w_H - c)^2 \left( k_H - 1 \right) H \) \( (w_H - c)^2 \left( k_H - 1 \right) H \) \( (w_H - c)^2 \left( k_H - 1 \right) H \) \( (w_H - c)^2 \left( k_H - 1 \right) H \)

Next, we use Lemma 4 to prove Proposition 5. Per-unit payment values \( u_H^* \) and \( w_H^* \) follow directly from Lemma 4(c) and (d). Lump-sum payment values \( \tau^*_L \) and \( \tau^*_H \) follow from Lemma 4(a) and (b), by substituting \( \tau \) from Eq. (9), and \( w_H^* \) and \( w_H^* \) from Lemma 4. Parts (L1), (L2), and (L5) follow from Lemma 2 with \( u_H^* = u_L^* \). Part (L3) follows from Eq. (9), and from Lemma 4(a) and (b). For Part (L4), observe Part 3 and that the expected total channel profit remains the same because \( \epsilon_L \), \( p_L \), and \( q_L \) values are the same. Parts (H1), (H2), and (H5) follow from Lemma 2 with \( w_H^* = w_H^* \). Part (H3) follows from Eq. (9), Lemma 4(a), (b), and Proposition 3. Part (H4) is due to the fact that \( w_H^* \) is a suboptimal solution for the OEM’s problem in (10).

**PROOF OF COROLLARY 1:** We use the term shutdown alternative to refer to the OEM’s alternative of not doing business with a high-quality-cost CM. The OEM prefers the shutdown alternative when \( (1 - \pi) P_{\text{OEM}}^L > P_{\text{OEM}}^H \) holds. Substituting \( P_{\text{OEM}}^L \) from Proposition 3(f), and \( P_{\text{OEM}}^H \) from Eq. (A8), this condition becomes

\[
\pi - \frac{(b_k^2 + A)(b_k^2 + 2b_Lk + A) - bk_L}{b_k^2 + bk_L - 1 + A} > 0.
\]

Let \( \phi(P_{\text{OEM}}^L) \) be the function on the left-hand side of the inequality. We observe that \( \phi(0) < 0 \) (due to Assumption 2), \( \phi(\infty) > 0 \), and that \( \phi(P_{\text{OEM}}^L) \) is a strictly increasing function. Hence, there exists a unique \( P_{\text{OEM}}^L \) value for which \( \phi(P_{\text{OEM}}^L) = 0 \). Let this threshold value be \( P_{\text{OEM}}^L \). Accordingly, the OEM prefers the shutdown alternative when \( P_{\text{OEM}}^L < P_{\text{OEM}}^L \), whereas she prefers working with both CM types when \( P_{\text{OEM}}^L = P_{\text{OEM}}^L \).

**PROOF OF PROPOSITION 6:** The value of information on the CM’s quality cost is the difference between the OEM’s expected profit under symmetric and asymmetric information scenarios. Let \( P_{\text{OEM}}^L \) and \( P_{\text{OEM}}^H \) denote the OEM’s profit under symmetric information, with a high- and low-quality-cost CM, respectively. From Proposition 3(f), \( P_{\text{OEM}}^L = (1 - \pi) P_{\text{OEM}}^H \) becomes

\[
P_{\text{OEM}}^L = \frac{(a - b c)^2}{4} \left( (b_k^2 + A)(b_k^2 + 2bk_L + A) - bk_L \right)
\]

\[
+ (1 - \pi)b_k(b_k^2 + 2bk_L + A) - bk_L
\]

\[
- P_{\text{CM}}^L.
\] (A5)

Next, we find \( P_{\text{OEM}}^L = \pi P_{\text{OEM}}^L + (1 - \pi) P_{\text{OEM}}^H \). From Lemma 2(d), we have \( P_{\text{OEM}}^L = \frac{(a - b c)^2}{4} \left( \frac{1}{\theta} - \frac{1}{\theta} \right) \). Note that Lemma 2 is valid under both symmetric and asymmetric information, although we present it in the symmetric information context. Substituting \( \tau^*_H \) from Proposition 5 and \( w_H^* \) from Lemma 4(d), we find

\[
P_{\text{OEM}}^L = \frac{(a - b c)^2}{4} \left( (b_k^2 + A)(b_k^2 + 2bk_L + A) - bk_L \right)
\]

\[
+ (1 - \pi)b_k(b_k^2 + 2bk_L + A) - bk_L
\]

\[
- P_{\text{CM}}^L.
\] (A6)

We have \( P_{\text{OEM}}^L = \frac{(a - b c)^2}{4} \left( \frac{1}{\theta} - \frac{1}{\theta} \right) \) from Proposition 5(L4). Substituting \( P_{\text{OEM}}^L \) from Proposition 3(f), and \( w_H^* \) from Lemma 4(d), we obtain

\[
P_{\text{OEM}}^L = \frac{(a - b c)^2}{4} \left( k_L(b_k^2 + 2bk_L - A - bk_L) - \frac{k_L}{k_H - 1 + A} \right)
\]

\[
- \frac{k_L}{k_H - 1 + A}.
\] (A7)

From (Eqs. (A6) and (A7), we have

\[
P_{\text{OEM}}^L = \pi P_{\text{OEM}}^L + (1 - \pi) P_{\text{OEM}}^H
\]

\[
= \frac{(a - b c)^2}{4} \left( \frac{1}{\theta} - \frac{1}{\theta} \right)
\]

\[
+ (1 - \pi)b_k(b_k^2 + 2bk_L - A - bk_L)
\]

\[
- \frac{k_L}{k_H - 1 + A}.
\] (A8)

Naval Research Logistics DOI 10.1002/nav
Using $\Pi_{\text{OEM}}$ from Eq. (A5) and $\Pi_{\text{OEM}}^{\text{CM}}$ from Eq. (A8), we find the value of information as $\Pi_{\text{OEM}}^{\text{CM}} - \Pi_{\text{OEM}} = \frac{(a-b)p}{k} - \frac{2}{k}(2\pi a + 2V_1 + 2bH_{\text{CM}} + \text{Diag}_{1})$, where $\Pi_{\text{OEM}}^{\text{CM}} = \Pi_{\text{OEM}} \frac{(a-b)p}{k} - \frac{2}{k}(2\pi a + 2V_1 + 2bH_{\text{CM}} + \text{Diag}_{1})$. Further simplifications yield the expression in the proposition. The expression is non-negative due to Assumptions 1 and 2.

PROOF OF PROPOSITION 7: First, we prove the following lemma that provides the solution as a function of the per-unit payment $w$, given a sales price $p$ that the OEM commits to.

LEMMA 5: If the OEM commits to a sales price $p$, the resulting optimal values as functions of the per-unit-payment $w$ are (a) $v^p(w) = \frac{a-bp+2\pi a}{k}$; (b) $q^p(w) = a - bp + \frac{2\pi a}{k}(w-c) + \frac{(w-c)}{k}$; (c) $t^p(w) = \Pi_{\text{R}}^p(a - bp + \frac{2\pi a}{k}(w-c) + \frac{(w-c)}{k}) - \Pi_{\text{CM}}^p$. This expression is non-negative due to Assumptions 1 and 2. Further simplifications yield the expression in the proposition. The expression is non-negative due to Assumptions 1 and 2.

PROOF OF PROPOSITION 8: From Proposition 7(e), the OEM’s expected profit with committed sales price $p$ is

$$\Pi_{\text{OEM}}^p = (a - bp)(p - c) + \frac{(p-c)^2}{k} - \Pi_{\text{R}}^p.$$  

This function is concave in $p$ due to Assumption 2, and it is maximized at $p^* = \frac{k(a-b)p}{4\pi a}$. This is the optimum sales price to commit for the OEM at stage 1. When the OEM commits to $p^*$, her expected profit from Eq. (A10) is

$$\Pi_{\text{OEM}}^p = (a - bp^*)(p^* - c) + \frac{(p^*-c)^2}{k} - \Pi_{\text{R}}^p = \frac{k(a-b)^2}{4\pi a} - \Pi_{\text{CM}}^p.$$  

We compare this profit with the OEM’s expected profit $\Pi_{\text{OEM}}^p$ in the no-commitment scenario from Proposition 3(f). Under Assumption 2, $\Pi_{\text{OEM}}^p > \Pi_{\text{OEM}}^p$ because $\frac{k(a-b)^2}{4\pi a} > \frac{k(a-b)^2}{4\pi a}$.

PROOF OF PROPOSITION 9: The proof follows directly from $\Pi_{\text{OEM}}^p = \Pi_{\text{CM}}^p$ from Proposition 8.

PROOF OF PROPOSITION 10: The proof follows parallel steps to the discussion in Section 4.2 and the proof of Proposition 5. It is available from the authors as an addendum to the article.

PROOF OF PROPOSITION 11: From Proposition 10, under asymmetric quality cost information, the OEM’s expected profit with committed sales price $p$ is $\Pi_{\text{OEM}}^p(p) = \Pi_{\text{OEM}}^p(p) - \Pi_{\text{CM}}^p + \Pi_{\text{CM}}^p$. This is the optimum sales price to commit for the OEM at stage 1. When the OEM commits to $p^*$, her expected profit from Eq. (A10) is

$$\Pi_{\text{OEM}}^p(p) = (a - bp^*)(p - c) - \Pi_{\text{R}}^p.$$  

We compare this profit with the OEM’s expected profit $\Pi_{\text{OEM}}^p$ in the no-commitment scenario from Proposition 3(f). Under Assumption 2, $\Pi_{\text{OEM}}^p > \Pi_{\text{OEM}}^p$ because $\frac{k(a-b)^2}{4\pi a} > \frac{k(a-b)^2}{4\pi a}$.

Finally, we substitute $w^p$, $w^p$, $w^p$, and $t^p$ from Proposition 10 into Eq. (A11) to find

$$\Pi_{\text{OEM}}^p(p) = (a - bp^*)(p - c) - \Pi_{\text{R}}^p.$$  

where $\theta = \frac{\sqrt{a^2 + 4\pi^2 b^2 k^2}}{2k}$. The function $\Pi_{\text{OEM}}^p(p)$ is concave in $p$ and it is maximized at $p^* = \frac{k(a-b)}{4\pi a}$. Next, we prove that the concavity condition $b > \theta$ holds. Because we have $\frac{k}{L} < b$ under Assumption 2, it suffices to show $\theta < \frac{k}{L}$, which holds if $\pi k_l + (1 - \pi)k_H^2 \\leq k_H^2(\pi k_2 + (1 - \pi)(k_H - k_2))$. Rearranging the terms, this condition is equivalent to $\pi (k_H - k_1) \leq k_H$ which always holds because $k_2 < k_1$ and $\pi < 1$. Next, we substitute $p^* = \frac{a-b}{4\pi a}$ into Eq. (A11) to find $\Pi_{\text{OEM}}^p = \frac{k(a-b)}{4\pi a} - \Pi_{\text{R}}^p$. We compare $\Pi_{\text{OEM}}^p$ to the OEM’s profit under no commitment, $\Pi_{\text{OEM}}^p$ from Eq. (A8). OEM’s profit is higher under commitment if $\frac{\theta}{\pi k_2 - k_H} > \frac{\pi}{\text{Diag}_{1} + 2bH_{\text{CM}} + \text{Diag}_{1}}$.
PROOF OF PROPOSITION 12: The value of information for the commitment scenario is determined as $\Pi_{CM}^{OEM} - \Pi_{CM}^{HC}$. Let $\Pi_{CM}^{OEM}$ and $\Pi_{CM}^{HC}$ denote the OEM’s profit in the commitment scenario under symmetric information, with a high- and low-quality-cost CM, respectively. From Proposition 8, $\Pi_{CM}^{OEM} = \pi R_{CM} + (1 - \pi) \Pi_{CM}^{HC} = \frac{a_b c \pi^2 - c_p}{2} - \frac{a_b c_b \pi}{2} + (1 - \pi) \Pi_{CM}^{HC}$. Observing $\Pi_{CM}^{OEM} = \frac{a_b c \pi^2 - c_p}{2} - \frac{a_b c_b \pi}{2}$ from Proposition 11 yields the expression in the proposition. The expression is non-negative due to Assumptions 1 and 2.

PROOF OF PROPOSITION 13: The proof follows from comparing the value of information in the no-commitment scenario from Proposition 6 with the value of information in the commitment scenario from Proposition 12. The comparison holds due to Assumptions 1 and 2.

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