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Product Design and Supply Chain Coordination Under Extended Producer Responsibility

Ravi Subramanian
College of Management, Georgia Institute of Technology, Atlanta, Georgia 30308, ravi.subramanian@mgt.gatech.edu

Sudheer Gupta
Faculty of Business Administration, Simon Fraser University, Burnaby, BC, Canada V5A 1S6, sudheerg@sfu.ca

Brian Talbot
Ross School of Business, University of Michigan, Ann Arbor, Michigan 48109, btalbot@umich.edu

Extended Producer Responsibility (EPR) legislation focuses on the life-cycle environmental performance of products and has significant implications for management theory and practice. In this paper, we examine the influence of EPR policy parameters on product design and coordination incentives in a durable product supply chain. We model a manufacturer supplying a remanufacturable product to a customer over multiple periods. The manufacturer invests in two design attributes of the product that impact costs incurred by the supply chain—*performance*, which affects the environmental impact of the product during use, and *remanufacturability*, which affects the environmental impact post-use. Consistent with the goals of EPR policies, the manufacturer and the customer are required to share the environmental costs incurred over the product's life cycle. The customer has a continuing need for the services of the product and optimizes between the costs of product replacement and the costs incurred during use. We demonstrate how charges during use and post-use can be used as levers to encourage environmentally favorable product design. We analyze the impact of supply chain coordination on design choices and profit and discuss contracts that can be used to achieve coordination, both under symmetric and asymmetric information about customer attributes.

Key words: Extended Producer Responsibility; product design; supply chain coordination; information asymmetry; contracts
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1. Introduction and Literature

With increasing public awareness and concern about the environmental impacts of products and production processes, goal-oriented approaches are being sought to encourage sustainable design and use of products. An excellent example of such an approach is Extended Producer Responsibility (EPR), which focuses on the life-cycle environmental performance of products. There are two related objectives of any EPR policy—shifting responsibility upstream toward the manufacturer and away from municipalities, and providing incentives to manufacturers to incorporate environmental considerations into the design of their products (OECD 2001). Product design decisions under EPR thus need to reflect life-cycle considerations including manufacturing, pricing, product use, post-use disposal, and remanufacturing. However, there is very little research that analytically examines the influence of EPR policies on the strategic decisions of product design, pricing, and supply chain coordination.

Consider a manufacturer of a diesel engine selling to a fleet operator. The manufacturer could undertake design measures to improve the environmental performance of the engine during use (e.g., greater energy efficiency that would translate into lower emissions),

or make the engine easier to remanufacture post-use (and, hence, minimize the amount of waste generated and disposed). A profit-maximizing manufacturer would trade off investments required to implement these measures against the possibility of generating higher revenues or lower costs over the product's economic life, while complying with EPR mandates. In a durable good context where the manufacturer and the customer interact repeatedly, it is also likely that the parties evaluate alternatives to selling, such as leasing, or solutions-based approaches such as installed base management. For example, under its "evergreen lease," the carpet manufacturer Interface leases a "floor-covering service" for a monthly fee, accepting responsibility for the maintenance and replacement of installed carpeting. This arrangement, together with the use of Interface's remanufacturable carpeting material, reduces material and land-filling costs. Schindler leases "vertical transportation services" in favor of selling elevators because leasing lets it capture the savings from its elevators' lower energy and maintenance costs (see Lovins et al. 1999 for further examples).

We address three main questions in this paper:

1. Do EPR programs provide adequate incentives to manufacturers to design environmentally friendly durable products? How do different EPR levers affect these incentives?
2. How can contracts be structured to improve supply chain profitability and environmental product design? How do these contracts compare in the specific context of EPR?
3. How do customer attributes affect incentives for product design and supply chain coordination? How does a lack of perfect information about these attributes affect such incentives?

Our models permit the consideration of commonly used financial EPR incentives (e.g., advance or end-of-life disposal fees, shared fees between producers and consumers, etc.) and design standards. We do not model the infrastructural elements of reverse supply chains. Specifically, we consider the following scenario. A single manufacturer supplies a remanufacturable, durable product to a single customer. Hauser and Lund (2003) note that frequent and expert buyers who possess substantial experience in purchasing remanufactured products and in evaluating their performance objectively are most often found in commercial and industrial markets. We assume that such a customer has a continuing need for the services of the product and optimizes between the costs of product replacement and the costs incurred during product use. We model two design attributes of the product—a unidimensional measure of environmental *performance* (such as energy efficiency) during product use, and a measure of product *remanufacturability*, modeled as the fraction of the product that can be recovered after use. EPR legislation generally requires that manufacturers take back products post-use. The portion of the product that cannot be recovered and has to be disposed of incurs a charge that might be shared between the manufacturer and the customer. In addition, product use results in environmentally harmful impacts (such as emissions of greenhouse gases and harmful particulates) during product use. For example, the European Commission (EC) recently recommended that airlines be included in the European Union (EU)'s Greenhouse Gas Emissions Trading Program, thus making them accountable for carbon dioxide emissions during flight operations. The UK Commission for Integrated Transport points out that future transport and climate change policy will involve significant point sources such as truck fleet operators and transportation companies in emissions trading. The Auto-Oil Program in the EU resulted in legislation that makes manufacturers responsible for emissions from light vehicles; also underway are proposals that aim to limit or impose charges on emissions from automobiles owned by individual customers. The EC is also considering "differentiated" emissions taxes charged on the basis of consumer behavior as one of its policy options (EC 2007).

Thus, design choices by the manufacturer affect not only production costs, but also the costs incurred during use and post-use. Moreover, customer behavior has a significant influence on the product's environmental impact. Driving habits are known to affect emissions from automobiles as much as engine design does. It is also well known that operating conditions have an impact on the energy efficiencies of electrical and electronic equipment, and industrial and household appliances. A manufacturer might not have complete information about customer attributes that affect the product's environmental impact. This information asymmetry can affect the manufacturer's design and pricing decisions and, in turn, environmental outcomes. The importance of considering heterogeneous customer behavior and information asymmetries among participants in the context of EPR has been recently recognized by other authors as well (e.g., Grimes-Casey et al. 2007). We analyze both the symmetric and asymmetric information scenarios with heterogeneous customer *types*.

EPR instruments available to the regulator are varied, although most fall under the general categories of product recovery targets, environmental performance standards, disposal charges, and charges for environmental impact during product use (OECD 2001). In this paper, we limit ourselves to two types of EPR policy levers—charges for environmental impact during use and charges for environmental impact post-use, both of which may be shared between the manufacturer and customer. These levers work by offering economic incentives for manufacturers to change product designs and for customers to change their consumption behavior. We abstract from the regulator's decision process for setting appropriate levels for these charges, and focus instead on how these policy levers influence upstream design choices, product replacement decisions, and coordination incentives in the supply chain.

A growing body of literature studies the interface between operational decisions and the environment in the context of closed-loop supply chains (see Atasu et al. 2008, Corbett and Kleindorfer 2001a, b, Guide and Van Wassenhove 2006a, b, and papers referenced therein). Toffel (2003) provides an excellent overview of recent developments in take-back legislation and their likely impacts on organizational decision making. Runkel (2003) examines how EPR influences the choice of product durability and social welfare. We draw from this stream of literature for our model constructs. A novel contribution of our work lies in the explicit incorporation of environmental legislation into managerial decisions related to remanufacturable product design and supply chain coordination. We also contrast various contractual alternatives including price-replacement interval contracts, two-part tariffs, and leasing in the specific context of EPR.

Several researchers have examined the economic and social efficiencies of various policy instruments such as taxes, subsidies, standards, and take-back requirements; e.g. Calcott and Walls (2000), Eichner and Pethig (2001), Fullerton and Wu (1998), Palmer and Walls (1997), and Dinan (1993). The typical objective in this stream of research is for the social planner to maximize net social surplus subject to resource constraints, material balance constraints, and production functions. This literature is primarily concerned with design attributes that affect the end-of-life environmental impact of products. An environmentally favorable design implies lower material consumption, higher fraction of product recycled, or lower cost of recycling (Calcott and Walls 2000, Dinan 1993, Fullerton and Wu 1998). A consistent finding is that a combined tax/subsidy, where there is a consumption good tax and a recycling subsidy (such as in a deposit–refund system) can yield the socially optimal product design and quantity of waste. Our focus, however, is on the managerial implications of EPR policies and resulting incentives for supply chain coordination. In addition, we model the customer's product replacement decision more richly and consider product design attributes that have environmental impacts both at end-of-life as well as during use.

We find that EPR levers have interesting impacts on the manufacturer's incentives. Lower environmental charges during product use lead the manufacturer to provide higher performance but lower remanufacturability. This is because a customer incurring lower costs during use replaces the product less often, thus lowering the manufacturer's incentive to invest in remanufacturability. Similarly, when the customer bears a greater share of costs during use, the manufacturer has a stronger incentive to provide higher remanufacturability; she also provides higher performance if the production cost does not increase significantly. Disposal costs are traditionally used to influence a product's end-of-life environmental impact. However, our results show that disposal charges could encourage designs that reduce the product's environmental impact during use.

We also examine how the structure of the supply chain affects incentives faced by the manufacturer and the customer. We show that a coordinated supply chain not only makes a higher profit but also chooses environmentally superior product attributes than an uncoordinated chain. We therefore examine contracts that can help achieve coordination and contrast them in the EPR context. In the symmetric information scenario, we show how arrangements such as price-replacement interval contracts, two-part tariffs, and leasing can be used to achieve coordination in a decentralized supply chain. When the manufacturer has incomplete information about the customer's product-use behavior, a menu of contracts can be used to help coordinate the chain. Our approach allows us to examine the impacts of both a lack of supply chain coordination, as well as a lack of perfect information about customer behavior, on incentives for environmental product design. In particular, we show that the effects of EPR levers on the manufacturer's design incentives depend on supply chain structure.

The remainder of the paper is organized as follows. Section 2 introduces the model. Section 3 presents the integrated supply chain benchmark. Section 4 includes the analysis for the decentralized supply chain with symmetric information. We first analyze a price-only contract, followed by contracts that help achieve coordination. Section 5 discusses these coordinating contracts. Section 6 presents the analysis of a coordinating contract under asymmetric information. Section 7 concludes the paper and provides directions for future research. All proofs are included in Appendix A.

2. The Model

A manufacturer supplies a remanufacturable, durable product to a single customer. The customer has a continuing need for the services of the product and obtains a fixed utility (or revenue) per period from the product. At the end of the product's economic life, the product is returned to the manufacturer, who remanufactures it for another cycle of use by the customer. We consider the manufacturer's planning horizon to be the time period over which design choices remain unchanged and during which it is viable to remanufacture the product. At the beginning of this horizon, the manufacturer decides on two design attributes of the product—one which determines the environmental performance of the product during product use, and the other which determines the product's environmental impact post-use. Design choices affect environmental costs borne by the supply chain and, hence, the optimal price charged by the manufacturer at each replacement instance as well as the replacement policy employed by the customer. Note that our usage of environmental costs does not refer to private abatement costs or external social costs but rather the environmental charges imposed on the supply chain by EPR legislation.

We model a unidimensional measure of environmental *performance* during product use q, analogous to the modeling of product performance or quality in Chen (2001), Kornish (2001), and Moorthy and Png (1992). The product's *remanufacturability* is determined by the second attribute θ. We model $\theta \in [0, 1]$ as the fraction of the product (say, by weight) that can be recovered after use, similar to Debo et al. (2005), Fleischmann et al. (2001), and Fullerton and Wu (1998). As in Debo et al. (2005) and Calcott and Walls (2000), θ influences the cost of production through the value recovered from post-use product. The cost of production is bounded above by the cost of manufacturing a new product, and decreases in θ. Let $c(q, \theta)$ denote the unit production cost and $k(q, \theta)$ denote the design cost borne by the manufacturer.

We consider two types of costs that the product incurs over its economic life. The first type of cost is incurred during product use. As discussed in Section 1, such costs are real and measurable. An airline bound by limits on carbon dioxide emissions will have to buy permits to cover emissions or pay a fine. The manufacturer can reduce these costs by manufacturing fuel-efficient engines, for example. The nature of product use by the customer also influences costs incurred during product use. The second type of cost relates to the disposal of the product at the end of its economic life. The portion of the product that cannot be recovered and has to be disposed of incurs landfilling or scrapping costs. The manufacturer can reduce disposal costs incurred at end-of-life by designing the product to be more remanufacturable.

We model two possible customer types: a *normal* customer ($i = 1$) incurs higher costs during product use than an *efficient* customer ($i = 2$). Let $e_i(q)$ denote the rate at which costs are incurred during customer type i's use of the product and let $w(\theta)$ denote the cost of waste disposal. Our analysis can be replicated if w depends on customer type, although we believe that customer behavior influences costs during product use to a greater extent than disposal costs. We look at two information scenarios. In the symmetric information scenario, customer type is common knowledge. In the asymmetric information scenario, a customer's type is his private information, and the manufacturer has prior beliefs that the customer is of type 1 (or normal) with probability ρ, where $\rho \in [0, 1]$. The manufacturer's beliefs and all cost parameters are common knowledge. We make the following functional assumptions:

Assumption A1. $c_q > 0$, $c_{qq} > 0$, $c_\theta < 0$.

Assumption A2. $k_q > 0$, $k_{qq} > 0$, $k_\theta > 0$, $k_{\theta\theta} > 0$, $k_{q\theta} = 0$.

Assumption A3. $e_{iq} < 0$, $e_{iqq} > 0$; $e_1 > e_2$; $|e_{1q}| < |e_{2q}|$.

Assumption A4. $w_\theta < 0$.

Assumption A5. $w|_{\theta=0} > c(q, \theta)|_{\theta=0}$.

Assumption A1 implies that the unit production cost decreases with remanufacturability θ and increases convexly in performance q. A2 implies that the manufacturer's design costs are separable in q and θ, and are increasing and convex in both q and θ. Both these assumptions are intuitive and are commonly used (Debo et al. 2005, Kim and Chhajed 2002, Moorthy and Png 1992). To give further structure to the problem, we assume k to be of the general form $k_1 u(q) + k_2 v(\theta)$, where u and v are polynomial functions with degree ≥ 2. Assumption A3 implies that cost during product use is decreasing and convex in q, and is decreasing in customer type. Moreover, the efficient customer makes better use of the product's performance; i.e., the rate of decrease in e with respect to q is higher for the efficient customer. Assumption A4 implies that the cost of waste disposal increases in the amount of waste disposed of. A5 assumes that the cost of complete product disposal is greater than the cost of producing a new product, thus ensuring that the supply chain always has an incentive to recover some value from the product at end-of-life.

EPR policies differ in specifications of minimum design standards (q_s and θ_s), if any, levels of the environmental charges e and w, as well as the divisions of these environmental charges between the manufacturer and the customer. Let α and β denote the EPR-mandated fractions of e and w, respectively, borne by the customer. Without loss of generality, we set q_s and $\theta_s = 0$.

The sequence of decisions is as follows. Let T denote the planning horizon. In a given EPR scenario, the manufacturer first chooses design features q and θ jointly. The manufacturer then chooses the price r to be offered to the customer for product replacements. In each period, customer type i earns a revenue ϕ and the supply chain incurs costs $e_i(q)$ from product use. At each product replacement instance, the supply chain incurs a disposal cost $w(\theta)$ and the manufacturer incurs a unit cost of remanufacturing the product $c(q, \theta)$. Note again that the aforementioned costs depend on the manufacturer's design choices.

The customer accepts r if he makes at least his reservation profit from employing an optimal product replacement policy, given q, θ, and r. To model the replacement decision, we adapt the classic equipment replacement models to our context. The customer's replacement decision in Clapham (1957) involves determining an optimum point in time to replace the product by trading off replacement costs against costs incurred during product use. A more general economic life model would consider discounting, as in Bellman (1955), but such a model lacks analytical tractability in our context. However, it can be verified numerically that the replacement policy in a discounted-profit model is structurally similar to that in the average-profit model used in this paper.

We use the following notation. Superscript M refers to the manufacturer, C the customer, and SC the supply chain. Subscript IN refers to an integrated supply chain, DS a decentralized supply chain under symmetric information. Subscripts PR, TP, and LS refer to price-replacement interval, two-part tariff, and leasing contracts under symmetric information, and AM refers to a decentralized supply chain under asymmetric information when a menu of contracts is used.

3. A Benchmark: Integrated Supply Chain

We first analyze the integrated supply chain. In each period of product use, the integrated supply chain with customer type i earns a revenue ϕ and faces an environmental cost gradient e_i. At each replacement instance, replacement cost c and disposal cost w are incurred. The average supply chain profit per period with customer type i and replacement interval t is

$$\begin{aligned}\Pi_{IN_i} &= \phi - \frac{c}{t} - \frac{1}{t}\int_0^t e_i x\,dx - \frac{w}{t} - \frac{k}{T}\\ &= \phi - \frac{(c+w)}{t} - \frac{e_i t}{2} - \frac{k}{T}.\end{aligned} \tag{1}$$

The optimal replacement interval given q and θ is determined by maximizing $\Pi_{IN_i}$with respect to t and is given by $\tau^*_{IN_i} = \sqrt{\frac{2(c+w)}{e_i}}$. This expression is analogous to the familiar EOQ formula for choosing the optimal order quantity, given the fixed cost of ordering, the unit cost of the product being ordered, and the inventory holding cost rate. The sum of the cost of the product and the cost of waste disposal is analogous to the fixed ordering cost in the EOQ model. The cost gradient e_i during product use is analogous to the holding cost rate. The integrated supply chain's profit is

$$\Pi^*_{IN_i} = \phi - \sqrt{2e_i(c+w)} - \frac{k}{T}. \tag{2}$$

The manufacturer in the integrated supply chain chooses q and θ to maximize (2). Proposition 1 shows that for sufficiently large design costs, the profit function in (2) is jointly concave in q and θ.

Proposition 1. *$\exists\ \bar{k}_1, \bar{k}_2$ such that $\forall k_1 > \bar{k}_1$* and $k_2 > \bar{k}_2$, *$\Pi^*_{IN_i}$ is jointly concave in q and θ. $(q^*_{IN_i}, \theta^*_{IN_i})$ uniquely maximizes $\Pi^*_{IN_i}$*, where

$$q^*_{IN_i} = \left\{q : \frac{\partial \Pi^*_{IN_i}}{\partial q} = 0\right\}$$

and

$$\theta^*_{IN_i} = \left\{\theta : \frac{\partial \Pi^*_{IN_i}}{\partial \theta} = 0\right\}.$$

Proof. See Appendix A.

We make the following additional assumption for the remainder of this paper.

Assumption A6. *Design costs are sufficiently large so that the manufacturer's or the integrated supply chain's profits are jointly concave with respect to q and θ.*

With Assumption A6, it follows that there exists a unique pair $\left(q^*_{IN_i}, \theta^*_{IN_i}\right)$that maximizes $\Pi^*_{IN_i}$. Proposition 2 compares the optimal design choices corresponding to the two customer types.

Proposition 2. $q^*_{IN_1} < q^*_{IN_2};\ \theta^*_{IN_1} > \theta^*_{IN_2}$

Proof. See Appendix A.

Proposition 2 shows that an efficient customer does not entirely drive superior environmental design choices, thus reflecting a fundamental trade-off that the manufacturer faces in making design choices while accounting for customer attributes and replacement behavior. While the manufacturer provides higher performance when the customer is efficient, she reduces the product's remanufacturability. This is because a supply chain with an efficient customer incurs lower costs during use and therefore replaces the product less often; this lowers the incentive for greater remanufacturability since remanufacturing and disposal costs are incurred less often.

4. Decentralized Supply Chain

We next analyze the scenario where the manufacturer and the customer are independent entities who privately maximize their profits. We assume in this section that the manufacturer and the customer share common knowledge of all cost parameters as well as the customer's type. We first characterize the performance of the decentralized supply chain under a price-only contract and contrast this performance to that of the integrated supply chain. Thereafter, we explore contracts that can coordinate the supply chain.

4.1. Price-Only Contract

Price-only contracts are commonly used and represent the simplest arrangement between independent entities in supply chains. We employ the usual backward induction technique to solve the model.

4.1.1. Customer's Problem. If the customer accepts the price r offered by the manufacturer, he incurs his share β of the product disposal cost w and pays a price r to the manufacturer at each replacement instance. In each period, customer type i earns revenue ϕ and incurs his share α of environmental costs e_i from product use. The customer chooses a replacement interval that maximizes his average profit per period

$$\Pi^{C}_{DS_i} = \phi - \frac{(r+\beta w)}{t} - \frac{\alpha e_i t}{2}.$$

The customer's optimal replacement interval is $\tau^*_{DS_i} = \sqrt{\frac{2(r+\beta w)}{\alpha e_i}}$. Substituting $\tau^*_{DS_i}$ for t, we have $\Pi^{C*}_{DS_i} = \phi - \sqrt{2\alpha e_i(r+\beta w)}$. Without loss of generality, we set the customer's reservation profit to zero. Since the customer will only accept the contract if he makes at least his reservation profit, the customer's participation constraint is $\phi - \sqrt{2\alpha e_i(r+\beta w)} \geq 0$.

4.1.2. Manufacturer's Problem. The manufacturer's objective is to maximize her average profit per period. Assuming that her reservation profit is zero, the optimization problem for the manufacturer is

$$\max_{(q,\theta),r} \Pi^{M}_{DS_i} = \frac{r - [c + (1-\beta)w]}{\tau^*_{DS_i}} - \frac{(1-\alpha)e_i \tau^*_{DS_i}}{2} - \frac{k}{T}, \quad (3)$$

$$\text{Subject to}: \; \phi - \sqrt{2\alpha e_i(r+\beta w)} \geq 0.$$

Manufacturer's Price Decision: We first solve for the manufacturer's price decision given q and θ.

Observation 1. *Given design choices q and θ, $\Pi^{M}_{DS_i}$ increases in the price $r \geq c$ charged to the customer.*

This result is not obvious because it is possible for the manufacturer to trade away the magnitude of revenue in each replacement instance for a higher frequency of product replacements. Corollary 1 follows (stated without proof).

Corollary 1.

(i) It is optimal for the manufacturer to price the product at $r^*_{DS_i} = \frac{\phi^2}{2\alpha e_i} - \beta w$.
(ii) The customer's optimal replacement interval is $\tau^*_{DS_i} = \frac{\phi}{\alpha e_i}$.
(iii) An efficient customer pays a higher price and replaces the product less frequently than a normal customer, i.e., $r^*_{DS_2} > r^*_{DS_1}$ and $\tau^*_{DS_2} > \tau^*_{DS_1}$.

The price charged by the manufacturer increases in the revenue earned by the customer and decreases in the costs incurred. Moreover, the manufacturer fully reimburses the customer his share of waste disposal costs. Therefore, the optimal replacement interval chosen by the customer is independent of β and w; the replacement interval depends only on revenue per period and the customer's share of costs during product use. However, as will be discussed later, disposal costs do influence the manufacturer's design choices.

Manufacturer's Design Decision: In the first stage of the sequence of decisions, the manufacturer chooses q and θ, incorporating the optimal price $r^*_{DS_i}$ and the customer's optimal replacement interval $\tau^*_{DS_i}$, to maximize

$$\Pi^{M*}_{DS_i} = \frac{\phi^2(2\alpha - 1) - 2\alpha^2 e_i(c+w)}{2\alpha\phi} - \frac{k}{T}. \quad (4)$$

To ensure non-negativity of the manufacturer's profit in (4), we assume that $\alpha > \frac{1}{2}$, i.e., the customer bears a larger share of costs during use. This assumption is likely to hold in most circumstances where the environmental impact of products during use is influenced by customer behavior. From Assumption A6 and Proposition 1 *mutatis mutandis*, the manufacturer's profit in (4) is jointly concave in q and θ. Hence, there exists a unique pair $(q^*_{DS_i}, \theta^*_{DS_i})$ that maximizes $\Pi^{M*}_{DS_i}$.

4.2. Discussion

We summarize the main results for the decentralized supply chain below and compare the outcomes to those in the integrated supply chain benchmark.

4.2.1. Impact of Customer Type. Recall that an efficient customer makes better use of the product's performance and incurs lower costs during product use than a normal customer. The following proposition summarizes the effects of customer type on the manufacturer's profit and design choices.

Proposition 3.

(i) $\Pi^{M*}_{DS_1} < \Pi^{M*}_{DS_2}$.

(ii) $q^*_{DS_1} < q^*_{DS_2}; \quad \theta^*_{DS_1} > \theta^*_{DS_2}$.

Proof. See Appendix A.

Thus, in an EPR regime where the manufacturer shares costs both during product use and at end-of-life, the manufacturer benefits from the customer being efficient despite the fact that the efficient type replaces the product less often. However, the environmental design implications of customer type are not that clear. Proposition 3(ii) shows that, while the efficient customer induces the manufacturer to design the product with lower environmental impact during use (i.e., higher q), he leads the manufacturer to design the product with higher environmental impact at end-of-life (i.e., lower θ). By assumption, the efficient customer incurs lower costs during product use but waste disposal costs are the same for both customer types. Under symmetric information, the manufacturer knows the customer's type, and can raise the price for the efficient customer in order to appropriate the customer's cost savings from being efficient. Since the efficient customer makes better use of product's performance (Assumption A3), the manufacturer's incentive to provide q is greater. The higher price leads the efficient customer to replace the product less often, which translates into a diminished incentive for the manufacturer to provide remanufacturability because the manufacturer faces disposal costs less often.

4.2.2. Impact of Supply Chain Coordination. Our focus is on the effect of coordination on profit and upstream product design in the particular context of EPR. The total profit for the decentralized supply chain is given by $\Pi^{SC*}_{DS_i} := \Pi^{M*}_{DS_i} + \Pi^{C*}_{DS_i} = \Pi^{M*}_{DS_i}$, since $\Pi^{C*}_{DS_i} = 0$. Proposition 4 summarizes the main results.

PROPOSITION 4.

(i) For the same design choices, the integrated supply chain always makes a higher profit than the decentralized supply chain, i.e., $\Pi^*_{IN_i} > \Pi^{SC*}_{DS_i}$.
(ii) The integrated supply chain's design choices are environmentally superior to those of the decentralized supply chain, i.e., $q^*_{IN_i} > q^*_{DS_i}$*, and* $\theta^*_{IN_i} > \theta^*_{DS_i}$.

PROOF. See Appendix A.

The result in Proposition 4(i) is as expected. The loss to the supply chain from a lack of coordination can be understood as follows. In the decentralized supply chain, the manufacturer prices the product above her marginal cost, i.e., $r > c + (1-\beta)w$, which affects the customer's product replacement frequency; for the same design choices, the customer in the decentralized supply chain replaces the product less frequently than what is optimal for the supply chain as a whole. Consequently, we can expect that the remanufacturability choice in the integrated supply chain would be superior to that in the decentralized supply chain. However, less obvious is our finding that the integrated supply chain also chooses superior performance. It can be verified that the replacement interval in the decentralized supply chain drops faster with increased performance than that in the integrated supply chain, implying that the integrated chain is better able to reduce costs through increased performance.

The manufacturer's optimal price in the decentralized case is $r^*_{DS_i} = \frac{\phi^2}{2\alpha e_i} - \beta w$, implying that the average revenue per period earned by the manufacturer is $\frac{r^*_{DS_i}}{\tau^*_{DS_i}} = \frac{\phi}{2} - \frac{\alpha\beta e_i w}{\phi}$. That is, the customer's revenue from product use does not entirely translate into net supply chain revenue (i.e., $\frac{r^*_{DS_i}}{\tau^*_{DS_i}} < \phi$), and any increase in the customer's per-period revenue ϕ from product use results in a smaller increase in total supply chain profit. While the integrated supply chain's profit increases linearly with ϕ, the supply chain profit in the decentralized case increases only concavely with respect to ϕ. Hence, as regulators expand the use and stringency of EPR instruments, firms have strong incentives to enter into contracts that achieve supply chain coordination. Proposition 4(ii) is relevant from a policy standpoint; it demonstrates that coordination not only results in higher supply chain profit but also drives environmentally superior product design choices.

Note, however, that supply chain coordination does not necessarily imply greater social welfare. By charging e and w, the regulator makes the manufacturer and the customer internalize the environmental externalities of the product. In principle, a social welfare-maximizing regulator would set e and w so as to equate the marginal environmental charge to the marginal environmental damage caused by the product. Since we treat the regulator's decisions as exogenous to our model, we do not analyze social welfare *per se*, although it would be a worthwhile exercise for future research. We explore the impact of EPR levers on design choices and firm profits below.

4.2.3. Impact of EPR Parameters. We look at comparative statics with respect to four parameters that are exogenous to our model: cost during product use (e), disposal cost at end-of-life (w), and the customer's share of these two costs (i.e., α and β, respectively). Tables B1 and B2 in Appendix B summarize the comparative statics results for design choices and profits, respectively. Proofs of these results are omitted for brevity and are available from the authors. We discuss the main effects below.

(a) Design choices:

- (i) $\frac{\partial q^*_{[]_i}}{\partial e_i} < 0$, $\frac{\partial \theta^*_{[]_i}}{\partial e_i} > 0$. *Lower costs during use (e) induce the manufacturer to provide higher performance (q), but lower remanufacturability (θ)*: The manufacturer reaps a greater benefit for the same increment in q when e is lower, since she shares a fraction of e and also since she can raise the price for a customer facing lower costs. However, since the manufacturer's optimal price increases as e decreases, the customer replaces the product less often, and the manufacturer therefore has a lesser incentive to invest in θ.
- (ii) $\frac{\partial q^*_{[]_i}}{\partial w} > 0$, $\frac{\partial \theta^*_{DS_i}}{\partial w} = 0$, $\frac{\partial \theta^*_{IN_i}}{\partial w} < 0$. *Higher waste disposal costs (w) lead the manufacturer to provide higher q. Moreover, higher w either has no effect on θ (in the uncoordinated supply chain) or leads to lower θ (in the coordinated supply chain)*: In the uncoordinated supply chain, as w increases, the manufacturer has to reduce the price charged to the customer to maintain customer participation and therefore makes a lower profit. Interestingly, the manufacturer compensates for this effect by investing in q and not θ. This is because the manufacturer always subsidizes the customer's share of w and effectively bears the entire waste disposal cost herself. Lower e, on the other hand, allows the manufacturer to increase her price to the customer. Thus, the manufacturer has an incentive to invest in q to reduce e rather than to invest in θ to reduce w. On the other hand, the optimal replacement interval in a coordinated supply chain is $\tau^*_{IN_i} = \sqrt{\frac{2(c+w)}{e_i}}$. With increase in w, this interval increases, i.e., the customer replaces the product less often. Thus, the manufacturer's incentive to invest in θ diminishes.
- (iii) $\frac{\partial \theta^*_{[]_i}}{\partial \alpha} > 0$; $\frac{\partial q^*_{[]_i}}{\partial \alpha} > 0$ if $c_q < |e_{iq}|$. *As the customer bears an increasing fraction of costs during use (i.e., as α increases), the manufacturer provides higher θ; the manufacturer also provides higher q if* $c_q < |e_{iq}|$: The customer replaces the product more often if he bears a higher fraction of costs during use, thus providing the manufacturer with an incentive to increase remanufacturability. Since the manufacturer benefits if the customer incurs lower e, the manufacturer increases q if doing so reduces e at a faster rate than the rate at which production cost increases.
- (iv) $\frac{\partial q^*_{[]_i}}{\partial \beta} = 0$, $\frac{\partial \theta^*_{[]_i}}{\partial \beta} = 0$. *The split of waste disposal costs between the manufacturer and the customer has no effect on product design*: As mentioned earlier, the manufacturer subsidizes the customer's share of w and effectively bears the entire waste disposal cost.

(b) Profit:

- (i) *The manufacturer's and supply chain's profits always decrease in e and w.*
- (ii) $\exists \alpha_0$ s.t. $\frac{\partial \Pi^{M*}_{DS_i}}{\partial \alpha} \gtrless 0$ for $\alpha \lesseqgtr \alpha_0$. *In the decentralized supply chain under symmetric information, the manufacturer's profit increases in α for small α and decreases for larger α*: For small α, the manufacturer's profit increases as the customer bears an increasing share of costs during product use, but when α is large the manufacturer cannot extract much rent from the customer.
- (iii) $\frac{\partial \Pi^{[]*}_{DS_i}}{\partial \beta} = 0$, $\frac{\partial \Pi^{[]*}_{AM_i}}{\partial \beta} = 0$. *Profits in the decentralized supply chain under both symmetric and asymmetric information are invariant with respect to β*: This again is because the manufacturer effectively bears all of the disposal costs at end-of-life.

5. Coordinating Contracts: Analysis and Implementation Under EPR

It is clear from our analysis thus far that coordination improves supply chain profitability and the product's environmental features. As has been argued in the supply chain literature, coordination can be achieved among entities in a supply chain through properly structured contracts (see Cachon 2003 for a review). In our setting, the key to achieving supply chain coordination is product replacements at the supply chain-optimal frequency. Because a price-only contract distorts the retailer's replacement decision, a coordinating contract needs at least two parameters. There are different ways in which a coordinating contract can be structured. First, the manufacturer can specify the replacement interval τ in addition to the price r to be paid by the customer at each replacement instance. Second, the manufacturer can offer the customer a two-part tariff (r, F) that requires the customer to pay a fixed fee F over the planning horizon in addition to the price r paid at each replacement instance. Third, as in leasing, the manufacturer can use a non-linear contract menu $\{(f(t), t)\}$, where the price for product replacements depends on the replacement frequency chosen by the customer. We derive each of these contracts and discuss them in the EPR context.

5.1. Price-Replacement Interval (r, τ) Contract

In this contract, the manufacturer takes charge of the replacement decision by specifying the replacement interval τ in addition to the price r for product replacements. Installed base management is an expanded version of such a contract, in which the manufacturer assumes responsibility for the replacement decision and also bundles maintenance services along with the sale or lease of its product. Several manufacturers such as Otis Elevators and Pitney Bowes manage equipment at user sites, collect used equipment from these sites, and install replacements (Lehtonen 2005). Our analysis complements that in Bhattacharya et al. (2005) in that we focus on evaluating a similar contractual arrangement in the context of EPR and assessing the impact on upstream product design.

The sequence of decisions is as follows. The manufacturer first chooses q and θ jointly. She then chooses the price $r \geq c$ for product replacements and the replacement interval τ. The customer accepts the pair (r, τ) if he makes at least his reservation profit. The profit for customer type i is $\phi - \frac{(r+\beta w)}{t} - \frac{\alpha e_i t}{2}$. The customer's participation constraint is $\Pi^C_{PR_i} \geq 0$, and the manufacturer optimizes her profit by solving

$$\max_{(q,\theta),(r,t)} \Pi^M_{PR_i} = \frac{r - [c + (1-\beta)w]}{t} - \frac{(1-\alpha)e_i t}{2} - \frac{k}{T}, \quad (5)$$

$$\text{Subject to}: \phi - \frac{r + \beta w}{t} - \frac{\alpha e_i t}{2} \geq 0.$$

Given q and θ, the manufacturer's profit increases in the price charged to the customer. Hence, it is optimal for the manufacturer to price the product at $r^*_{PR_i} = \phi t - \beta w - \frac{\alpha e_i t^2}{2}$. Substituting $r^*_{PR_i}$ for r in (5), we have $\Pi^M_{PR_i} = \phi - \frac{(c+w)}{t} - \frac{e_i t}{2} - \frac{k}{T}$, which is concave in t. Hence, $\tau^*_{PR_i} = \sqrt{\frac{2(c+w)}{e_i}} = \tau^*_{IN_i}$ uniquely maximizes the manufacturer's profit. Thus, $r^*_{PR_i} = \phi\sqrt{\frac{2(c+w)}{e_i}} - \alpha c - w$. Substituting $\tau^*_{PR_i}$ for t, we have $\Pi^{M*}_{PR_i} = \phi - \sqrt{2e_i(c+w)} - \frac{k}{T}$, which is identical to the integrated supply chain's profit in (2). Thus, the manufacturer chooses the same q and θ as in the integrated supply chain benchmark, and the supply chain is fully coordinated. Comparing r and τ under the price-replacement interval contract and under the price-only contract in Section 4.1, we note the following:

$$r^*_{PR_i} - r^*_{DS_i} = -\frac{\left[\phi - \alpha\sqrt{2e_i(c+w)}\right]^2}{2\alpha e_i} < 0$$

$$\tau^*_{PR_i} = \tau^*_{IN_i} = \sqrt{\frac{2(c+w)}{e_i}} < \sqrt{\frac{2(r+\beta w)}{e_i}} = \tau^*_{DS_i}.$$

In other words, under the price-replacement interval contract, the manufacturer provides a price discount to induce the customer to accept more frequent replacements, similar to an "all units quantity discount" schedule (Dolan 1987). Also note that

$$\frac{r^*_{PR_i}}{\tau^*_{PR_i}} - \frac{r^*_{DS_i}}{\tau^*_{DS_i}} = \frac{\phi}{2} - \frac{\sqrt{e_i}(\alpha c + w)}{\sqrt{2(c+w)}} + \frac{\alpha\beta e_i w}{\phi} > 0$$

i.e., the manufacturer's average revenue per period is higher under the price-replacement interval contract than in the decentralized supply chain with a price-only contract.

Installed base management contracts can thus increase supply chain profit and provide greater incentives to the manufacturer to invest in environmentally favorable product design. One disadvantage of such contracts, though, is that the customer does not get to choose the replacement interval. This might pose a hurdle for implementation at least in some situations. The next two contracts that we discuss achieve coordination while allowing the customer to choose the replacement interval. We provide a comparative discussion of these contracts in Section 5.4.

5.2. Two-Part Tariff

In this contract, the manufacturer chooses a pair (r, F), where r is the price charged to the customer for product replacements and F is a fixed fee for the duration of the planning horizon. Such contracts are commonly suggested to coordinate channels (Dolan 1987, Jeuland and Shugan 1983). The sequence of decisions is as follows. The manufacturer first chooses the design features (q, θ) and then decides the two-part tariff (r, F) that maximizes her profit. The customer accepts (r, F) if he makes at least his reservation profit after choosing the optimal replacement interval. The customer's profit is given by $\Pi^C_{TP_i} = \phi - \frac{(r+\beta w)}{t} - \frac{\alpha e_i t}{2} - \frac{F}{T}$. The manufacturer's problem, subject to the customer's participation constraint, is

$$\max_{(q,\theta),(r,F)} \Pi^M_{TP_i} = \frac{r - [c + (1-\beta)w]}{t} - \frac{(1-\alpha)e_i t}{2} + \frac{F}{T} - \frac{k}{T},$$

$$\text{Subject to}: \quad \phi - \frac{(r + \beta w)}{t} - \frac{\alpha e_i t}{2} - \frac{F}{T} \geq 0.$$

It can be verified that the manufacturer's profit is maximized (although not uniquely) at price $r^*_{TP_i} = (2-\alpha)(c+w) - \beta w$, and fixed fee $F^*_{TP_i} = [\phi - \sqrt{2e_i(c+w)}]T$. At this combination of price and fixed fee, the customer's incentives are aligned with those of the supply chain and the customer chooses the supply chain-optimal replacement interval $\tau^*_{TP_i} = \tau^*_{IN_i} = \sqrt{\frac{2(c+w)}{e_i}}$. As a result, the manufacturer's profit is identical to that of the integrated supply chain and she chooses the supply chain-optimal q and θ. We note that the price-replacement interval contract in Section 5.1 is a special case of the two-part tariff contract with the fixed fee restricted to zero. In the price-replacement interval contract, the manufacturer offers a specific replacement interval to the customer whereas in the two-part tariff contract, the manufacturer allows the customer to choose the replacement interval. However, with symmetric information, the manufacturer can fully anticipate and factor the customer's choice of the replacement interval in deciding the value of r in the two-part tariff.

The intuition behind this contract is as follows. The manufacturer prices the product at her effective marginal cost, thus making the customer the "residual claimant." The customer then faces the appropriate incentives and chooses the supply chain-optimal replacement frequency. The manufacturer's effective marginal cost is $c + (1-\beta)w + (1-\alpha)\frac{et^2}{2}$ (where t is the replacement interval), which equals $(2-\alpha)(c + w) - \beta w$ at the supply chain-optimal replacement interval. Without the fixed fee, the customer's expected profit per period equals that of the integrated supply chain, i.e., $\phi - \sqrt{2e_i(c+w)}$. The manufacturer extracts the total profit of the customer over the planning horizon via the fixed fee. Note, however, that multiple combinations of price and the fixed fee can achieve coordination.

5.3. Leasing

Starting with Coase (1972), many researchers have examined the implications of selling versus leasing a durable product for the manufacturer's pricing and distribution strategies (see Bulow 1982, Desai and Purohit 1999). However, research to date has not examined the implications of leasing when manufacturers are legally responsible for life-cycle environmental costs and may therefore have an incentive to invest in environmentally favorable product design.

The sequence of decisions is as follows. The manufacturer first chooses q and θ jointly. She then chooses a menu $\{(f_i(t), t)\}$ that specifies combinations of per-period product usage fees and corresponding replacement intervals. The customer chooses a combination from the menu such that his profit is maximized. Note that because the customer does not own the product, he returns the product to the manufacturer at end-of-lease and is not liable for product disposal costs (White et al. 1999). The customer still incurs his share of costs during product use. The customer's profit is given by $\Pi^C_{LS_i} = \phi - f_i(t) - \frac{\alpha e_i t}{2}$. The manufacturer's problem is

$$\max_{(q,\theta),\{f_i,t\}} \Pi^M_{LS_i} = f_i(t) - \frac{(c+w)}{t} - \frac{(1-\alpha)e_i t}{2} - \frac{k}{T},$$

$$\text{Subject to}: \ \phi - f_i(t) - \frac{\alpha e_i t}{2} \geq 0.$$

Under symmetric information, the manufacturer can design a contract such that the customer's participation constraint is binding. Thus, the manufacturer charges a per-period leasing fee $f_i(t) = \phi - \frac{\alpha e_i t}{2}$, which exactly equals the customer's average profit per period and which decreases in the replacement interval t. In particular, the customer would accept the contract where $t = \tau^*_{LS_i} = \tau^*_{IN_i} = \sqrt{\frac{2(c+w)}{e_i}} = \tau^*_{PR_i}$ and $f_i(t) = f^*_{LS_i} = \phi - \frac{\alpha}{2}\sqrt{2e_i(c+w)}$. Thus, the price-replacement interval contract in Section 5.1 is a special case of the leasing contract. For any $(f_i(t), t)$ chosen by the customer, the manufacturer's profit is $\Pi^M_{LS_i} = \phi - \frac{(c+w)}{t} - \frac{e_i t}{2} - \frac{k}{T}$, which equals the integrated supply chain's profit in (2) when $t = \sqrt{\frac{2(c+w)}{e_i}}$. The manufacturer chooses the supply chain-optimal q and θ when $t = \tau^*_{LS_i}$ and $f_i(t) = f^*_{LS_i}$.

5.4. Discussion

Given symmetric information, all three contracts—price-replacement interval, two-part tariff, and leasing—coordinate the supply chain as expected. However, there are important differences in the ways by which these contracts achieve coordination, the manner in which they might be implemented, and their relevance to EPR.

5.4.1. Coordination Mechanism and Customer Participation. The price-replacement interval contract works by having the manufacturer take charge of product replacements, even though the customer legally owns the product and is liable for costs during product use and at end-of-life. On the other hand, the customer never owns the product in a leasing contract and thus cannot be held accountable for end-of-life disposal costs, although the customer is free to choose the replacement interval (note that we assume an operating lease, as opposed to a capital lease in which ownership transfers to the lessee at the end of the lease term). The choice between these two contracts in practice would depend on customer preferences and certain product characteristics. Customers might prefer the price-replacement interval contract for complex products that tend to have relatively long product life cycles and for which close substitutes are not so easily available. Examples include large-scale network servers and commercial photocopiers. However, leasing may be attractive for products such as small-scale computer equipment and automobiles for which close substitutes are more easily available and for which product disposal is costly relative to the price of the product. Note that most current EPR legislation focuses on the latter type of products. The EU's WEEE directive targets electronic and electrical equipment, and the ELV directive requires automobile manufacturers to take back vehicles. Customers' attitudes toward risk could play a role in the implementability of two-part tariff contracts. If the fixed fee in a two-part tariff is charged upfront, a high level of uncertainty in future environmental legislation would deter customer participation.

5.4.2. Implementation and Manufacturer's Perspective.

All of the contracts discussed above require that the manufacturer know all customer parameters, including customer type, the revenue earned per period, and environmental costs incurred. Even a simple price-only contract requires the manufacturer to have this information for her to maximize profit (Section 6 treats the scenario of asymmetric information). However, the contracts differ in terms of transaction costs involved in design and implementation. A price-only contract is obviously the simplest and has the least transaction costs, followed by two-part tariff. In practice, a leasing contract might also impose some conditions that constrain product use in order to prevent abnormal wear and tear; penalties could be imposed on the customer depending on the condition of the end-of-lease product. Moreover, since the manufacturer maintains ownership of the leased product throughout its life cycle, she is the one who faces the uncertainty in environmental legislation. Price-replacement interval contracts tend to be costly due to the administrative burden on the manufacturer, especially when dealing with a customer base that is widely dispersed. Even so, several manufacturers have expanded their reliance on installed base management contracts in the recent past because such contracts lock in customers, thereby increasing revenues and creating entry barriers (Lehtonen 2005). Also, such contracts imply a transition from selling the product to providing product-service bundles, thus replacing a possibly lumpy revenue stream with a more level one. Also, from an environmental standpoint, such "servicizing" effectively reduces the amount of durable product waste that ends up in landfills (Reiskin et al. 2000).

6. Asymmetric Information

We now analyze the scenario of asymmetric information about customer attributes. We capture the manufacturer's uncertainty about the customer's costs through a prior probability distribution on customer type. For exposition, we restrict ourselves to two possible types for the customer: type 1 or *normal* and type 2 or *efficient*. The manufacturer's prior beliefs are that the customer is normal with probability ρ and efficient with probability $1-\rho$, where $\rho \in [0,1]$. Consistent with our analysis in the earlier sections, we assume that a normal customer incurs higher costs during product use than an efficient customer, i.e., $e_1 > e_2$.

In Section 6.1, we illustrate how the manufacturer can design a contract menu to improve supply chain profit under asymmetric information. While we derive a menu of contracts with parameters similar to that in Section 5.1, the other contracts studied in Section 5 can similarly be analyzed under asymmetric information about customer attributes.

6.1. A Menu of Contracts

The manufacturer can offer a contract menu designed in such a way that each customer type would choose exactly the contract intended for it (Laffont and Tirole 1993). Invoking the revelation principle, we can restrict our attention to direct revelation mechanisms. Given her prior beliefs ρ and $1-\rho$ on the customer being type 1 (normal) and type 2 (efficient), respectively, the manufacturer's problem is to choose a menu $\{(r_{AM_1}, \tau_{AM_1}), (r_{AM_2}, \tau_{AM_2})\}$ subject to incentive compatibility (IC) and individual rationality (IR) constraints for the customer. IR constraints ensure that the customer cannot be worse off by accepting the manufacturer's contract. IC constraints ensure that it is in the interest of the customer to choose the contract intended for his type.

The sequence of events is as follows. The manufacturer first chooses design attributes (q, θ) for the product. She then offers the contract menu $\{(r_{AM_1}, \tau_{AM_1}), (r_{AM_2}, \tau_{AM_2})\}$ to the customer. The customer accepts the menu if he can make at least his reservation profit; he chooses the contract that maximizes his profit. Thereafter, the customer replaces the product at the contracted replacement frequency and pays the contracted price at each replacement instance. Thus, the contract analyzed here can be viewed as a price-replacement interval contract under asymmetric information. The manufacturer's optimization problem is

$$\begin{aligned}\max_{(q,\theta),\{(r_{AM_1},\tau_{AM_1}),(r_{AM_2},\tau_{AM_2})\}} & E\Pi^M_{AM} \\ &= \rho\left[\frac{(r_{AM_1}-c)}{\tau_{AM_1}} - \frac{(1-\alpha)e_1\tau_{AM_1}}{2} - \frac{(1-\beta)w}{\tau_{AM_1}} - \frac{k}{T}\right] \\ &\quad + (1-\rho)\left[\frac{(r_{AM_2}-c)}{\tau_{AM_2}} - \frac{(1-\alpha)e_2\tau_{AM_2}}{2} - \frac{(1-\beta)w}{\tau_{AM_2}} - \frac{k}{T}\right],\end{aligned} \tag{6}$$

$$\begin{aligned}\text{Subject to : } \mathbf{IC}_i : & \Pi^C_{AM_i}(r_{AM_i}, \tau_{AM_i}) \geq \Pi^C_{AM_i}(r_{AM_j}, \tau_{AM_j}); \\ & i = 1,2; \quad j \neq i, \text{ and} \\ \mathbf{IR}_i : & \Pi^C_{AM_i}(r_{AM_i}, \tau_{AM_i}) \geq 0; \quad i = 1,2\end{aligned}$$

where $\Pi^C_{AM_i}(r_{AM}, \tau_{AM}) = \phi - \frac{(r_{AM}+\beta w)}{\tau_{AM}} - \frac{\alpha e_i \tau_{AM}}{2}$ denotes customer type i's profit from choosing (r_{AM}, τ_{AM}) from the contract menu. IC constraints ensure that a type 1 customer is better off choosing (r_{AM_1}, τ_{AM_1}) and, similarly, that a type 2 customer is better off choosing (r_{AM_2}, τ_{AM_2}). We first analyze the subgame where the manufacturer decides the contract, given design choices (q, θ). Proposition 5 characterizes the optimal contract.

Proposition 5. *Given her priors ρ and $1-\rho$ on customer types 1 and 2, respectively, it is optimal for the manufacturer to offer the menu $\left\{(r^*_{AM_1}, \tau^*_{AM_1}), (r^*_{AM_2}, \tau^*_{AM_2})\right\}$, where*

$$r^*_{AM_1} = \phi\tau^*_{AM_1} - \frac{\alpha e_1 (\tau^*_{AM_1})^2}{2} - \beta w,$$

$$\tau^*_{AM_1} = \sqrt{\frac{2(c+w)}{e_1 + \left(\frac{1-\rho}{\rho}\right)\alpha(e_1 - e_2)}};$$

$$r^*_{AM_2} = \phi\tau^*_{AM_2} - \frac{\alpha e_2 (\tau^*_{AM_2})^2}{2} - \frac{\alpha\tau^*_{AM_1}\tau^*_{AM_2}(e_1 - e_2)}{2} - \beta w,$$

$$\tau^*_{AM_2} = \sqrt{\frac{2(c+w)}{e_2}}.$$

Proof. See Appendix A.

We assume that the customer would weakly prefer the contract intended for his type when indifferent between the two contracts offered. Note that the contract menu is structured in such a way that a type 1 customer is held to his reservation profit by choosing $(r^*_{AM_1}, \tau^*_{AM_1})$, whereas a type 2 customer makes positive profit by choosing $(r^*_{AM_2}, \tau^*_{AM_2})$. Since the manufacturer's profit increases in price, she would want to increase r_{AM_2} in order to extract more rent from a type 2 customer while ensuring that both customer types reveal themselves truthfully through their choices. She decreases the replacement interval τ_{AM_1} below the supply chain-optimal replacement interval for a type 1 customer under symmetric information; i.e., $\tau^*_{AM_1} < \tau^*_{PR_1} = \tau^*_{IN_1}$ (see Proposition 6). At the same time, she sets price r_{AM_1} such that she extracts all of the type 1 customer's profit. While the revenue the manufacturer receives from a type 1 customer is effectively lower than under symmetric information, the optimal menu allows the manufacturer to receive a higher revenue from a type 2 customer masquerading as type 1; i.e., the manufacturer's profit from customer type 2 is higher at $(r^*_{AM_1}, \tau^*_{AM_1})$ than at $(r^*_{PR_1}, \tau^*_{PR_1})$. To induce a type 2 customer to choose $(r^*_{AM_2}, \tau^*_{AM_2})$, she has to leave at least as much rent as the type 2 customer would get from choosing $(r^*_{AM_1}, \tau^*_{AM_1})$. She sets the replacement interval intended for a type 2 customer equal to the supply chain-coordinating replacement interval under symmetric information, i.e., $\tau^*_{AM_2} = \tau^*_{PR_2} = \tau^*_{IN_2}$, but drops the price just enough so that the type 2 customer is indifferent between choosing $(r^*_{AM_1}, \tau^*_{AM_1})$ and $(r^*_{AM_2}, \tau^*_{AM_2})$. A type 1 customer obviously has no incentive to choose $(r^*_{AM_2}, \tau^*_{AM_2})$. The proposed contract thus constitutes a separating equilibrium of the subgame. Proposition 6 compares the optimal replacement intervals and prices for the various scenarios.

Proposition 6.

(i) $\tau^*_{DS_1} > \tau^*_{IN_1} \geq \tau^*_{AM_1}$; $\tau^*_{DS_2} > \tau^*_{IN_2} = \tau^*_{AM_2}$;

$\tau^*_{DS_2} > \tau^*_{IN_2} = \tau^*_{AM_2} > \tau^*_{IN_1} \geq \tau^*_{AM_1}$.

(ii) $r^*_{DS_1} > r^*_{AM_1}$; $r^*_{DS_2} > r^*_{AM_2}$.

Proof. See Appendix A.

Proposition 7 compares profits under the symmetric and asymmetric information scenarios. For exposition, we introduce some more notation. Let $\Pi^M_{AM_i} := \frac{(r_{AM_i} - c)}{\tau_{AM_i}} - \frac{(1-\alpha)e_i\tau_{AM_i}}{2} - \frac{(1-\beta)w}{\tau_{AM_i}} - \frac{k}{T}$ and $\Pi^{M*}_{AM_i} := \Pi^M_{AM_i}(r^*_{AM_i}, \tau^*_{AM_i})$. Then, the manufacturer's optimal expected profit from offering the menu as in Proposition 5 is $E\Pi^{M*}_{AM} = \rho\Pi^{M*}_{AM_1} + (1-\rho)\Pi^{M*}_{AM_2}$, since customer type i chooses $(r^*_{AM_i}, \tau^*_{AM_i})$ in the separating equilibrium. Similarly, expected customer profit can be written as $E\Pi^{C*}_{AM} = \rho\Pi^{C*}_{AM_1} + (1-\rho)\Pi^{C*}_{AM_2}$, where $\Pi^{C*}_{AM_i} = \Pi^C_{AM_i}(r^*_{AM_i}, \tau^*_{AM_i})$. Observe that when $\rho = 1$, $\tau^*_{AM_1} = \sqrt{\frac{2(c+w)}{e_1}} = \tau^*_{IN_1}$ and $E\Pi^{M*}_{AM} = \Pi^{M*}_{AM_1} = \Pi^*_{IN_1}$, and when $\rho = 0$, $E\Pi^{M*}_{AM} = \Pi^{M*}_{AM_2} = \Pi^*_{IN_2}$.

Proposition 7. $\Pi^{M*}_{AM_1} \leq \Pi^*_{IN_1} = \Pi^*_{PR_1} \leq E\Pi^{M*}_{AM} \leq \Pi^{M*}_{AM_2} \leq \Pi^*_{IN_2} = \Pi^*_{PR_2}$.

Proof. See Appendix A.

Comparing the menu of contracts under asymmetric information and the coordinating contracts under symmetric information, we note the following:

(i) The manufacturer earns a lower profit from either customer type under asymmetric information than she would under symmetric information.

(ii) The manufacturer earns a higher profit from customer type 2 (efficient) than from customer type 1 (normal) both under symmetric and asymmetric information.

(iii) The manufacturer's expected profit from offering a menu of contracts under asymmetric information is bounded below by her profit from selling to a type 1 customer under symmetric information and above from selling to a type 2 customer under symmetric information. Thus, the manufacturer would prefer a price-replacement interval contract with an efficient customer than with a customer of unknown behavior.

The above findings are consistent with those in the literature on supply chain contracting under asymmetric information (e.g., see Corbett et al. 2004, Özer and Wei 2006), although the impact of asymmetric information about customer attributes on product design decisions in the context of EPR has not been examined before. The manufacturer leaves some information rent on the table when she faces uncertainty about the customer's costs during product use. We summarize the implication for total supply chain profit in Corollary 2.

COROLLARY 2. *The total expected supply chain profit under the mechanism described in Proposition 5 is bounded below by the profit of the integrated supply chain with a type 1 customer, and above by the profit of the integrated supply chain with a type 2 customer; i.e.,* $\Pi^*_{IN_1} \leq E\Pi^{M*}_{AM} + E\Pi^{C*}_{AM} \leq \Pi^*_{IN_2}$.

PROOF. See Appendix A.

Manufacturer's Design Choices: Having characterized the manufacturer's optimal contract design, we now analyze the manufacturer's product design decision. Maintaining Assumption A6, we have that the manufacturer's expected profit $E\Pi^{M*}_{AM}$ is jointly concave in q and θ. Denote q^*_{AM} and θ^*_{AM} as the manufacturer's profit-maximizing choices under asymmetric information and the optimal contract menu. Proposition 8 characterizes the optimal design choices.

PROPOSITION 8.

(i) $q^*_{IN_1} \leq q^*_{AM} \leq q^*_{IN_2}$.

(ii) $\theta^*_{IN_1} \geq \theta^*_{AM} \geq \theta^*_{IN_2}$.

PROOF. See Appendix A.

Under asymmetric information and the optimal menu of contracts, the manufacturer's design choices lie between the coordinated supply chain's choices with customer types 1 and 2. In particular, an *environmentally positive* uncertainty regarding customer type (i.e., the manufacturer believes the customer might be efficient) leads the manufacturer to provide better environmental performance in the product with an attendant loss in product remanufacturability. On the other hand, an *environmentally negative* uncertainty (i.e., the manufacturer believes the customer might be inefficient) leads to opposite effects on the manufacturer's choices of performance and remanufacturability.

6.2. Discussion

As is clear from the analysis above, lack of perfect information about customer behavior complicates the manufacturer's decisions. To induce revelation from the customer, the manufacturer has to give up some rent and cannot always implement the supply chain-optimal replacement frequency. This, in turn, affects her incentives to invest in environmentally beneficial product design. Consequently, the impacts of EPR levers on environmental and profit outcomes are different under asymmetric information than the impacts discussed in Section 4.2.3 for the case of symmetric information. Comparative statics results are summarized in Tables B1 and B2 in Appendix B. We discuss the main effects that are different under asymmetric information.

(i) If the environmental cost during use for a type 1 customer (e_1) is large relative to that for a type 2 customer (e_2), an increase in e_1 can lead the manufacturer to invest in higher performance q, contrary to the outcome under symmetric information where an increase in e always leads the manufacturer to reduce q (see Table B1). This behavior can be understood as follows: as e_1 increases, with e_2 fixed, the extent of information asymmetry is larger, and the manufacturer makes smaller profits because she needs to drop both $r^*_{AM_1}$ and $r^*_{AM_2}$ to satisfy the IC and IR constraints. While the optimal contract menu adjusts the replacement interval to keep a type 1 customer at his reservation profit, a type 2 customer benefits; his profits increase in the difference $(e_1 - e_2)$. To partially compensate for her loss in profits, the manufacturer increases her investment in q because higher q lowers both e_1 and e_2, thus allowing the manufacturer to increase her prices and, therefore, her profit. If e_1 is close to e_2, the impact of information asymmetry is small and q decreases in e_1 and e_2—as is the case with symmetric information.

(ii) Under asymmetric information, larger w leads to higher profit for a type 2 customer, and induces the manufacturer to provide lower remanufacturability (θ). With increasing w faced by both customer types, the manufacturer is forced to charge a lower price in order that the IR and IC constraints remain satisfied. Therefore, a type 2 customer's profit increases in w, similar to the effect discussed in (i) above. Moreover, the replacement interval increases with w, leading to a diminished incentive for the manufacturer to provide θ—as is the case with a coordinated supply chain under symmetric information.

7. Conclusion and Future Work

In this paper, we analyzed design incentives faced by a manufacturer producing and selling a remanufacturable product to a customer when EPR policies require both actors to bear environmental charges over the product's life cycle. Our analysis provides a rich picture of the impacts of various EPR levers by accounting for the fact that profit-maximizing manufacturers and customers in supply chains will react optimally in response to changes in environmental charges. Below, we summarize how we address the three research questions presented in Section 1.

(i) Disposal costs are traditionally used to influence a product's end-of-life environmental impact. However, our results imply that disposal charges could be used to encourage designs that reduce the product's environmental impact during use. Moreover, higher charges for environmental impact during product use can lead to better remanufacturability that reduces the end-of-life environmental impact of the product. Additionally, as the customer bears a larger share of charges during product use, the manufacturer has a greater incentive to design the product to be more remanufacturable.

(ii) We examined the impacts of a lack of supply chain coordination on environmental product design choices under symmetric and asymmetric information. For the case of symmetric information, we showed that coordination leads not only to higher supply chain profit as expected, but also to environmentally more favorable product design. We analyzed contracts that can help achieve coordination in a decentralized supply chain—including price-replacement interval, two-part tariff, and leasing—and contrasted them in the context of EPR.

(iii) A supply chain with an efficient customer incurs lower costs during use and therefore replaces the product less often. However, this lowers the manufacturer's incentive to design the product with greater remanufacturability, since remanufacturing and disposal costs are incurred less often. Thus, an efficient customer does not unequivocally lead to superior product design. The contracts that we studied under symmetric information recognize these tradeoffs and help align supply chain incentives. If the manufacturer lacks perfect information about customer attributes that affect charges incurred during product use, the manufacturer can offer a menu of contracts consisting of price and replacement interval pairs such that a customer would choose the contract intended for his type. The resulting design choices by the manufacturer are impacted by her uncertainty regarding the customer's type. An *environmentally positive* uncertainty regarding customer type (i.e., the manufacturer believes the customer might be efficient) leads the manufacturer to provide better environmental performance in the product with an attendant loss in product remanufacturability. On the other hand, an *environmentally negative* uncertainty (i.e., the manufacturer believes the customer might be inefficient) leads to opposite effects on the manufacturer's choices of performance and remanfacturability.

Several extensions to this work merit treatment in future research. In assuming that remanufacturing is profitable to the manufacturer and is also preferred by the customer, we abstracted from the interactions between new and remanufactured products. We also assumed that a single manufacturer sells to a single customer. The effects of considering multiple customers and heterogeneous customer utilities are worth evaluating. In addition, competition between manufacturers for customer demand can change upstream outcomes in interesting ways. We studied the effects of information asymmetry by focusing on costs incurred during product use. Asymmetric information can be modeled and analyzed for other parameters as well, such as the disposal cost incurred at end-of-life. Uncertainty could be incorporated into the model in other ways. There could be uncertainty in the success of design efforts, in the likelihood that a returned product can be remanufactured, and in environmental policies or liabilities over time (Snir 2001). Also, an important concern in remanufacturing is the uncertainty in both the quality and the quantity of product returns (Fleischmann et al. 2001, 2002). Finally, additional insights into EPR policy design can be facilitated by endogenizing the policy parameters of the model. Explicitly treating the regulator's decision of setting various EPR parameters will enable an assessment of social welfare-maximizing policy choices that go beyond our focus on environmental product design attributes and supply chain profit.

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Appendix A: Proofs

Proof of Proposition 1.

$$\frac{\partial \Pi^*_{IN_i}}{\partial q} = g_1(q,\theta) - k_1 u_q; \quad \frac{\partial^2 \Pi^*_{IN_i}}{\partial q^2} = g_{1q}(q,\theta) - k_1 u_{qq}.$$

$$\frac{\partial \Pi^*_{IN_i}}{\partial \theta} = g_2(q,\theta) - k_2 v_\theta; \quad \frac{\partial^2 \Pi^*_{IN_i}}{\partial \theta^2} = g_{2\theta}(q,\theta) - k_2 v_{\theta\theta}.$$

$\frac{\partial^2 \Pi^*_{IN_i}}{\partial q \partial \theta} = g_3(q,\theta)$, where g_1, g_2, and g_3 denote (for brevity) the functions of q and θ resulting from the said differentiations.

The Hessian matrix of $\Pi^*_{IN_i}$ with respect to q and θ is therefore

$$\begin{bmatrix} g_{1q} - k_1 u_{qq} & g_3 \\ g_3 & g_{2\theta} - k_2 v_{\theta\theta} \end{bmatrix}.$$

The determinant of the above matrix is positive for sufficiently large k_1 and k_2. Thus, for sufficiently large k_1 and k_2, the Hessian matrix of $\Pi^*_{IN_i}$ with respect to q and θ is negative definite, yielding the result. □

Proof of Proposition 2.

$$\frac{\partial \Pi^*_{IN_i}}{\partial q} = -\frac{e_i c_q + (c+w)e_{iq}}{\sqrt{2e_i(c+w)}} - \frac{k_q}{T},$$

and

$$\frac{\partial \Pi^*_{IN_i}}{\partial \theta} = -\sqrt{\frac{e_i}{2(c+w)}}(c_\theta + w_\theta) - \frac{k_\theta}{T}.$$

With Assumption A6, it suffices to show that $\frac{\partial \Pi^*_{IN_2}}{\partial q} - \frac{\partial \Pi^*_{IN_1}}{\partial q} > 0$, and $\frac{\partial \Pi^*_{IN_2}}{\partial \theta} - \frac{\partial \Pi^*_{IN_1}}{\partial \theta} < 0$.

$$\begin{aligned} &\frac{\partial \Pi^*_{IN_2}}{\partial q} - \frac{\partial \Pi^*_{IN_1}}{\partial q} \\ &= \frac{1}{\sqrt{2(c+w)}}\left[c_q(\sqrt{e_1} - \sqrt{e_2}) + (c+w)\left(\frac{e_{1q}}{\sqrt{e_1}} - \frac{e_{2q}}{\sqrt{e_2}}\right)\right] \\ &> 0, \text{ since } c_q > 0,\ e_1 > e_2, \text{ and } e_{1q} > e_{2q}. \end{aligned}$$

$$\begin{aligned} \frac{\partial \Pi^*_{IN_2}}{\partial \theta} - \frac{\partial \Pi^*_{IN_1}}{\partial \theta} &= \frac{(c_\theta + w_\theta)}{\sqrt{2(c+w)}}(\sqrt{e_1} - \sqrt{e_2}) \\ &< 0, \text{ since } c_\theta < 0,\ w_\theta < 0, \text{ and } e_1 > e_2. \end{aligned}$$

□

Proof of Observation 1.

$$\Pi^M_{DS_i} = \frac{e_i[r(2\alpha - 1) + w(2\alpha\beta - \alpha - \beta) - \alpha c]}{\sqrt{2\alpha e_i(r + \beta w)}} - \frac{k}{T}, \quad \text{(A1)}$$

$$\frac{\partial \Pi^M_{DS_i}}{\partial r} = \frac{\sqrt{2e_i}[r(2\alpha - 1) + w(2\alpha\beta + \alpha - \beta) - \alpha c]}{4\sqrt{\alpha}(r + \beta w)^{\frac{3}{2}}} > 0.$$

□

Proof of Proposition 3.

(i) From (4), it is easy to verify that $\Pi^{M*}_{DS_i}$ increases in i, since $e_1 > e_2$. □

(ii) $\frac{\partial \Pi^{M*}_{DS_i}}{\partial q} = -\frac{\alpha}{\phi}[e_i c_q + (c+w)e_{iq}] - \frac{k_q}{T}$, and $\frac{\partial \Pi^{M*}_{DS_i}}{\partial \theta} = -\frac{\alpha}{\phi} e_i(c_\theta + w_\theta) - \frac{k_\theta}{T}$. With Assumption A6, it suffices to show that $\frac{\partial \Pi^{M*}_{DS_2}}{\partial q} - \frac{\partial \Pi^{M*}_{DS_1}}{\partial q} > 0$, and $\frac{\partial \Pi^{M*}_{DS_2}}{\partial \theta} - \frac{\partial \Pi^{M*}_{DS_1}}{\partial \theta} < 0$.

$$\begin{aligned} \frac{\partial \Pi^{M*}_{DS_2}}{\partial q} - \frac{\partial \Pi^{M*}_{DS_1}}{\partial q} &= -\frac{\alpha}{\phi}[c_q(e_2 - e_1) + (c+w)(e_{2q} - e_{1q})] \\ &> 0, \text{ since } e_1 > e_2,\ e_{1q} > e_{2q}, \text{ and } c_q > 0. \end{aligned}$$

$$\begin{aligned} \frac{\partial \Pi^{M*}_{DS_2}}{\partial \theta} - \frac{\partial \Pi^{M*}_{DS_1}}{\partial \theta} &= -\frac{\alpha}{\phi}[(c_\theta + w_\theta)(e_2 - e_1)] \\ &< 0, \text{ since } c_\theta < 0,\ w_\theta < 0, \text{ and } e_1 > e_2. \end{aligned}$$

□

Proof of Proposition 4.

(i) From (2), we have

$$\Pi^*_{IN_i} = \phi - \sqrt{2e_i(c+w)} - \frac{k}{T}$$

And from (4), we have

$$\Pi^{M*}_{DS_i} = \frac{\phi^2(2\alpha - 1) - 2\alpha^2 e_i(c+w)}{2\alpha\phi} - \frac{k}{T}.$$

Therefore, for the same design choices,

$$\begin{aligned} &\Pi^*_{IN_i} - \Pi^{M*}_{DS_i} \\ &= \frac{2\alpha\phi^2 - 2\alpha\phi\sqrt{2e_i(c+w)} - \phi^2(2\alpha - 1) - 2\alpha^2 e_i(c+w)}{2\alpha\phi} \\ &= \frac{\left[\phi - \alpha\sqrt{2e_i(c+w)}\right]^2}{2\alpha\phi} > 0. \end{aligned}$$

□

(ii) Since $\Pi^{M*}_{DS_i}$ and $\Pi^*_{IN_i}$ are both jointly concave in q and θ, it suffices to show that $\frac{\partial \Pi^*_{IN_i}}{\partial q} > \frac{\partial \Pi^{M*}_{DS_i}}{\partial q}$, and that $\frac{\partial \Pi^*_{IN_i}}{\partial \theta} > \frac{\partial \Pi^{M*}_{DS_i}}{\partial \theta}$. From (2) and (4) we have

$$\frac{\partial \Pi^{M*}_{DS_i}}{\partial q} = -\frac{\alpha}{\phi}\left[e_i c_q + (c+w)e_{iq}\right] - \frac{k_q}{T}$$

and

$$\frac{\partial \Pi^*_{IN_i}}{\partial q} = -e_{iq}\sqrt{\frac{c+w}{2e_i}} - \frac{k_q}{T}.$$

Hence,

$$\begin{aligned}\frac{\partial \Pi^*_{IN_i}}{\partial q} - \frac{\partial \Pi^{M*}_{DS_i}}{\partial q} &= \frac{-\phi e_{iq}\sqrt{c+w} + \alpha\sqrt{2e_i}\left[e_i c_q + (c+w)e_{iq}\right]}{\phi\sqrt{2e_i}}\\ &> 0, \text{since } e_{iq} < 0,\ c_q > 0, \text{ and } \Pi^*_{IN_i} \geq 0 \Rightarrow\\ &\phi > \alpha\sqrt{2e_i(c+w)}.\end{aligned}$$

And

$$\frac{\partial \Pi^{M*}_{DS_i}}{\partial \theta} = -\frac{\alpha}{\phi} e_i(c_\theta + w_\theta) - \frac{k_\theta}{T}$$

and

$$\frac{\partial \Pi^*_{IN_i}}{\partial \theta} = -(c_\theta + w_\theta)\sqrt{\frac{e_i}{2(c+w)}} - \frac{k_\theta}{T}.$$

Hence,

$$\begin{aligned}\frac{\partial \Pi^*_{IN_i}}{\partial \theta} - \frac{\partial \Pi^{M*}_{DS_i}}{\partial \theta} &= -\frac{(c_\theta + w_\theta)[\phi\sqrt{e_i} - \alpha e_i\sqrt{2(c+w)}]}{\phi\sqrt{2(c+w)}}\\ &> 0, \text{since } c_\theta < 0,\ w_\theta < 0, \text{ and } \Pi^*_{IN_i} \geq 0 \Rightarrow\\ &\phi > \alpha\sqrt{2e_i(c+w)}.\end{aligned}$$

□

Proof of Proposition 5. $\Pi^C_{AM_2}(r_{AM_1}, \tau_{AM_1}) > \Pi^C_{AM_1}(r_{AM_1}, \tau_{AM_1})$ since $e_2 < e_1$. Therefore, from IC$_2$ we have

$$\begin{aligned}&\Pi^C_{AM_2}(r_{AM_2}, \tau_{AM_2}) \geq \Pi^C_{AM_2}(r_{AM_1}, \tau_{AM_1})\\ &> \Pi^C_{AM_1}(r_{AM_1}, \tau_{AM_1}) \geq 0.\end{aligned} \tag{A2}$$

IR$_1$ must bind. If not, looking at (A2), IR$_2$ would also not bind. Both r_{AM_1} and r_{AM_2} can then be increased without violating the IC and IR conditions, resulting in an increase in the manufacturer's profit. Also note that, at optimality, IC$_2$ must bind. If IC$_2$ does not bind, we must have

$$\begin{aligned}&\Pi^C_{AM_2}(r_{AM_2}, \tau_{AM_2}) > \Pi^C_{AM_2}(r_{AM_1}, \tau_{AM_1})\\ &> \Pi^C_{AM_1}(r_{AM_1}, \tau_{AM_1}) = 0,\end{aligned} \tag{A3}$$

in which case r_{AM_2} can be increased without violating the IC and IR conditions, resulting in an increase in the manufacturer's profit. Solving for $\Pi^C_{AM_1}(r_{AM_1}, \tau_{AM_1}) = 0$ and $\Pi^C_{AM_2}(r_{AM_2}, \tau_{AM_2}) = \Pi^C_{AM_2}(r_{AM_1}, \tau_{AM_1})$ yields the result. □

Proof of Proposition 6.

(i) We know from Sections 3 and 4.1.2 that $\tau^*_{DS_i} > \tau^*_{IN_i}$. It is straightforward to verify that when $\rho < 1$, $\tau^*_{IN_1} > \tau^*_{AM_1}$, and when $\rho = 1$, $\tau^*_{IN_1} = \tau^*_{AM_1}$. From Proposition 5, we know that $\tau^*_{AM_2} = \tau^*_{IN_2}$. Therefore, $\tau^*_{DS_2} > \tau^*_{IN_2} = \tau^*_{AM_2}$. That $\tau^*_{DS_2} > \tau^*_{IN_2} = \tau^*_{AM_2} > \tau^*_{IN_1} \geq \tau^*_{AM_1}$ follows from above and from the fact that $\tau^*_{IN_2} > \tau^*_{IN_1}$. □

(ii) We know that $\Pi^C_{DS_1}(r^*_{DS_1}, \tau^*_{DS_1}) = 0$, i.e., $r^*_{DS_1} = \phi\tau^*_{DS_1} - \frac{\alpha e_1 (\tau^*_{DS_1})^2}{2} - \beta w$. Also, from Proposition 5, we know that $r^*_{AM_1} = \phi\tau^*_{AM_1} - \frac{\alpha e_1 (\tau^*_{AM_1})^2}{2} - \beta w$. $r^*_{DS_1} > r^*_{AM_1}$ if

$$\phi\left(\tau^*_{DS_1} - \tau^*_{AM_1}\right) > \frac{\alpha e_1\left[\left(\tau^*_{DS_1}\right)^2 - \left(\tau^*_{AM_1}\right)^2\right]}{2};$$

i.e., if $\phi > \frac{\alpha e_1(\tau^*_{DS_1} + \tau^*_{AM_1})}{2}$;
i.e., if $\phi \geq \alpha e_1 \tau^*_{DS_1}$, since $\tau^*_{DS_1} > \tau^*_{AM_1}$ from part (i) above;
i.e., if $\phi \geq \sqrt{2\alpha e_1(r + \beta w)}$, which is implied by the customer's participation constraint.

Also, we know that $\Pi^C_{DS_2}(r^*_{DS_2}, \tau^*_{DS_2}) = 0$, i.e., $r^*_{DS_2} = \phi\tau^*_{DS_2} - \frac{\alpha e_2 (\tau^*_{DS_2})^2}{2} - \beta w$. From Proposition 5, we know that $r^*_{AM_2} = \phi\tau^*_{AM_2} - \frac{\alpha e_2 (\tau^*_{AM_2})^2}{2} - \frac{\alpha\tau^*_{AM_1}\tau^*_{AM_2}(e_1 - e_2)}{2} - \beta w$. $r^*_{DS_2} > r^*_{AM_2}$ if

$$\phi(\tau^*_{DS_2} - \tau^*_{AM_2}) > \frac{\alpha e_2\left[(\tau^*_{DS_2})^2 - (\tau^*_{AM_2})^2\right]}{2},$$

since $e_1 > e_2$;

i.e., if $\phi > \frac{\alpha e_2(\tau^*_{DS_2} + \tau^*_{AM_2})}{2}$;
i.e., if $\phi \geq \alpha e_2 \tau^*_{DS_2}$, since $\tau^*_{\mathrm{DS}_2} > \tau^*_{\mathrm{AM}_2}$ from part (i) above;
i.e., if $\phi \geq \sqrt{2\alpha e_2(r + \beta w)}$, which is implied by the customer's participation constraint. □

Proof of Proposition 7. We prove Proposition 7 in steps.

(a) When $\rho \in (0, 1)$, although $\Pi^C_{AM_1}(r^*_{AM_1}, \tau^*_{AM_1}) = 0$, we have $\tau^*_{AM_1} \neq \tau^*_{IN_1}$, implying that the replacement interval for a type 1 customer is different than the supply chain coordinating replacement interval. When $\rho = 1$, we have $\Pi^{M*}_{AM_1} = \Pi^{*}_{IN_1}$. Therefore, $\Pi^{M*}_{AM_1} \leq \Pi^{*}_{IN_1}$.

(b) From the proof of Proposition 5, we know that when $\rho \in (0, 1)$, $\Pi^{C}_{AM_2}(r^*_{AM_2}, \tau^*_{AM_2}) = \Pi^{C}_{AM_2}(r^*_{AM_1}, \tau^*_{AM_1}) > 0$, implying that customer type 2 makes a positive profit as a result of asymmetric information. Hence, the manufacturer's profit from type 2 customer, i.e., $\Pi^{M*}_{AM_2}$, has to be less than the profit of the coordinated supply chain with a type 2 customer. When $\rho = 0$, we have $\Pi^{M*}_{AM_2} = \Pi^{*}_{IN_2}$. Therefore, $\Pi^{M*}_{AM_2} \leq \Pi^{*}_{IN_2}$.

(c) When $\rho = 0$, $\Pi^{M*}_{AM_1} = 0$ (since $\tau^*_{AM_1} = 0$), and $\Pi^{M*}_{AM_2} = \Pi^{*}_{IN_2} > \Pi^{M*}_{AM_1}$. When $\rho = 1$, using the expressions for $\tau^*_{AM_1}$ and $\tau^*_{AM_2}$ in Proposition 5, we have

$$\Pi^{M*}_{AM_2} - \Pi^{M*}_{AM_1} = \frac{2(c+w)(\tau^*_{AM_2} - \tau^*_{AM_1}) + (\tau^*_{AM_1})^2 \tau^*_{AM_2} e_1 (1-\alpha) - \tau^*_{AM_1}\tau^*_{AM_2} e_2 (\tau^*_{AM_2} - \alpha\tau^*_{AM_1})}{2\tau^*_{AM_1}\tau^*_{AM_2}} \tag{A4}$$

$$= \frac{4(c+w)(\tau^*_{AM_2} - \tau^*_{AM_1}) - \alpha\,(\tau^*_{AM_1})^2\,\tau^*_{AM_2}(e_1 - e_2)}{2\tau^*_{AM_1}\tau^*_{AM_2}}. \tag{A5}$$

The numerator on the right hand side of (A5) is >0 if

$$\begin{aligned} &4(c+w)(\tau^*_{AM_2} - \tau^*_{AM_1}) > \alpha\,(\tau^*_{AM_1})^2\,\tau^*_{AM_2}(e_1 - e_2) \\ &\text{i.e., if } 2(\tau^*_{AM_2} - \tau^*_{AM_1}) > \alpha\tau^*_{AM_2}\frac{(e_1 - e_2)}{e_1} \qquad \text{(A6)} \\ &\qquad \text{i.e., if } \sqrt{e_1}(2-\alpha) > \alpha\sqrt{e_2}. \end{aligned}$$

Since $\alpha \in [0, 1]$, (A6) is always true. Hence, when $\rho = 1$, we still have $\Pi^{M*}_{AM_1} < \Pi^{M*}_{AM_2}$. From (A4) and Proposition 5, we can verify that

$$\frac{\partial}{\partial\rho}\left(\Pi^{M*}_{AM_2} - \Pi^{M*}_{AM_1}\right) = -\frac{\alpha^2\sqrt{2(c+w)}(e_1 - e_2)^2}{4\rho^{\frac{3}{2}}\left[\alpha(e_1 - e_2)(1-\rho) + \rho e_1\right]^{\frac{3}{2}}} < 0.$$

Therefore, the minimum of $\Pi^{M*}_{AM_2} - \Pi^{M*}_{AM_1}$ would occur at $\rho = 1$. But $\Pi^{M*}_{AM_2} - \Pi^{M*}_{AM_1} > 0$ at $\rho = 1$. Therefore, $\Pi^{M*}_{AM_1} < \Pi^{M*}_{AM_2}$.

(d) At $\rho = 1$, $\Pi^{M*}_{AM_1} = \Pi^{*}_{IN_1}$. Therefore, from part (c) above, when $\rho = 1$, $\Pi^{M*}_{AM_2} > \Pi^{*}_{IN_1}$.

(e) We know that when $\rho = 1$, $E\Pi^{M*}_{AM} = \Pi^{M*}_{AM_1} = \Pi^{*}_{IN_1}$, and when $\rho = 0$, $E\Pi^{M*}_{AM} = \Pi^{M*}_{AM_2} = \Pi^{*}_{IN_2}$. We will show that $\frac{\partial(E\Pi^{M*}_{AM})}{\partial\rho} < 0$. From Proposition 5 and (6), we have

$$\frac{\partial(E\Pi^{M*}_{AM})}{\partial\rho} = \frac{(c+w)}{\sqrt{2}AB}\left[-A(e_1 - e_2)[2\rho(1-\alpha) + \alpha] + 2Be_2\right], \tag{A7}$$

$$\frac{\partial^2(E\Pi^{M*}_{AM})}{\partial\rho^2} = \frac{\sqrt{2}\alpha^2(c+w)^2(e_1 - e_2)^2}{4B^3} > 0,$$

where $A = \sqrt{e_2(c+w)}$ and $B = \sqrt{\rho(c+w)[\alpha(e_1 - e_2)(1-\rho) + \rho e_1]}$. The roots of the right-hand side of (A7) are $\frac{-(1-\alpha)(e_1-e_2) \pm \sqrt{-(1-\alpha)e_2(e_1-e_2)}}{2\left[(1-\alpha)^2 e_1 + \alpha(1-\alpha)e_2\right]}$, which are imaginary. Hence, $E\Pi^{M*}_{AM}$ decreases convexly in ρ from $\Pi^{*}_{IN_2}$ at $\rho = 0$ to $\Pi^{*}_{IN_1}$ at $\rho = 1$.

The result follows from parts (a) through (e). □

Proof of Corollary 2. From Proposition 7, we have $\Pi^{M*}_{AM_1} \leq \Pi^{*}_{IN_1} \leq E\Pi^{M*}_{AM} \leq \Pi^{M*}_{AM_2} \leq \Pi^{*}_{IN_2}$. Therefore, we must have $E\Pi^{M*}_{AM} + E\Pi^{C*}_{AM} \geq \Pi^{*}_{IN_1}$. Denote $\Pi^{SC*}_{AM_i} := \Pi^{M*}_{AM_i} + \Pi^{C*}_{AM_i}$. Then, $E\Pi^{M*}_{AM} + E\Pi^{C*}_{AM} = \rho\Pi^{SC*}_{AM_1} + (1-\rho)\Pi^{SC*}_{AM_2}$. Since $\tau^*_{AM_2} = \tau^*_{IN_2}$, we have $\Pi^{SC*}_{AM_2} = \Pi^{*}_{IN_2}$. In order to show that $E\Pi^{M*}_{AM} + E\Pi^{C*}_{AM} \leq \Pi^{*}_{IN_2}$, it suffices to show that $\Pi^{SC*}_{AM_1} < \Pi^{SC*}_{AM_2}$. Since $\Pi^{M*}_{AM_2} > \Pi^{M*}_{AM_1}$ (from part (c) of the proof of Proposition 7), and $\Pi^{C*}_{AM_2} > \Pi^{C*}_{AM_1} = 0$ (from the proof of Proposition 5), we therefore have $\Pi^{SC*}_{AM_1} < \Pi^{SC*}_{AM_2}$. □

Proof of Proposition 8.

(i) We know that when $\rho = 1$, $E\Pi^{M*}_{AM} = \Pi^{M*}_{AM_1} = \Pi^{*}_{IN_1}$, and when $\rho = 0$, $E\Pi^{M*}_{AM} = \Pi^{M*}_{AM_2} = \Pi^{*}_{IN_2}$. We also know from Proposition 7 that $\Pi^{*}_{IN_1} \leq E\Pi^{M*}_{AM} \leq \Pi^{*}_{IN_2}$, and that $E\Pi^{M*}_{AM}$ decreases convexly in ρ from $\Pi^{*}_{IN_2}$ at $\rho = 0$ to $\Pi^{*}_{IN_1}$ at $\rho = 1$. It suffices to show when $\rho \in (0, 1)$, that

(a) $\frac{\partial(E\Pi^{M*}_{AM})}{\partial q} < \frac{\partial\Pi^{*}_{IN_2}}{\partial q}$ implying that $q^*_{AM} < q^*_{IN_2}$, and

(b) $q^*_{AM} < q^*_{IN_1} < q^*_{IN_2}$ is impossible.

Proof of (a).

$$\frac{\partial\Pi^{*}_{IN_2}}{\partial q} - \frac{\partial(E\Pi^{M*}_{AM})}{\partial q} = \frac{\partial}{\partial q}\Big[\alpha(1-\rho)\tau^*_{AM_1}(e_1 - e_2) + \rho\left(e_1\tau^*_{AM_1} - e_2\tau^*_{AM_2}\right)\Big]. \tag{A8}$$

Recall that $\tau^*_{AM_1} < \tau^*_{AM_2}$, $e_1 > e_2$, $e_{iq} < 0$, and $e_{1q} > e_{2q}$. Denote $D := \alpha(e_1 - e_2)(1-\rho) + \rho e_1$. Verify that

$\tau^*_{AM_{1q}} = \frac{\tau^*_{AM_1}}{2(c+w)}c_q - \frac{\tau^*_{AM_1}}{2D}D_q$, and $\tau^*_{AM_{2q}} = \frac{\tau^*_{AM_2}}{2(c+w)}c_q - \frac{\tau^*_{AM_2}}{2e_2}e_{2q}$. By expanding and collecting terms, we can verify that the right-hand side of (A8) is >0, yielding the result.

Proof of (b). By contradiction. Assume for some ρ that $q^*_{AM}(\rho) < q^*_{IN_1} < q^*_{IN_2}$. Denote $f := \frac{\partial(E\Pi^{M*}_{AM})}{\partial q}$. q^*_{AM} satisfies $f = 0$. Using implicit differentiation, we have $\frac{\partial q^*_{AM}}{\partial \rho} = -\frac{\partial f/\partial \rho}{\partial f/\partial q^*_{AM}}$. $\frac{\partial q^*_{AM}}{\partial \rho}$ is well behaved since f is well behaved and $\frac{\partial f}{\partial q^*_{AM}} < 0$. Hence, it must be true for some ρ_0, that $\frac{\partial q^*_{AM}}{\partial \rho} > 0$, or $\frac{\partial f}{\partial \rho} > 0$. For convenience, denote $q^*_{AM_0} := q^*_{AM}(\rho_0)$. We will show that it is impossible that $\frac{\partial f}{\partial \rho} > 0$ at $q^*_{AM_0}$.

$$\frac{\partial f}{\partial \rho} = \frac{\partial^2 (E\Pi^{M*}_{AM})}{\partial \rho \partial q} = \frac{\partial}{\partial q}\left[-\alpha' \tau^*_{AM_1}(e_1 - e_2) + e_2 \tau^*_{AM_2}\right],$$
$$\text{where } \alpha' = 1 - \alpha + \frac{\alpha}{2\rho} > 0. \tag{A9}$$

Recall from Proposition 6 that $\tau^*_{AM_2} = \tau^*_{IN_2}$. From (a) above, we must have $\frac{\partial \Pi^*_{IN_2}}{\partial q}|_{q=q^*_{AM_0}} > 0$. From (1), this translates into $\frac{\partial}{\partial q}e_2\tau^*_{IN_2} = \frac{\partial}{\partial q}e_2\tau^*_{AM_2} < 0$. Therefore, the right-hand side of (A9) can be >0 only if $\frac{\partial}{\partial q}\left[\tau^*_{AM_1}(e_1 - e_2)\right] < 0$. But, we can verify that $\frac{\partial}{\partial q}\left[\tau^*_{AM_1}(e_1 - e_2)\right] > 0$. Thus, we have a contradiction.

(ii) When $\rho = 1$, $E\Pi^{M*}_{AM} = \Pi^{M*}_{AM_1} = \Pi^*_{IN_1}$, and when $\rho = 0$, $E\Pi^{M*}_{AM} = \Pi^{M*}_{AM_2} = \Pi^*_{IN_2}$. We know from Proposition 7 that $\Pi^*_{IN_1} \leq E\Pi^{M*}_{AM} \leq \Pi^*_{IN_2}$, and that $E\Pi^{M*}_{AM}$ decreases convexly in ρ from $\Pi^*_{IN_2}$ at $\rho = 0$ to $\Pi^*_{IN_1}$ at $\rho = 1$. We also know from Proposition 2 that $\theta^*_{IN_1} > \theta^*_{IN_2}$. It suffices to show when $\rho \in (0, 1)$, that

(c) $\frac{\partial(E\Pi^{M*}_{AM})}{\partial \theta} < \frac{\partial \Pi^*_{IN_1}}{\partial \theta}$ implying that $\theta^*_{AM} < \theta^*_{IN_1}$, and
(d) $\frac{\partial(E\Pi^{M*}_{AM})}{\partial \theta} > \frac{\partial \Pi^*_{IN_2}}{\partial \theta}$ implying that $\theta^*_{AM} > \theta^*_{IN_2}$.

Proof of (c).

$$\begin{aligned}\frac{\partial \Pi^*_{IN_1}}{\partial \theta} - \frac{\partial(E\Pi^{M*}_{AM})}{\partial \theta} &= \frac{\partial}{\partial \theta}\left[-e_1\tau^*_{IN_1} + D\tau^*_{AM_1} + e_2\tau^*_{AM_2}(1-\rho)\right]\\ &= \frac{(c_\theta + w_\theta)}{2(c+w)}\left[\Pi^*_{IN_1} - E\Pi^{M*}_{AM}\right]\\ &> 0, \text{ since } \Pi^*_{IN_1} < E\Pi^{M*}_{AM},\ c_\theta < 0, \text{ and } w_\theta < 0.\end{aligned}$$

Proof of (d).

$$\begin{aligned}\frac{\partial \Pi^*_{IN_2}}{\partial \theta} - \frac{\partial(E\Pi^{M*}_{AM})}{\partial \theta} &= \frac{\partial}{\partial \theta}\left[\alpha(1-\rho)\tau^*_{AM_1}(e_1 - e_2) + \rho(e_1\tau^*_{AM_1} - e_2\tau^*_{AM_2})\right]\\ &= \frac{(c_\theta + w_\theta)}{2(c+w)}\left[\Pi^*_{IN_2} - E\Pi^{M*}_{AM}\right]\\ &< 0, \text{ since } \Pi^*_{IN_2} > E\Pi^{M*}_{AM},\ c_\theta < 0, \text{ and } w_\theta < 0.\end{aligned}$$

□

Appendix B

Table B1 Comparative Statics: Design with respect to Environmental Costs and Parameters

	Sign of 1st derivative of optimal q and θ w.r.t.									
	e_1		e_2		W		α		β	
Section/scenario	q	θ	q	θ	q	θ	q	θ	q	θ
3 Integrated "IN"										
Type 1 customer	–[1]	+	0	0	+	–	NA	NA	NA	NA
Type 2 customer	0	0	–	+	+	–	NA	NA	NA	NA
4.1 Decentralized "DS"										
Type 1 customer	–	+	0	0	+	0	±[2]	+	0	0
Type 2 customer	0	0	–	+	+	0	±	+	0	0
6.1 Asymmetric information "AM"										
	±	+	±	+	+	–	±	+	0	0

[1] e.g., $\frac{\partial q^*_{IN_1}}{\partial e_1} < 0$.

[2] e.g., $q^*_{DS_1}$ is unimodal in α.

Table B2 Comparative Statics: Profit with respect to Environmental Costs and Parameters

	Sign of 1st and 2nd derivatives w.r.t.									
	e_1		e_2		w		α		β	
Section/scenario	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
3 "IN"										
Type 1 customer, SC profit	–[1]	+[2]	0	0	–	+	NA	NA	NA	NA
Type 2 customer, SC profit	0	0	–	+	–	+	NA	NA	NA	NA
4.1 "DS"										
Type 1 customer, SC profit = Manufacturer profit	–	0	0	0	–	0	±	–	0	0
Type 2 customer, SC profit = Manufacturer profit (Customer profit = 0)	0	0	–	0	–	0	±	–	0	0
6.1 "AM"										
SC profit	–	±	–	±	–	+	–	±	0	0
Manufacturer profit	–	+	–	+	–	+	–	+	0	0
Type 2 customer profit	+	–	–	–	+	–	+	–	0	0

[1] e.g., $\frac{\partial \Pi^*_{IN_1}}{\partial e_1} < 0$.

[2] e.g., $\frac{\partial^2 \Pi^*_{IN_1}}{\partial e_1^2} > 0$.

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