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Quality Improvement Incentives and Product Recall Cost Sharing Contracts

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As companies outsource more product design and manufacturing activities to other members of the supply chain, improving end-product quality has become an endeavor extending beyond the boundaries of the firms' in-house process capabilities. In this paper, we discuss two contractual agreements by which product recall costs can be shared between a manufacturer and a supplier to induce quality improvement effort. More specifically, we consider (i) cost sharing based on selective root cause analysis (Contract S), and (ii) partial cost sharing based on complete root cause analysis (Contract P). Using insights from supermodular game theory, for each contractual agreement, we characterize the levels of effort the manufacturer and the supplier would exert in equilibrium to improve their component failure rate when their effort choices are subject to moral hazard. We show that both Contract S and Contract P can achieve the first best effort levels; however, Contract S results in higher profits for the manufacturer and the supply chain. For the case in which the information about the quality of the supplier's product is not revealed to the manufacturer (i.e., the case of information asymmetry), we develop a menu of contracts that can be used to mitigate the impact of information asymmetry. We show that the menu of contracts not only significantly decreases the manufacturer's cost due to information asymmetry, but also improves product quality.

Key words: reliability; quality control; contracts; product design; supply chain coordination; information asymmetry
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1. Introduction

In 2004, a consumer research study in the auto industry reported initial product quality as the second most important factor affecting consumers' purchasing decision after product price (J.D. Power and Associates 2004).[1] The large number of product recalls and lawsuits in the auto industry demonstrate how undetected quality problems and related production delays can lead to a huge profit loss and degrade a company's brand equity. For instance, in 2007, Ford's concerns about a design related quality problem in cruise control switches resulted in a recall of 3.6 million vehicles manufactured between 1992 and 2004, increasing the total number of vehicles recalled for the same quality problem to 9.6 million (Associated Press 2007). In the electronics industry, in April 2007, Sanyo agreed to share with the manufacturer Lenovo, the $17 million cost of recalling 205,000 Sanyo made laptop battery packs that can overheat because of a flaw in the product design (Nystedt 2007). In May 2007, the Consumer Product Safety Commission, the National Highway Traffic Safety Administration, and Evenflo Company Inc. announced a recall of Evenflo embrace infant car seat/carriers because of a malfunctioning handle. A total of 450,000 units, manufactured in the United States and China, were sold nationwide through department stores and baby items stores (*CNNMoney* 2007).

These are just a few examples that demonstrate that recalls are common in a variety of industries and often are associated with substantial present and future costs to a company. The cost and scale of recalls necessitate a deeper understanding of how to manage the quality improvement incentives of multiple supply chain partners to ensure better product performance.

Product recalls result from a lack of quality assurance in the manufacturing and/or design processes of one or many supply chain partners and can affect a large number of products manufactured over extended periods of time. For example, in a recent

[1] Initial product quality is measured by the number of quality problems manifesting themselves during the first 90 days after purchase.

study, Ford reported that 76% of the company's quality problems stem from its first tier suppliers (Sherefkin 2002).

Today, extended quality improvement efforts take various forms. For instance, manufacturers in the auto industry are more willing to involve suppliers during the product development process to ensure early detection and elimination of quality problems (Kisiel 2007). In addition to preventive initiatives, it is also becoming a common practice among manufacturers to present suppliers with quality cost sharing agreements to ensure accountability of quality problems and to create incentives for process improvement (Balachandran and Radhakrishnan 2005). In this paper, we address the optimal design of a recall cost sharing contract when both the supplier's and the manufacturer's quality improvement efforts are subject to moral hazard and when the manufacturer has uncertainty regarding the quality of the supplier's process. In this context, we discuss the optimal use of product failure root cause analysis information in the design of cost sharing schemes.

Previous research on contract design in quality management has studied the *fixed share rate contract*[2] (Contract F) as the external quality cost (such as recall cost) sharing scheme between a manufacturer and a supplier. In this paper, we introduce two new contract formats to share product recall related external quality costs in the supply chain: (i) the *selective root cause analysis contract* (Contract S), which is characterized by a unit part price (p), a fixed recall cost share rate (R), paid by the supplier,[3] and a threshold product failure time ($\overline{T}$); and (ii) the *partial cost allocation contract* (Contract P), which is characterized by a unit part price (p), a fixed cost share rate (R_m) paid by the supplier if the manufacturer is responsible for the product failure, and a fixed cost share rate (R_s) paid by the supplier if the supplier is responsible for the product failure. A critical component of both contract formats is the *root cause analysis information*, which reveals the supply chain member who is responsible for the quality problem in the product. Contract S uses this information only if the product failure occurs before a threshold time ($\overline{T}$), which we will refer to as the *root cause analysis threshold*, and allocates the total recall cost to the party at fault. Otherwise, the cost is shared according to a fixed rate (R). Under Contract P, root cause analysis information is *always* used in the cost allocation process, the total recall cost is *always* shared between the parties, and the supply chain member who is responsible for the recall incurs a larger share of the recall cost.

Considering a single-manufacturer, single-supplier supply chain structure, we address the following research questions regarding these contractual agreements:

- How effective are selective root cause analysis and partial cost allocation contracts in coordinating the manufacturer's and the supplier's quality improvement efforts when the effort levels are not observable and therefore are subject to moral hazard?
- Which contract format is optimal for the manufacturer? How do the fixed share rate contract, selective root cause analysis contract, and the partial cost allocation contract compare with respect to the manufacturer's profits as well as the quality of the final product?
- If the exact information about the supplier's initial quality is not available, can the manufacturer design a menu of selective root cause analysis contracts to screen supplier type as well as to induce quality improvement effort? Under what circumstances does knowing the supplier's initial quality result in significant savings for the manufacturer? How much does the quality of the final product under the menu of contracts differ from that under perfect information (i.e., when the manufacturer knows the exact initial quality of supplier's product)?

In the following section, we present the contribution of our paper in the context of the existing literature on quality and supply chain management. Then, we present the basic modeling framework and the assumptions of our model in §3. Section 4 develops a detailed analysis of Contract S and Contract P under the complete information assumption. We present an extensive numerical study in §5, which examines the profitability of these contracts for the manufacturer as well as for the total supply chain. Section 6 investigates the case of information asymmetry and derives the optimal menu of selective root cause analysis contracts. Section 7 presents a numerical study to compare the cost efficiency and product quality under different contracts in cases of information asymmetry. A summary of our findings and directions for future research are presented in §8.

2. Literature

The main focus of this research is on modeling the process improvement incentives of supply chain members when their effort choices are not observable and there is information asymmetry with regards to their existing process capability. Therefore, by jointly modeling moral hazard and adverse selection issues, this paper contributes to several streams of research each of which we review below.

[2] Under a fixed share rate contract, the supplier assumes R percentage of the total external quality cost, while the manufacturer pays for the $(1-R)$ percentage, irrespective of who is at fault for the quality problem.

[3] The supplier shares R percentage of the total recall cost, while the manufacturer pays the remaining $(1-R)$ percentage.

In operations management, a group of papers discusses the design of quality cost sharing contracts among manufacturers and suppliers. In a game theoretic set-up, Reyniers and Tapiero (1995a, b) and Lim (2001) model suppliers' choice of process quality and manufacturers' choice of inspection strategy. Their model characterizes the Nash equilibrium of the supplier-manufacturer quality game in terms of the cost sharing parameters for internal (rework) and external (warranty) quality costs, assuming a fixed rate for sharing external quality costs between the parties. We, however, model a more general contract format for sharing external quality costs resulting from a recall. A special case of our contract of interest is the fixed share rate contract studied in the above papers.

Baiman et al. (2000) analyze the relationship between product quality, cost of quality, and the information that can be contracted on. In a risk neutral setting, the supplier invests in reducing the process defect rate and the manufacturer invests in the inspection quality of the incoming part. Both decisions are subject to moral hazard. Like Reyniers and Tapiero (1995a, b) and Lim (2001), they also assume that the external quality costs are shared at a fixed rate. In a subsequent paper (Baiman et al. 2001), the authors investigate the link between product design, contractible information, and the supplier's investment in process quality. In contrast to this paper, which considers fixed share rate contract, we focus on a broader set of contract formats to share external product failure costs and show that, even though the root cause analysis can perfectly determine the party responsible for product failure, it is not optimal for the supply chain to share quality costs based on this information for all failures occurring during the contract period. We propose a contract with selective root cause analysis which differentiates early failures from late failures to coordinate the quality improvement efforts of supply chain members.

In a subsequent paper, Baiman et al. (2003) examine a product structure exhibiting the weakest link property and investigate how the internal and external failure cost sharing mechanisms impact supplier selection when there is an adverse selection problem. Their analysis considers moral hazard only on the supplier side, whereas we model moral hazard both on the manufacturer and on the supplier side. Furthermore, like previously cited work, their analysis also assumes that the external quality costs are shared at a fixed rate, which is, in fact, a special case of the contract we investigate.

Balachandran and Radhakrishnan (2005) consider a double moral hazard situation in quality investment effort, in which the final product consists of components made by a buyer and a supplier. Although their paper focuses on the best use of incoming *inspection information* to achieve the first best effort levels from the supply chain partners, in this paper we investigate the best use of root cause analysis information about external failures to achieve first best effort levels from supply chain members. Furthermore, Balachandran and Radhakrishnan (2005) model the fixed share rate contract for allocating the costs of *internal failures*, whereas we consider a more general contracting arrangement for *external failures*.

In a recent paper, Zhu et al. (2007) look at a buyer who designs a product and owns the brand, yet outsources the production to a supplier. Both the buyer and the supplier incur quality related costs that are shared by a fixed share rate contract. The Zhu et al. (2007) model captures the effect of the buyer's involvement in ensuring product quality. They also endogenously model the effect of operational decisions such as the buyer's ordering quantity and the supplier's production lot size. Unlike Zhu et al. (2007), we look at a setting where the manufacturer is involved in the production process and his effort affects the final quality of the product and discuss two new contract formats to share external quality costs.

A related supply chain management paper by Corbett and DeCroix (2001) discusses the use of a shared savings contract (assuming a fixed share rate between a supplier and a buyer) to induce supplier and buyer effort that reduces indirect material consumption. Although the modeling of effort in our paper has some similarity to their modeling constructs, we investigate the use of contractual formats to share external quality costs resulting from a recall rather than the cost of indirect materials.

Based on data from the automotive and the pharmaceutical industries, a number of political economy research papers investigate the real total cost of a recall for a manufacturer. For instance, Jarrell and Peltzman (1985), Barber and Darrough (1996), and Rupp (2004) study the cost attributes of recalls in the U.S. automotive industry and find that the indirect costs such as brand equity loss, consumer goodwill loss, and loss in firm value are in fact much larger than the direct costs of a recall such as product collection and repair cost. The findings of this stream of empirical research serve as a basis for some of our assumptions regarding the manufacturer's unit recall cost.

In summary, this paper introduces two new contractual formats for sharing the external quality costs of product recalls; in particular, we focus on the best use of root cause analysis information and its impact on the quality of the final product under both *complete* and *asymmetric* information assumptions. In this respect, our findings enrich the growing literature in this area and help managers to better understand the *cost efficiency* of these contractual agreements and their impact on *product quality*.

3. Modeling Framework

We investigate the implications of contract choice to share product recall costs on manufacturer's and supplier's quality improvement efforts and on supply chain profits. To this end, we consider a manufacturer who produces a product that consists of two components, one of which he procures from a single supplier at a unit price p. The manufacturer procures a total of M components from the supplier and uses them to manufacture M units of the good to be sold in the market. The product generates a unit revenue of r for the manufacturer. We denote the manufacturer's unit production cost by u_m, and the supplier's by u_s. At the time of contracting, both the manufacturer and the supplier know M. For example, when an auto manufacturer discusses a contract for, say, the oil pump used in the engine of a particular 2008 car model, he has a good estimate of how many of those model cars are planned for production in the year 2008.[4] If M represents this number, then the quality cost sharing contract covers M components.

After the product is sold to the customer, during its useful life, it can fail to perform its function if any one of its components fails to do so. Baiman et al. (2003) define this product failure behavior as the "weakest link property." Component failure can result from either a design or a manufacturing related problem in the supplier's or the manufacturer's process. In 2002, a study by A.T. Kearney Inc., a global management consulting firm, of a large North American auto manufacturer's external quality failures showed that although 25% of the external quality problems were design issues, only 15% and 21% of the problems were related to the manufacturer's assembly and the supplier's manufacturing processes, respectively. The manufacturing and/or assembly related external quality problems are often easily fixed by reinstalling a nondefective component in the product. On the other hand, design related external failures are more costly to manufacturers because design flaws often affect multiple product generations (models) and reveal themselves only after the customer has used the product for a period of time (*Automotive News* 2005). Relative to manufacturing related quality problems, design flaws are more costly to resolve as they may require redesigning multiple components and their interfaces in a product. Root cause analysis bears particular importance for design related recalls because the flawed design decisions may not be readily obvious to supply chain partners. Given the high cost and challenges in resolving design related quality problems, this paper discusses contracts to share external quality costs, more specifically recall costs, resulting from product design flaws.

Current literature defines product quality as the likelihood of producing a nondefective unit from either the manufacturer's or the supplier's process (e.g., Reyniers and Tapiero 1995a, b). This way of modeling product quality is more relevant to manufacturing related defects that exist at the time of product purchase. We consider quality problems that unveil themselves during product usage and are due to unanticipated and undetected modes of design failures. Therefore, we model quality as *the survival likelihood of the product design subject to varying modes of usage during the useful life of the product*. Ex ante to procurement and production, the manufacturer and the supplier can choose to exert costly effort to reduce their component's design failure rate by carefully testing the design characteristics. In practice, the process of eliminating the many ways in which a design failure can occur is called *failure mode and effect analysis* (FMEA) and is performed by the manufacturer and/or the supplier during the product development stage prior to manufacturing (Stamatis 2004).

Below we present the assumptions underlying our model. The detailed description and justification of our assumptions can be found in Online Appendix A (provided in the e-companion).[5]

Assumption A1. *We assume that M products are manufactured and sold, and are either with the customers or in the distribution channel when a recall is issued. Once a particular problem has revealed itself, and the recall is issued, the manufacturer fixes the particular quality problem in all M products.*

Assumption A2. *We denote the recall cost* per unit *as ω and assume it to be independent of the root cause of the quality problem. At the time of contracting, both the manufacturer and the supplier agree on an estimate of ω.*

Assumption A3. *We denote the* unit cost *of root cause analysis by $c_r = C_r/M$, where C_r is the relevant fixed cost of the root cause analysis and M is the total number of products subject to a recall. We assume that the root cause analysis perfectly identifies the component that caused the quality problem.*

Assumption A4. *The manufacturer and the supplier have inherent process capabilities modeled by the initial failure rate of their components due to a design related quality problem. The initial failure rates are common knowledge to both parties and are denoted by $\lambda_m'^0$ and $\lambda_s'^0$ for the manufacturer and the supplier, respectively. The failure rates are assumed to be time homogeneous* (*i.e., constant failure rate*).

[4] Manufacturers usually have an estimate for the production quantity when they contact their suppliers to order material; see Production Planning and Control Hierarchy, Hopp and Spearman (2001), Nahmias (2000).

[5] An electronic companion to this paper (which contains all online appendices) is available as part of the online version that can be found at http://mansci.journal.informs.org/.

In our model, we assume that the supplier and the manufacturer will exert costly effort to improve the quality of their components and reduce the design failure rate. We use η_m and η_s to denote the amount of quality improvement effort exerted by the manufacturer and the supplier, respectively, where $0 \le \eta_m \le 1$ and $0 \le \eta_s \le 1$.

Under the effort level η_m (effort level η_s), the manufacturer (the supplier) can reduce the failure rate of his (her) component from the initial value $\lambda_m'^0$ (value $\lambda_s'^0$) to $\lambda_m'^0[1-\eta_m]$ (to $\lambda_s'^0[1-\eta_s]$). Given the constant failure rate assumption, the failure time distribution of the product (after quality improvement) that results in a recall will follow an exponential distribution with a failure rate of $\lambda_m'^0(1-\eta_m)+\lambda_s'^0(1-\eta_s)$. The effort choices of the manufacturer and the supplier are not observable. Consequently, neither the manufacturer nor the supplier can enforce a level of effort in the cost sharing contract. We will refer to the game played between the manufacturer and the supplier as *the quality improvement effort game*.

Assumption A5. *In our model, the contract negotiated between the manufacturer and the supplier covers external quality costs (recall costs) for a duration of T periods, which will denote the duration that the product is in use by the consumers. Without loss of generality, we normalize T to* 1.

Given M and the exponential lifetime distribution assumption, the probability of observing the first product failure that results in a recall is given by $1-e^{-M[\lambda_m'^0(1-\eta_m)+\lambda_s'^0(1-\eta_s)]}$. To further simplify the exposition, we define the aggregate failure rates as $\lambda_m^0 = M\lambda_m'^0$ and $\lambda_s^0 = M\lambda_s'^0$. Then, the failure time probability distribution simplifies to $1-e^{-[\lambda_m^0(1-\eta_m)+\lambda_s^0(1-\eta_s)]}$. Note that, if a product fails, the failure is going to be due to the supplier's component with probability $\lambda_s^0(1-\eta_s)/(\lambda_m^0(1-\eta_m)+\lambda_s^0(1-\eta_s))$. This probability would be $\lambda_m^0(1-\eta_m)/(\lambda_m^0(1-\eta_m)+\lambda_s^0(1-\eta_s))$ for the manufacturer. We consider the manufacturer's and the supplier's processes to be stochastically independent, i.e., joint failures do not occur.

Above, we assume that the manufacturer initiates a recall when the first product failure is observed. In practice, this would be the case when product failure leads to severe consequences for the consumer, and therefore delaying the recall decision imposes a high product liability risk to the manufacturer. When such risks are low, the manufacturer may wait to initiate a recall until N (where $N > 1$) product failures are observed (Rupp and Taylor 2002). In §8, we elaborate on this point and discuss the implications of this assumption for our model insights.

Assumption A6. *Improvements in the product design failure rate are costly to both parties. More specifically, the efforts of η_s and η_m result in an effort cost of $C_s(\eta_s)$ and $C_m(\eta_m)$ (per unit component) for the supplier and the manufacturer, respectively.*

Table 1 Basic Notation

r = selling price of the manufacturer's product
u_m = unit production cost of the manufacturer
u_s = unit production cost of the supplier
M = total number of products subject to recall
ω = unit recall cost
c_r = unit root cause analysis cost
p_0 = unit part procurement price under no cost sharing
p = unit part procurement price
η_s^k = supplier's effort level under contract k
η_m^k = manufacturer's effort level under contract k
T = useful life of the product in the market
$C_s(\eta_s)$ = cost of effort for the supplier
$C_m(\eta_m)$ = cost of effort for the manufacturer
$\lambda_s'^0$ = supplier's initial per unit failure rate
$\lambda_m'^0$ = manufacturer's initial per unit failure rate
λ_s^0 = supplier's initial aggregate failure rate
λ_m^0 = manufacturer's initial aggregate failure rate

We consider $C_s(\eta_s)$ and $C_m(\eta_m)$ to be twice continuously differentiable on $[0,1)$, and convex increasing in effort so that $C_s'(\eta_s) > 0$ and $C_m'(\eta_m) > 0$ for $(\eta_s, \eta_m) \in (0,1] \times (0,1]$ and $C_s''(\eta_s) > 0$, and $C_m''(\eta_m) > 0$ for $(\eta_s, \eta_m) \in [0,1] \times [0,1]$, for the manufacturer and the supplier, respectively.

In what follows, we would like to avoid boundary solutions to the manufacturer's and the supplier's effort decisions. To this end, we assume that there are "low hanging" quality improvement opportunities for both parties. This requirement is formalized by $C_s'(0) = 0$ and $C_m'(0) = 0$. Also, given the limited physical, financial, and intellectual resources of firms, we will assume that it is prohibitively more expensive to show incremental effort at high effort levels. More specifically, we will assume $\lim_{\eta_s \to 1} C_s'(\eta_s) = \infty$ and $\lim_{\eta_m \to 1} C_m'(\eta_m) = \infty$. We summarize our notation in Table 1.

4. Complete Information About Component Quality

In this section, we focus on the quality improvement effort game under complete information. Specifically, we assume that the manufacturer and supplier are fully informed about each others' initial component failure rates (i.e., the initial state of the component quality prior to quality improvement effort). This usually occurs when the supplier and the manufacturer have been working together for several years, and therefore both parties have a good idea of each other's process capabilities.

As a benchmark, we start by characterizing the total supply chain profits and the final product quality in a centrally coordinated system, in which both quality improvement effort decisions of the manufacturer and the supplier are made by a central planner. We refer to the total supply chain profits and the final quality of the product under this case as the first best. Then, in a decentralized supply chain, we discuss how the quality improvement effort game would be played out under Contract S and Contract P.

The main focus of our paper is on designing cost sharing contracts that maximize the manufacturer's expected profit in a decentralized supply chain. The framework of our models is based on a Stackelberg game in which the manufacturer is the leader. The manufacturer moves first and offers the cost sharing contract to the supplier. This is generally the case in the automotive and electronics industries, where the manufacturer has the power in the supply chain and often dictates the terms of trade with his supplier (Barkholz and Sherefkin 2007, Sherefkin and Armstrong 2003, BearingPoint Consulting 2008, Nystedt 2007). That is the main reason why many papers on quality management and supply chain contracting have also made similar assumptions with regards to the manufacturer being the Stackelberg leader in the supply chain (see Baiman et al. 2000, 2001, 2003; Lim 2001; Cachon 2003).

In our decentralized models, the manufacturer takes the initial step and designs the contract. When designing the contract, the manufacturer provides sufficient incentives for the supplier so that the supplier accepts the cost sharing contract. As we will explain later, the incentive provided to the supplier to have her accept a cost sharing contract is an increase in the part price paid by the manufacturer for each component procured from the supplier.

From the manufacturer's profit maximization perspective, we investigate whether it is ever optimal to induce first best effort levels in a decentralized supply chain. Interestingly, we show in Lemma 1 that when cost of root cause analysis is negligible, i.e., $c_r = 0$, the optimal contract for the manufacturer is also the contract that coordinates the effort decisions of the manufacturer and the supplier and attains the first best quality and profits. We also show that, for the decentralized settings, an effort coordinating Contract S or Contract P, or both, does exist. Subsequently, we present an extensive numerical study that examines the manufacturer's optimal contract when $c_r > 0$.

In the rest of the analysis, Π_i^k and η_i^k will denote the profit function and the effort level of supply chain member i under model (contract) k. The subscript i will take values of s and m, denoting the supplier and the manufacturer, respectively. The superscript k will take the values of C, N, S, P, and F, denoting the centrally coordinated (first best), no sharing, selective root cause analysis, partial cost allocation, and fixed share rate models, respectively. For proofs of all analytical results see the online appendix.

4.1. Centralized Supply Chain

In this section, we consider the case where a central planner maximizes total supply chain profits by jointly selecting the quality improvement efforts η_s^* and η_m^*. The central planner's optimization problem is given by

$$\underset{\eta_s,\,\eta_m}{\text{Max}}: \Pi^C = r - u_m - u_s - \omega\big[1 - e^{-[\lambda_m^0(1-\eta_m)+\lambda_s^0(1-\eta_s)]}\big] - C_m(\eta_m) - C_s(\eta_s), \tag{1}$$

where r is the product selling price, and u_m and u_s are the unit production costs of the manufacturer and the supplier, respectively.

To ensure concavity of the central planner's maximization problem, we require $\partial^2\Pi^C/\partial\eta_m^2 < 0$ and $\partial^2\Pi^C/\partial\eta_s^2 < 0$, which can be translated into lower bounds on $C_m''(\eta_m)$ and $C_s''(\eta_s)$. Specifically, let $C_m''(\eta_m) > \omega(\lambda_m^0)^2$ and $C_s''(\eta_s) > \omega(\lambda_s^0)^2$ for $\forall(\eta_s, \eta_m) \in [0,1] \times [0,1]$, then:

Proposition 1. *If $C_m''(\eta_m) > \omega(\lambda_m^0)^2$ and $C_s''(\eta_s) > \omega(\lambda_s^0)^2$ for $\forall(\eta_s, \eta_m) \in [0,1] \times [0,1]$ hold, then there exists unique first best supplier and manufacturer efforts $(\eta_s^{*C}, \eta_m^{*C})$ that satisfy the following first order optimality conditions*:

$$\frac{\partial \Pi^C}{\partial \eta_m} = \omega\lambda_m^0 e^{-[\lambda_m^0(1-\eta_m^{*C})+\lambda_s^0(1-\eta_s^{*C})]} - C_m'(\eta_m^{*C}) = 0,$$

$$\frac{\partial \Pi^C}{\partial \eta_s} = \omega\lambda_s^0 e^{-[\lambda_m^0(1-\eta_m^{*C})+\lambda_s^0(1-\eta_s^{*C})]} - C_s'(\eta_s^{*C}) = 0.$$

Note that $\partial^2\Pi^C/(\partial\eta_m\partial\eta_s) = \omega\lambda_m^0\lambda_s^0 e^{-[\lambda_m^0(1-\eta_m^{*C})+\lambda_s^0(1-\eta_s^{*C})]} > 0$, which implies complementarity between effort choices; i.e., η_m^{*C} (η_s^{*C}) is increasing with η_s^C (η_m^C), for all η_s^C, $\eta_m^C \in [0,1]$, and vice versa. The complementarity between effort choices increases with the unit recall cost ω and the initial failure rates of the supplier and the manufacturer. This implies that the interaction effect between effort choices is more significant for newly designed products, which are more likely to have a higher number of design flaws (higher λ_m^0 or λ_s^0) than products that have been on the market for a period of time and have already undergone quality improvements. Because a stronger interaction between effort decisions demands more coordinated decision making, the effort coordinating contracts discussed in this paper may be of greater importance for products that have higher initial failure rates.

In the above formulation, we assume that, upon a recall, all sold and/or distributed items (i.e., all M units) are returned to the manufacturer for repair. This type of consumer recall response behavior is observed for high value products (e.g., automotive and electronics) when product failure has severe safety consequences for the customer. However, for a number of product categories, it is not unusual to have less than a 100% response rate. For example, low value products (low price products), old products, or products that consumers perceive to have low risk are associated with low recall response rates from consumers (Government Consumer Safety Research 2000). When only a fraction of sold items is returned upon recall, the centrally coordinated model as well as the decentralized models under Contract S and Contract P can easily be revised by multiplying ω by the anticipated response rate. In the conclusion section, we further discuss how modeling less than a 100% response rate from consumers would impact our insights.

In the rest of the paper, we refer to the optimal effort levels $(\eta_s^{*C}, \eta_m^{*C})$ and the final product quality in the centralized system, respectively, as the *first best effort* and *first best quality*. We also call the optimal total expected supply chain's profit as the *first best profit*. Note that, the first best effort (first best quality) represents the optimal resolution of the trade-off between the quality improvement effort cost and the recall cost in a centralized system. We use the first best quality as a benchmark to evaluate the quality of the final product in the decentralized supply chain systems.

Next, we examine decentralized supply chain models under different cost sharing agreements (i.e., no cost sharing, selective root cause analysis, and partial cost allocation), where the supplier and the manufacturer maximize their own profits. The fundamental questions we address are as follows: Under which contractual agreement(s) can a decentralized supply chain achieve the first best profit (or the first best quality)? If the contracts cannot achieve the first best profit (or the first best quality), how do they perform relative to the first best benchmarks? We start first with the no cost sharing case.

4.2. No Cost Sharing (N)

In this section, we consider a decentralized setting in which the manufacturer internalizes total recall costs, even though in some cases the supplier may be at fault. In this setting, although the manufacturer exerts some effort to improve his component failure rate, the supplier has no incentive to improve the quality of her component.

The manufacturer's and the supplier's optimization problems are given respectively by

$$\max_{\eta_m}: \Pi_m^N = r - u_m - p_0 - \omega\left[1 - e^{-[\lambda_m^0(1-\eta_m)+\lambda_s^0(1-\eta_s)]}\right] - C_m(\eta_m), \tag{2}$$

$$\max_{\eta_s}: \Pi_s^N = p_0 - u_s - C_s(\eta_s), \tag{3}$$

where p_0 is the manufacturer's part procurement cost. We consider $p_0 \geq u_s$ to ensure that the supplier attains nonnegative profits under the no cost sharing scenario. Note that p_0 does not affect the effort choices of the manufacturer or the supplier but allocates the supply chain profits between the two parties.

The next proposition summarizes optimal supplier and manufacturer effort levels under no cost sharing.

Proposition 2. *Under no cost sharing, the supplier exerts zero effort. The manufacturer underinvests in effort relative to the first best (i.e., $\eta_m^{*N} < \eta_m^{*C}$) even though he fully internalizes all costs associated with his effort choice.*

Under no cost sharing, the optimal manufacturer effort increases with the effort exerted by the supplier. Specifically, the manufacturer's best response function $\eta_m^{*N}(\eta_s^{*N})$ is increasing in η_s^{*N}. This observation, which follows from the positive cross partial derivative of the manufacturer's profit function in η_s and η_m, shows that there is complementarity between the effort choices of the manufacturer and the supplier. Under no cost sharing, the supplier exerts minimum effort because she does not internalize any costs. Therefore, $\eta_s^{*N} < \eta_s^{*C}$. From the complementarity of effort decisions, it follows that $\eta_m^{*N}(\eta_s^{*N} = 0) < \eta_m^{*N}(\eta_s^{*N} = \eta_s^{*C}) = \eta_m^{*C}$. Hence, the analysis of this case demonstrates that even though the manufacturer internalizes all costs associated with his effort choice, due to complementarity between effort choices, he *underinvests* in effort in equilibrium. Consequently, the no sharing scheme not only *directly* affects the effort exerted by the supplier, but also *indirectly* leads to less than the first best level of effort from the manufacturer.

4.3. Selective Root Cause Analysis Contract (Contract S)

In this section, we study the optimal Contract S that maximizes the manufacturer's profit. Before we show this, we would like to emphasize that a contract that leads to higher total supply chain profits also leads to higher profits for the manufacturer, who is modeled as the Stackelberg leader in the supply chain. The conventional approach is that the manufacturer, being the Stackelberg leader, determines the allocation of the total supply chain profits to his supply chain partners. Suppose fraction ν of the total supply profits is allocated to the manufacturer and $(1-\nu)$ to the supplier. Regardless of the exact value of ν, it is clear that for any given value of ν, a contract that results in higher total expected supply chain profit also results in higher expected profits for the manufacturer and the supplier. Therefore, the ranking of the contracts with respect to the total supply chain profits also mimics the ranking of the contracts with respect to the manufacturer's and the supplier's profits.

Interestingly, we find that when the root cause analysis cost is negligible, the optimal contract for the manufacturer (and the supply chain) is an *effort coordinating contract*, which we define as follows:

Definition 1. An effort coordinating contract is a contract that, when implemented in a decentralized system, results in the first best effort levels from the manufacturer and the supplier and therefore attains the first best quality.

Under an effort coordinating contract, when the manufacturer and the supplier maximize their own profits, the optimal effort levels are found to be the first best effort.

Note that, although in a centralized supply chain the first best efforts (η_s^{*C}, η_m^{*C}) result in the maximum total expected profit (first best profit): (i) there is no guarantee that these effort levels also maximize total expected profits in a decentralized the supply chain, and (ii) even if in some cases these effort levels maximize the total expected supply chain profit in a decentralized system, there is no guarantee that a contract exists that can induce these effort levels (i.e., there is no guarantee that an effort coordinating contract always exists). In Lemma 1, we present a condition under which the first best effort levels also maximize the total expected supply chain profit (and hence the manufacturer's profits) in a decentralized system. In Proposition 3, we show that Contract S is flexible enough to be designed as an effort coordinating contract.

Lemma 1. *In a decentralized supply chain, if the root cause analysis cost is negligible (i.e., $c_r = 0$), then an effort coordinating contract maximizes the manufacturer's as well as the total supply chain profits and attains first best quality and profits.*

In practice, if the product architecture is separable (as a result of decoupling, no function sharing, or modular design, see Baiman et al. 2001), then a product failure can easily be traced to a particular component. In contrast, with nonseparable product architecture, it is more difficult (if not impossible) to trace a product failure to a single component. Therefore, for separable product architectures, it is much cheaper to perform the root cause analysis when implementing a cost sharing contract. Lemma 1 shows, when this is the case, in a decentralized supply chain, an effort coordinating contract also maximizes the manufacturer's and the total supply chain profits and attains the first best quality and profits.

Next, we show that there exists an effort coordinating Contract S. Under Contract S, the cost allocation rule is defined as a function of the product's time to failure that results in product recall. If product failure occurs before the root cause analysis threshold time $\overline{T}$, the party responsible for the quality problem is identified through root cause analysis and incurs total recall costs. Otherwise (i.e., if product failure occurs after $\overline{T}$), the supplier only shares a percentage R of the total recall cost.

In practice, we observe a trend toward differentiating quality problems based on their time of occurrence. For example, by centralizing part failure data collected from dealerships, General Motors was one of the first to develop a monitoring system to differentiate early failures from late failures (White 1999). Early failures are classified as special cause quality problems. For these types of product failures, the company pursues a detailed root cause analysis. This information is instantly fed into the design process to eliminate design faults (White 1999). In this paper, we identify ways in which this information can be used for cost sharing purposes.

Contract S is a more general and flexible contract format than the fixed share rate contract, previously modeled in the supply chain management literature. In fact, the fixed share rate contract is a special case of Contract S when $\overline{T} = 0$. As will be discussed below, unlike the fixed share rate contract, the flexibility in the structure of Contract S is critical to obtaining the first best level of effort from the supply chain members.

Under Contract S, the manufacturer and the supplier solve the following optimization problems, respectively:

$$\underset{\eta_m}{\text{Max}}: \Pi_m^S = r - u_m - p - (\omega + c_r)G[1 - e^{-\Lambda_T \overline{T}}] - \omega(1-R)[e^{-\Lambda_T \overline{T}} - e^{-\Lambda_T}] - C_m(\eta_m), \quad (4)$$

$$\underset{\eta_s}{\text{Max}}: \Pi_s^S = p - u_s - (\omega + c_r)(1-G)[1 - e^{-\Lambda_T \overline{T}}] - R\omega[e^{-\Lambda_T \overline{T}} - e^{-\Lambda_T}] - C_s(\eta_s), \quad (5)$$

where $\Lambda_T = \lambda_m^0(1-\eta_m) + \lambda_s^0(1-\eta_s)$ and $G = \lambda_m^o(1-\eta_m)/[\lambda_m^o(1-\eta_m) + \lambda_s^o(1-\eta_s)]$. Note that p is the price under Contract S, where $p \geq p_0$ and $p - p_0$ is the incentive given to the supplier to accept the cost sharing contract.

Our interest is in understanding whether one can design a Contract S that achieves the first best effort levels from supply chain partners. The next proposition describes the equilibrium outcome of the effort game under Contract S, when the manufacturer's and the supplier's initial failure rates are not drastically different (i.e., when $\lambda_s^0 = l\lambda_m^0$, where $l \in [0.36, 2.73]$). See Proposition 3(a) in the online appendix for details.[6]

Proposition 3. *Positive cross partial derivatives of the manufacturer's and the supplier's objective functions ensure that the effort game is supermodular under the selective root cause analysis contract. Furthermore,*

(i) *Supermodularity ensures the existence of at least one Nash equilibrium;*

(ii) *The best response functions $\eta_m^{*S}(\eta_s)$ and $\eta_s^{*S}(\eta_m)$ are both increasing in their arguments;*

[6] Note that $l \in [0.36, 2.73]$ is a sufficient condition that guarantees the supermodularity of the game. In our numerical study we observed cases that violated this condition and the game was still supermodular.

(iii) *The set of equilibria is a chain; i.e., if there are multiple equilibria, they can be ordered as follows: for any pair of equilibria* $(\hat{\eta}_m^{*S}, \hat{\eta}_s^{*S})$ *and* $(\tilde{\eta}_m^{*S}, \tilde{\eta}_s^{*S})$ *either* $\hat{\eta}_m^{*S} \geq \tilde{\eta}_m^{*S}$ *and* $\hat{\eta}_s^{*S} \geq \tilde{\eta}_s^{*S}$ *or* $\hat{\eta}_m^{*S} \leq \tilde{\eta}_m^{*S}$ *and* $\hat{\eta}_s^{*S} \leq \tilde{\eta}_s^{*S}$;

(iv) *If there are multiple equilibria, then for any pair of equilibria* $(\hat{\eta}_m^{*S}, \hat{\eta}_s^{*S})$ *and* $(\tilde{\eta}_m^{*S}, \tilde{\eta}_s^{*S})$, *where* $\hat{\eta}_m^{*S} \geq \tilde{\eta}_m^{*S}$ *and* $\hat{\eta}_s^{*S} \geq \tilde{\eta}_s^{*S}$ *then* $\Pi_m^{*S}(\hat{\eta}_m^{*S}, \hat{\eta}_s^{*S}) \geq \Pi_m^{*S}(\tilde{\eta}_m^{*S}, \tilde{\eta}_s^{*S})$ *and* $\Pi_s^{*S}(\hat{\eta}_m^{*S}, \hat{\eta}_s^{*S}) \geq \Pi_s^{*S}(\tilde{\eta}_m^{*S}, \tilde{\eta}_s^{*S})$.

Although supermodularity ensures the existence of at least one Nash equilibrium, it does not rule out multiple equilibria. However, the equilibria are Pareto rankable and there is a most preferred and a least preferred equilibrium by both parties. From part (iv) of Proposition 3, it follows that both parties prefer the equilibrium where they both show higher effort. Therefore, in what follows, we will be focusing on the most preferred equilibrium (Pareto optimal equilibrium) and avoid the issues associated with multiple equilibria when analyzing the effort coordinating contract (Cachon and Netessine 2004).

The next proposition presents closed-form solutions to the effort coordinating contract parameters that achieve the first best effort levels in the asymmetric effort game with $c_r = 0$ and the symmetric effort game[7] with $c_r \geq 0$. The optimal contract parameters for the asymmetric effort game with $c_r \geq 0$ cannot be characterized in closed-form solutions; therefore, for clarity of exposition, we present a detailed analysis of this case in the online appendix.

Proposition 4. (i) *In the asymmetric effort game with* $c_r \geq 0$, *there exists a unique effort coordinating Contract S defined by* $(R^*, \bar{T}^*)$ *that achieves the first best effort levels from the manufacturer and the supplier.*

(ii) *In the asymmetric effort game with* $c_r = 0$, *the effort coordinating Contract S is given by*

$$R^* = \frac{\lambda_s^0(1-\eta_s^{*C})}{\Lambda_T^{*C}} \quad \text{and} \quad \bar{T}^* = -\frac{\mathrm{Ln}\left(1-\Lambda_T^{*C} e^{-\Lambda_T^{*C}}\right)}{\Lambda_T^{*C}},$$

where $\Lambda_T^{*C} = \lambda_m^0(1-\eta_m^{*C}) + \lambda_s^0(1-\eta_s^{*C})$ *and* $\bar{T}^* < 1$.

(iii) *In the symmetric effort game with* $c_r \geq 0$, *the effort coordinating Contract S is given by*

$$\bar{T}^* = \frac{-\mathrm{Ln}(1-\Lambda_T^{*C} e^{-\Lambda_T^{*C}})}{\Lambda_T^{*C}},$$

where $\bar{T}^* < 1$ *and* $R^* = 0.5$.

We gain the following insights from Proposition 4. First, notice that when both agents exert their first best effort levels, the share rate R is proportional to each party's product failure rate at the first best effort level. Second, one can easily show that the fixed share rate contract ($\bar{T}^* = 0$) and the cost sharing contract that *always* uses root cause analysis information ($\bar{T}^* = 1$) cannot attain first best effort levels. We summarize these insights in the following corollaries.

Corollary 1. *In an effort coordinating Contract S, optimal* $\bar{T}^* > 0$; *therefore, the fixed share rate contract, which is a special case of the selective root cause analysis contract when* $\bar{T} = 0$, *cannot achieve the first best effort levels and coordinate the supply chain. Furthermore, setting* $\bar{T} = 0$ *(i.e., the fixed share rate contract) leads to underinvestment in efforts by the manufacturer and the supplier.*

Corollary 1 shows that the fixed share rate contract cannot coordinate the quality improvement effort levels. More interestingly, in the next corollary, we point out that to achieve the first best quality level, one does not need to always use the root cause analysis information, even if it were costless and could perfectly identify the party at fault.

Corollary 2. *In an effort coordinating Contract S, optimal* $\bar{T}^* < 1$; *therefore, always performing root cause analysis and allocating the recall cost to the party responsible for the quality problem, even if it were costless to do so, would not attain the first best effort levels. Furthermore, setting* $\bar{T} = 1$ *would lead to an overinvestment in effort by the manufacturer and the supplier.*

Lastly, we observe that $d\bar{T}^*/d\Lambda_T^{*C} < 0$. This implies that when the coordinated total aggregate failure rate at the first best is smaller, (i.e., high effort is exerted at the first best), then the root cause analysis threshold, $\bar{T}^*$, is larger, resulting in a higher likelihood of sharing recall costs based on root cause analysis information. In other words, the more both parties improve the quality of their components, the more both sides are likely to determine the party at fault in case of a failure that results in a recall.

4.4. Partial Cost Allocation Contract (Contract P)

In this section, we introduce an alternative cost allocation rule that can also achieve the first best effort levels from the manufacturer and the supplier. Under this cost allocation scheme, the cost is *always* shared between the manufacturer and the supplier. However, the sharing rates are adjusted according to the root cause analysis information. More specifically, we denote R_m and $(1-R_m)$ as the supplier's and the manufacturer's share of the recall cost, respectively, when the *manufacturer* is at fault. Similarly R_s and $(1-R_s)$ are the supplier's and the manufacturer's share of the recall cost, respectively, when the *supplier* is at fault. Under the partial cost allocation scheme, we have $0 \leq R_m \leq 1$ and $0 \leq R_s \leq 1$ and $R_s \geq R_m$. The last inequality ensures that the supplier assumes a larger fraction of the recall cost when she is at fault compared to the case when the manufacturer is at fault.

[7] In the symmetric game, the manufacturer and the supplier have identical effort cost functions and initial product failure rates.

Analogous to the selective root cause analysis contract, we will consider an effort game under Contract P, in which the manufacturer's and the supplier's strategies are complements. Furthermore, we will focus on the Pareto optimal equilibrium outcome of this game, where both parties show high effort. (See Online Appendix B for a discussion of the supermodularity condition and elimination of multiple equilibria.)

Proposition 5. (i) *In the asymmetric effort game with* $c_r = 0$, *if there exists* R_s^* *and* R_m^*, *such that*

$$R_m^* = \frac{e^{2\lambda'_T}}{(-e^{\lambda_T^0} + e^{\lambda'_T})(\lambda_T^{*C})} \cdot \{e^{\lambda_T^0}\lambda_m^{*C} + e^{\lambda'_T}[(\lambda_s^{*C})^2 - \lambda_m^{*C}(1-\lambda_s^{*C})] + e^{\lambda_T^0}(\lambda_s^{*C}\lambda_s^0 - \lambda_m^{*C}\lambda_m^0) - e^{\lambda'_T}Z\},$$

$$R_s^* = R_m^* + \frac{\lambda_T^{*C}[1-\lambda_T^0]}{e^{\lambda_T^{*C}}}$$

and $0 \le R_s^*, R_m^* \le 1$, *then there exists an effort coordinating partial cost allocation contract that achieves the first best level of effort where* $\lambda_T^0 = \lambda_m^0 + \lambda_s^0$, $\lambda_i^{*C} = \lambda_i^0(1-\eta_i^{*C})$ *for* $i = s, m$, $\lambda_T^{*C} = \lambda_s^{*C} + \lambda_m^{*C}$, $\lambda'_T = \lambda_T^0 - \lambda_T^{*C}$, *and* $Z = \lambda_s^{*C} \cdot (2 - \eta_m^{*C} - \eta_s^{*C})\lambda_m^0\lambda_s^0 + \lambda_s^{*C}(1+\lambda_s^{*C})\lambda_s^0 - \lambda_m^{*C}\lambda_m^0(1-\lambda_s^{*C})$.

(ii) *In the symmetric effort game with* $c_r \ge 0$, *if there exists* R_s^* *and* R_m^*, *such that*

$$R_m^* = \frac{A^*D^* - B^*\lambda_m^0 e^{-\lambda_T^{*C}} + A^*\lambda_s^0 e^{-\lambda_T^{*C}}}{B^*C^* + A^*D^*},$$

$$R_s^* = R_m^* \frac{A^*}{(A^*-C^*)} - \frac{\lambda_m^0 e^{-\lambda_T^{*C}}}{(A^*-C^*)}$$

and $0 \le R_s^*, R_m^* \le 1$, *then there exists a coordinating partial cost allocation contract that achieves the first best level of effort. The expressions* $A^* = -(1 + c_r/\omega) \cdot (G'_m H - GH'_m)$, $B^* = (1 + c_r/\omega)(G'_s H - GH'_s)$, $C^* = (1 + c_r/\omega)H'_m$, *and* $D^* = (1 + c_r/\omega)H'_m$ *are evaluated at* $(\eta_m^{*C}, \eta_s^{*C})$. *Furthermore,*

$$H = 1 - e^{-[\lambda_m^o(1-\eta_m) + \lambda_s^o(1-\eta_s)]},$$

$$H'_i = -\lambda_i^0 e^{-(\lambda_m^0(1-\eta_m) + \lambda_s^0(1-\eta_s))},$$

$$G = \frac{\lambda_m^o(1-\eta_m)}{\lambda_m^o(1-\eta_m) + \lambda_s^o(1-\eta_s)}, \qquad G'_m = -K(1-G),$$

$$G'_s = GK\frac{\lambda_s^o}{\lambda_m^o}, \quad \text{and} \quad K = \frac{\lambda_m^o}{\lambda_m^o(1-\eta_m^C) + \lambda_s^o(1-\eta_s^C)}.$$

In practice, it is not unusual to encounter situations in which a supplier, particularly if it is a small-sized company, faces budget constraints that limit the maximum cost allocated to the firm. In such situations, even if the supplier is at fault, the manufacturer may choose to refrain from allocating total costs to the supplier, as it may lead to her bankruptcy (Sherefkin and Armstrong 2003). One example is Bremi Auto-Elektrik, a supplier of ignition coils for Volkswagen AG. In February 2003, VW recalled about 500,000 VW and Audi vehicles in the United States, from the 2002 and 2004 model years, to replace their faulty ignition coils. The recall cost for VW was \$83 million, whereas Bremi's annual revenue was estimated at approximately \$40 million (Sherefkin and Armstrong 2003).

Under such circumstances, our findings are particularly interesting in the sense that even if the supplier does not internalize the full liability and costs associated with her part failure, we show that the first best effort levels and quality can still be attained if the share rates are set optimally as demonstrated in the above proposition.

Although both effort coordinating Contracts S and P result in the first best profits for the total supply chain and maximize manufacturer's profits when the root cause analysis is zero, these effort coordinating contracts lead to different total expected supply chain profits when the root cause analysis is greater than zero.

Corollary 3. *When the root cause analysis cost is significant (i.e.,* $c_r > 0$*), at the coordinated first best effort level, Contract S results in higher total supply chain profits than Contract P.*

Notice that $\overline{T}^* < 1$, which implies that at the first best level of effort there is a smaller likelihood that a root cause analysis will be performed under Contract S than under Contract P. This results in smaller expected root cause analysis costs for Contract S than for Contract P. Because under the first best effort levels, the effort and the expected recall costs are the same for both contracts, a smaller expected root cause analysis cost leads to higher total supply chain profits for Contract S. As the root cause analysis threshold $\overline{T}^*$ gets larger, which occurs when it is critical to induce higher effort and achieve lower failure rate at the first best effort, the cost difference between the two contracts diminishes.

5. Efficiency of Contracts

In the previous section, we showed that both Contract S and Contract P can be designed to coordinate the manufacturer's and the supplier's quality improvement efforts (attain the first best effort levels) in the decentralized setting. Also, we showed that when the root cause analysis cost is zero, the effort coordinating contracts P and S result in the maximum total supply chain profits (first best profits) as well as the maximum profits for the manufacturer. When the root cause analysis cost is not zero, Corollary 3 shows that, at the first best effort levels, Contract S results in higher expected profits for the supply chain than Contract P. In this section, we examine whether, for cases with nonzero root cause analysis cost, the superiority of Contract S extends beyond the first best effort levels.[8] Specifically, we consider cases in which root cause analysis is not zero, and we evaluate the gap between the performance of each contract with that of a centralized system. We also provide insights into the factors that impact this gap.

We would like to emphasize that, as we mentioned before, contracts that result in higher total expected supply chain profit, will also result in higher expected profit for the manufacturer and for the supplier. Therefore, in this section we evaluate contracts based on their total expected supply chain performance. Furthermore, because the revenue ($=r \times M$) is constant, comparing contracts based on total expected supply chain profits is equivalent to comparing contracts based on total expected supply chain costs. Thus, we compare total expected costs of different contracts in a decentralized system with that of a centralized system.

We measure contract performance along two dimensions: (i) the total expected supply chain cost and (ii) the final product quality, measured by the final product failure rate after quality improvement efforts. We define a cost inefficiency index (C_I) and a quality inefficiency index (Q_I) to compare the decentralized supply chain performance to that of the centrally coordinated system. More specifically, we calculate *cost* inefficiency index C_I and *quality* inefficiency index Q_I as

$$C_I^k = \frac{SC^k - SC^C}{SC^C} \times 100\%, \qquad Q_I^k = \frac{\Lambda_T^k - \Lambda_T^C}{\Lambda_T^C} \times 100\%,$$

where SC^k and Λ_T^k are the total expected supply chain cost and the final product failure rate (i.e., quality) under Contract k, and SC^C and Λ_T^C are the total supply chain cost and final product failure rate of the centrally coordinated supply chain. Note that lower values of $|C_I|$ and $|Q_I|$ report a performance closer to the centrally coordinated system.

Online Appendix E presents the details of 12,960 cases that we examined in our numerical study. Table 2 reports the average and the maximum values of C_I and Q_I across 12,960 cases. From our numerical analysis, we gain the following insights regarding the comparison among the three contracts: fixed share rate, Contract S, and Contract P.

• We find that the manufacturer prefers the selective root cause analysis contract over the fixed share rate and the partial cost allocation contracts in terms of the average and the maximum total expected costs

[8] Note that when $c_r > 0$, the first best effort levels do not necessarily maximize the manufacturer's profits or the total expected supply chain profits in a decentralized setting.

Table 2 Cost and Quality Index Comparisons

	Contract F (%)	Contract S (%)	Contract P (%)
Average cost inefficiency index	5.17	3.64	31.27
Maximum cost inefficiency index	19.73	16.39	100.04
Average quality inefficiency index	54.57	24.74	−22.41
Maximum quality inefficiency index	290	121	−0.04

Note. Note that a negative quality index reports an overinvestment in quality improvement effort relative to the first best effort levels.

(profits). As Table 2 shows, on average, the total expected supply chain cost of Contract S is lower than that under Contract F and Contract P.

• The gap in cost efficiency between the selective root cause analysis contract and fixed share rate contract increases as (i) the gap between the unit recall cost (ω) and the unit root cause analysis cost (c_r) increases, (ii) the initial failure rate increases leading to higher investment in effort, and (iii) the sales volume of the product increases, leading to an increase in the likelihood of observing product failure. We also observe that when the convexity of the effort cost function increases, the selective root cause analysis contract performs significantly better than the fixed share rate because, due to the high cost of effort, the fixed share rate contract drastically underinvests in effort when compared to Contract S. However, because Contract S involves root cause analysis and determines the responsible party for product failure, Contract S results in higher quality and lower expected recall cost in the supply chain. This suggests that when making incremental quality improvement is more difficult (i.e., for instance, when several easily identifiable quality improvement opportunities have already been implemented), then Contract S is a better alternative for cost sharing than Contract F.

• The selective root cause analysis contract not only results in a much smaller total supply chain cost compared to fixed share rate contract, but also results in a better quality product. As Table 2 shows, the quality of the final product under the selective root cause analysis contract is, on average, more than twice better than that under the fixed share rate contract.

• We find that, in general, the gap between the product quality under the selective root cause analysis contract and that in a centralized system increases as (i) the unit root cause analysis cost increases, (ii) the convexity of the manufacturer's (supplier's) effort cost function increases, especially when the convexity of the supplier's (the manufacturer's) effort cost function is low, and (iii) the initial failure rates of the manufacturer and the supplier increase.

• The gap in cost efficiency between the selective root cause analysis contract and the partial cost allocation contract generally decreases when (i) the unit recall cost increases, (ii) the convexity of the effort cost function decreases, and (iii) the initial failure rates of the manufacturer and the supplier increase. Note that, under Contract P, the manufacturer's and the supplier's quality improvement efforts not only impact the product's aggregate failure rate and the likelihood of a recall, but also, once the product has failed and the recall is initiated, determine who will eventually assume the recall responsibility, i.e., the cost share rate. As a result of these two confounding effects of effort on the manufacturer's and the supplier's profit functions, we observe overinvestment in effort and 22.41% better product quality than that in the centralized system. This improved quality, however, brings about, on average, a 31.27% additional cost as compared to the centralized system.

• On average, the product quality was closer to the first best effort levels under the selective root cause analysis contract than under the fixed share rate and partial cost allocation contracts.

6. Asymmetric Information About Supplier's Component Quality

In §§4 and 5, we showed that, under complete information about the supplier's initial component quality (prior to quality improvement effort), compared to the fixed share rate and the partial cost allocation contracts, the selective root cause analysis contract results in higher total expected supply chain profits as well as higher expected profits for the manufacturer. In this section, we further study the efficiency of Contract S when the manufacturer does not have complete information about the supplier's initial component quality. We present a mixed model of adverse selection followed by moral hazard on the supplier side and investigate the effectiveness of the selective root cause analysis contract to screen supplier type as well as to induce quality improvement effort.[9]

Consistent with the extant literature (Lim 2001; Baiman et al. 2000, 2001, 2003; Laffont and Martimort 2002), we make the following assumptions:

Assumption B1. *We assume that the supplier's process can be of either a low quality process (i.e., high failure) type with probability α or a high quality process (i.e., low failure) type with probability $1-\alpha$, where $0<\alpha<1$. Furthermore, the high failure type supplier has an initial failure rate of $\lambda^0_{s_H}$ whereas the low failure type supplier has an initial failure rate of $\lambda^0_{s_L}$, where $\lambda^0_{s_H} > \lambda^0_{s_L}$. At the time of contracting, the supplier knows her type, whereas the manufacturer knows that the supplier can have failure rates $\lambda^0_{s_H}$ or $\lambda^0_{s_L}$ with probability α and $(1-\alpha)$, respectively.*

Assumption B2. *To capture the impact of information asymmetry on the supplier side, we assume that the manufacturer has already invested quality improvement effort in his process when he offers a contract to the supplier. We will denote the manufacturer's failure rate by λ^0_m.*

Assumption B2 represents cases in which a quality level for the manufacturer's component has already been decided and a limited budget is assigned for it. Thus, the failure rate λ^0_m in our model represents the manufacturer's final component failure rate. In our numerical study of the asymmetric information, we study a more general case in which the manufacturer also exerts optimal effort to improve his process quality (refer to §7).

Assumption B3. *We will assume that there are two types of quality improvement efforts that the supplier of type j can exert, i.e., high effort $\eta^H_{s_j}$ and low effort $\eta^L_{s_j}$, independent of the supplier type. From the convexity assumption on the effort cost function, it follows that $C_{s_j}(\eta^H_{s_j}) > C_{s_j}(\eta^L_{s_j})$.*

Low quality effort η^L corresponds to a marginal improvement in the supplier's component quality, whereas high quality effort η^H corresponds to a significant improvement in her product quality. We believe that, although simple enough to make our analysis tractable, this assumption captures the dynamics of the effort decision in our setting and its impact on the the optimal menu of contracts. Furthermore, in the real world, the decision on how to improve quality is sometimes limited to two or three options. Thus, assuming two effort levels is also not far from many cases in practice. We also performed a numerical study in §7 in which we study a more general case with continuous effort functions.

Assumption B4. *We assume that the supplier's quality improvement effort is not contractible; therefore, it cannot be specified in a contract.*

Hence, in addition to the adverse selection problem stated in Assumption B1, the manufacturer also faces a moral hazard problem on the supplier side. In what follows, we model the following sequence of events.

Step 1. The manufacturer moves first and offers a menu of selective root cause analysis contracts to the supplier.

Step 2. The supplier j either rejects the menu or accepts one of the contracts from the menu.

Step 3. The supplier j exerts effort $\eta^b_{s_j}$, where $b=L$ and $b=H$ will denote the low and high effort levels, respectively.

[9] During the course of our numerical study we observed that for a wide range of parameter values, Contract S always outperformed Contracts P and F in the asymmetric information case. Therefore, in this section, we particularly focus on Contract S.

Step 4. The manufacturer procures the part, manufactures the product, and sells it at price r.

Step 5. The final quality of the product and the recall cost is realized and shared according to the contract accepted in Step 2.

The manufacturer offers a menu of selective root cause analysis contracts $\{S_L, S_H\}$, where $S_L = (p_L, R_L, \overline{T}_L)$ denotes the contract designed for the low failure type supplier and $S_H = (p_H, R_H, \overline{T}_H)$ is the contract designed for the high failure type supplier. Laffont and Martimort (2002) show that, in a mixed model of moral hazard and adverse selection, the revelation principle (Kreps 1990) still applies, and therefore, one can focus on the menu of contracts that induces a truthful revelation of the supplier type. After a contract is accepted from the menu, the supplier chooses the investment in quality improvement effort that maximizes her profits.

To ensure truthful revelation of the supplier type, the menu of contracts should be *incentive compatible*. Secondly, for a contract to be accepted by the suppliers, their *participation constraints* must be satisfied. Lastly, to induce optimal effort in equilibrium, two *moral hazard incentive constraints* must hold depending on the effort level that the manufacturer wants to induce from each supplier type. For a detailed discussion, and the proofs of our analytical results see Online Appendix C.

In Lemma 2 we present a sufficient condition under which a menu of Contract S that ensures the separation of supplier types exists.

Lemma 2. *A sufficient condition to ensure the separation of supplier types in equilibrium under a menu of selective root cause analysis contracts is given by* $\lambda_m^0 + \lambda_{s_H}^0 (1 - \eta_{s_H}^L) < 1$.

Lemma 2 states that when the largest attainable failure rate is bounded from above by one, then screening of supplier types is possible using a menu of contracts. Note that $\lambda_m^0 + \lambda_{s_H}^0 (1 - \eta_{s_H}^L)$ is the failure rate of the final product that results in a recall. It is not unrealistic to assume that this failure rate is less than one, because given a constant failure rate of recall related failures, the above condition implies that the probability of a failure that results in a recall should be less than 63%, which is much larger than what really occurs in practice. Therefore, this condition is not a restrictive assumption.

The intuition behind this condition becomes clear when it is rewritten as $\lambda_m^0 < 1 - \lambda_{s_H}^0 (1 - \eta_{s_H}^L)$, which imposes an upper bound on the manufacturer's failure rate. Now consider an extreme case, where λ_m^0 is very large, much larger than the failure rates of both supplier types. In this case, the failure would be the manufacturer's fault with probability one. Under these circumstances, the menu of contracts consists of two contracts that have $\overline{T}_H^*$ and $\overline{T}_L^*$ very close to one. This implies that R_H^* and R_L^* have almost no impact on separating the supplier type. Thus, both suppliers have an incentive to choose the contract with the higher price, because under both contracts, with probability one, the recall will be the manufacturer's fault.

Proposition 6. *In an incentive compatible menu of selective root cause analysis contracts, which ensures separation of supplier types, it is sufficient that the high failure rate supplier has a lower fixed share rate* ($R_H < R_L$) *and a lower root cause analysis threshold* ($\overline{T}_H < \overline{T}_L$) *than the low failure rate type supplier.*

Proposition 6 shows that the manufacturer uses a higher root cause analysis threshold time (which, ceteris paribus, results in a higher likelihood of performing root cause analysis) and a higher cost share rate for the low failure rate supplier to deter the high failure rate supplier from mimicking him or her. Thus, the manufacturer makes it more costly for the high failure rate (low quality) supplier to misrepresent his or her type while not imposing a huge cost burden on the low failure rate (high quality) supplier.

Below we list our insights regarding the optimal menu of selective root cause analysis contract. (Please refer to Online Appendix C for proofs of these remarks.)

Remark 1. It is optimal to induce high effort from a high failure rate supplier (i.e., $\eta_{s_H}^H$) when the information rent given to the low failure rate supplier and the incremental effort cost is less than the savings in expected recall cost incurred at the higher effort level.

Remark 2. When it is optimal for the manufacturer to induce low effort from the high failure rate supplier (i.e., $R_H^* = 0$ and $\overline{T}_H^* = 0$), then it is optimal to induce the centrally coordinated (first best) effort level ($\eta_{s_L}^{*C}$) from the low failure rate supplier.

Remark 3. When $R_H^* > 0$ and $\overline{T}_H^* > 0$ (i.e., when it is optimal to induce high effort from the high failure rate supplier), then it is optimal to induce high effort from the low failure rate supplier when the savings in external quality costs dominate the information rent and the incremental effort cost incurred due to high effort.

In summary, we show that even when the manufacturer does not have complete information about the process quality of his supplier, he could design a menu of selective root cause analysis contracts to both screen supplier types and at the same time induce supplier effort. To ensure separation of supplier types, in the optimal menu of contracts, the high failure rate supplier is allocated a smaller share of total cost (smaller R) and a smaller root cause analysis threshold ($\overline{T}$) than the cost sharing contract designed for the low failure rate supplier (i.e., $R_L^* > R_H^*$ and $\overline{T}_L^* > \overline{T}_H^*$). Because the manufacturer's problem involves both an adverse selection and a moral hazard issue, we find that if the manufacturer were to induce high effort from the high failure rate supplier, then he would need to allocate higher information rent. Therefore, the existence of an adverse selection problem adds an information cost to inducing effort in the moral hazard problem. In the selective root cause analysis contract, the contract parameters R and $\overline{T}$ provide the much needed flexibility to the manufacturer to handle this effort inducement versus information rent trade-off in the supply chain. In Online Appendix D, we present an algorithm that yields the manufacturer's optimal menu of contracts.

7. Numerical Study for the Information Asymmetry Case

In the previous section, we presented analytical results that provide some insights into the properties of the optimal menu of selective root cause analysis contracts. In this section, we perform an extensive numerical study, and we investigate the implications of information asymmetry. Specifically, we address the following questions:

1. The value of information: How much does knowing the information about the supplier's failure rate (i.e., the supplier type) improve the manufacturer's costs[10] and the quality of the final product? Under what circumstances is the value of this information significant?

2. The value of a menu of contracts: How much does using a menu of selective root cause analysis contracts reduce the manufacturer's cost? What is the impact of implementing the menu of contracts on the quality of the final product? Under what circumstances is the impact of the menu of contracts on the manufacturer's cost and on the final product quality significant?

Our numerical study is based on more general systems in which (i) the quality improvement effort is a continuous decision variable and assumes a value between zero and one and (ii) the manufacturer can also exert quality improvement effort between zero and one. Online Appendix E presents the details of 5,400 cases that we examined in our numerical study. To establish a basis of comparison to represent the case with no perfect information, we evaluate the manufacturer's total expected cost when he designs a single optimal selective root cause analysis contract based on the higher supplier failure rate.[11] We call this contract the *conservative case*. Furthermore, we refer to the manufacturer's optimal expected cost when he knows the exact supplier's failure rate before contracting as the *perfect information case*. Next, we present the value of knowing the supplier type information measured by the impact of this information on the manufacturer's total expected costs and the final product quality.

7.1. Value of Information

To investigate the value of perfect information about the supplier's product quality (i.e., failure rate), for each of our 5,400 cases, we compared the manufacturer's cost and product quality under perfect information with those in the conservative case through the following metrics:

$$VOI_{\text{cost}} = \frac{MC^{*\text{Conserv.}} - MC^{*\text{Perfect}}}{MC^{*\text{Perfect}}} \times 100\%,$$

$$VOI_{\text{quality}} = \frac{\Lambda_T^{*\text{Conserv.}} - \Lambda_T^{*\text{Perfect}}}{\Lambda_T^{*\text{Perfect}}} \times 100\%,$$

where $MC^{*\text{Conserv.}}$ is the manufacturer's optimal expected cost under the conservative scenario, and VOI_{cost} is the percent decrease in the manufacturer's total expected cost if he can acquire the supplier's failure rate information. In contrast, VOI_{quality} is the percent decrease in the failure rate (i.e., percent increase in quality) of the final product, if the manufacturer acquires information about the supplier's failure rate.

7.1.1. Impact on Costs. Based on our numerical study, we found that knowing the supplier's failure rate information can decrease the manufacturer's cost, on average, by 10.14%. We also observed that, in some cases, the value of information can be as high as 46.28%. The value of information increases when (i) the difference between the failure rates of the high and the low quality supplier increases, (ii) the unit recall cost is high compared to the unit cost of root cause analysis, and (iii) the initial failure rate of the manufacturer is less than the initial failure rate of the supplier.

We also observed that, all else being equal, the value of information has its maximum value when the likelihood of high failure rate supplier, $\alpha = 0.5$ (which represents the maximum variability of the supplier's failure rate).

We find that information is particularly valuable to a manufacturer when he has a good production process in place that is characterized by a lower failure rate. When this is the case, the likelihood of a recall resulting from the supplier's component quality is higher. Consequently, the value of information about

[10] Because the manufacturer's revenues are constant and are independent of the effort decisions, maximization of the manufacturer's profits is equivalent to minimization of his expected total cost. Therefore, comparing the menu of contracts in terms of optimal profits is equivalent to comparing the menu of contracts in terms of total expected cost.

[11] Assuming a conservative failure rate ensures that both type of suppliers accept the contract offered by the manufacturer.

supplier's component quality is higher. Therefore, for a manufacturer with good internal process capabilities, it is critical to know with what type of supplier he is contracting.

7.1.2. Impact on Quality. Although the manufacturer's expected cost always decreases as he receives perfect information (i.e., VOI_{cost} is always positive), this does not mean that the quality of the final product also improves when perfect information becomes available. We observed that in 1,658 out of 5,400 cases of our numerical study, the VOI_{quality} was negative, which indicates that the quality of the final product is lower in scenarios with perfect information. Specifically, we found that in the 1,658 cases that VOI_{quality} was negative, the average and the minimum of VOI_{quality} were -1.6% and -12%, respectively. The remaining 3,742 had positive VOI_{quality}, with an average and a maximum of 2.3% and 89.06%, respectively.

Note that the optimal contracts under both conservative and perfect information are designed to capture the best trade-off between effort cost and expected recall cost (and thus to minimize the manufacturer's total expected cost). Minimization of the manufacturer's total expected cost does not necessarily guarantee the improvement in product quality. However, it is interesting to find cases when having perfect information about the supplier's initial product quality improves both supply chain cost and final product quality. These correspond to cases with negative VOI_{quality}. We observed this in the following cases: (i) when both manufacturer and supplier produce low quality components (i.e., the initial failure rates of the manufacturer and the supplier are high), (ii) when the manufacturer produces a better quality component than the supplier (i.e., the supplier's failure rate is higher than the manufacturer's failure rate), and (iii) when the unit recall cost is high, then having perfect information about the supplier's quality significantly improves the quality of the final product.

Our numerical results show that the products for which failure can lead to serious safety hazards (i.e., product failure can lead to a high recall cost, e.g., the tire recall experienced by Ford and Firestone), it is critical to know the internal process capabilities of the supplier and its product's failure rate. Therefore, in these cases, the manufacturer can benefit from a long term relationship with its supplier where he acquires a better understanding of the supplier's product and process characteristics.

7.2. Value of a Menu of Contracts

In the previous section we provided insights into cases in which the value of perfect information about supplier failure rate can reduce the manufacturer's cost significantly. Those cases present an opportunity to capture some of the value of information by implementing a menu of contracts. In this section, we investigate how much of the value of perfect information can be captured through the optimal menu of selective root cause analysis contracts. To measure this, we use the following two metrics:

$$VOM_{\text{cost}} = \frac{MC^{*\text{Conserv.}} - MC^{*\text{Menu}}}{MC^{*\text{Perfect}}} \times 100\%,$$

$$VOM_{\text{quality}} = \frac{\Lambda_T^{*\text{Conserv.}} - \Lambda_T^{*\text{Menu}}}{\Lambda_T^{*\text{Perfect}}} \times 100\%,$$

where $MC^{*\text{Menu}}$ is the manufacturer's total cost if it offers the optimal menu of contracts to the supplier. On the other hand, VOM_{cost} (VOM_{quality}) is the improvement in the manufacturer's expected cost (quality) under an optimal menu of Contract S as a percentage of the cost (quality) under complete information.

For each of 5,400 cases of our numerical study, we obtained the optimal menu of contracts, and we calculated the manufacturer's expected cost as well as the quality of the final product.

7.2.1. Impact on Costs. Based on our numerical study, we found that using the optimal menu of contracts can decrease the manufacturer's cost, on average, by 9.35%. Comparing this number with the average VOI_{cost} (which represents the average value of perfect information), we see that the menu of contracts, on average, captures 92% (=1 − (10.14% − 9.35%)/10.14%) of the value of perfect information. We also observed that, similar to the value of perfect information, the maximum value of the menu (i.e., the maximum VOM_{cost}) was also as high as 46.3%. These observations imply that the optimal menu of selective root cause analysis contracts is an efficient way to deal with information asymmetry.

We observe that the same conditions that result in the higher value of information (i.e., conditions discussed in §7.1) also result in higher value for the menu. This is expected because, if the menu captures a large fraction of the value of information, and if the value of information is high, so is the value of the menu.

7.2.2. Impact on Quality. To investigate the impact of implementing the optimal menu of contracts on final product quality, we study the VOM_{quality} for all of our 5,400 cases. We observe that implementing the optimal menu of contracts results in higher final product quality compared to that under the conservative case. Specifically, we find that VOM_{quality} has an average and a maximum of 13.79% and 102.93%, respectively. The improvement in product quality under the menu of contracts is larger when (i) the manufacturer has a better initial quality than the supplier, (ii) there is a larger difference between the initial product quality of the two supplier types, and (iii) the unit recall cost is larger.

Note that, in case of asymmetric information, higher product quality relative to the complete information case is the result of the manufacturer's and the supplier's overinvestment in quality improvement effort under a menu of contracts. This happens because, to separate supplier types, the manufacturer is forced to induce inefficient effort levels and this results in overinvestment in effort. It is only through this distortion (overinvestment in effort relative to the perfect information case) that the manufacturer ensures the suppliers do not mimic each other's type. However, the better product quality through overinvestment in effort does not come free for the manufacturer and the supply chain. The profit of the manufacturer and the supply chain are lower in the asymmetric information case than under the perfect information case. One can think about this effort distortion phenomenon as the cost of information asymmetry between the supplier and the manufacturer.

Finally, we must mention that there was not a significant difference in the value of information (or the value of a menu) across cases of zero versus nonzero root cause analysis cost. This is not unexpected, because the existence of nonzero root cause analysis cost does not impact the level of uncertainty in the asymmetric information case.

In conclusion, our numerical experiments show that implementing a menu of selective root cause analysis contracts is particularly valuable for a firm when the product is new to the market (i.e., the initial failure rates are generally high), the manufacturer has a relatively better process capability than his supplier (i.e., lower initial failure rate of the manufacturer as compared to the supplier), and the supplier is new to the manufacturer, in the sense that the manufacturer has less information about the supplier's process capability and faces greater uncertainty about the supplier type (a large range of possible supplier initial failure rates).

8. Conclusion

As design, engineering, and manufacturing activities evolve into the shared responsibility of supply chain members, manufacturers face the challenging task of managing their suppliers' incentives to invest in improving process quality. In this paper, we focus on recall instances, and we introduce two external quality cost sharing contracts to improve final product quality when both the manufacturer's and the supplier's quality improvement effort decisions are subject to moral hazard and when there is information asymmetry between the manufacturer and the supplier regarding the supplier's process quality. The extant literature has discussed the fixed share rate contract, which allocates quality costs to supply chain members irrespective of the root cause of the quality problem. In this paper, we focus on understanding how the root cause analysis information should be used in contract design.

Under the complete information assumption, we first show that, when the root cause analysis cost is negligible, the optimal contract for the manufacturer is an effort coordinating contract (P or S) that attains the first best effort levels from the manufacturer and the supplier. Interestingly, we find that, to coordinate quality improvement effort decisions in a supply chain, it is not always necessary to use the root cause analysis information to allocate quality costs even if this information is perfect and available at no cost. In fact, we find that always allocating the total recall cost to the party who is at fault and has the sole responsibility for the quality problem can lead to overinvestment in quality improvement effort and can be costly to the supply chain. A selective root cause analysis contract, which adjusts the cost sharing rule to the time of failure, overcomes the overinvestment problem, and attains the first best effort levels from the supply chain members.

When the root cause analysis cost is not negligible, we find that from the manufacturer's and from the total supply chain perspective, the selective root cause analysis contract consistently performs better than the fixed share rate and the partial cost allocation contracts. Furthermore, on average, the product quality is closer to the first best quality under the selective root cause analysis contract than under the fixed share rate and partial cost allocation contracts. The partial cost allocation contract results in overinvestment in quality improvement effort leading to a lower product failure rate than that in the centralized system. This improved quality, however, brings about additional costs as compared to a centralized system.

In the last section of the paper, we relaxed the complete information assumption and introduced a mixed model of adverse selection and moral hazard to investigate the effectiveness of a menu of selective root cause analysis contracts to both screen supplier type and induce quality improvement effort. Even when the manufacturer does not have complete information about the process quality of his supplier, we show that one can design a menu of selective root cause analysis contracts to both screen supplier type and induce supplier effort. Our numerical analysis also shows that by implementing a menu of selective root cause analysis contracts, a manufacturer can attain a very close to perfect information outcome.

In this paper, we made some assumptions in order to provide a first cut analysis of the contract design problem in a product recall setting. Our future research will relax these assumptions to develop further understanding of additional aspects of recall management. For example, we assume that the response rate to a recall announcement is 100% from the consumers. Our model and analysis can easily be extended to include less than perfect consumer response. In general, we find that, as the response rate decreases, the expected unit recall cost decreases, which leads to lower incentives for the supply chain members to improve product quality. Also, we assumed that the recall is initiated whenever the first product failure is observed. In practice, when the quality failure does not constitute a huge risk to consumers, the manufacturer may choose to initiate a recall only after a number of product failures are observed. The decision of when to initiate a recall is certainly an interesting one. We leave the joint modeling of contract design and recall timing for future research.

The supply chain we consider consists of a single manufacturer and a single supplier. A direct extension of this study is to look into a network of suppliers and understand the design of external quality cost sharing contracts for recalls with multiple suppliers.

9. Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

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