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Effects of E-Waste Regulation on New Product Introduction

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This paper investigates the impact of e-waste regulation on new product introduction in a stylized model of the electronics industry. Manufacturers choose the development time and expenditure for each new version of a durable product, which together determine its quality. Consumers purchase the new product and dispose of the last-generation product, which becomes e-waste. The price of a new product strictly increases with its quality and consumers' rational expectation about the time until the next new product will be introduced. "Fee-upon-sale" types of e-waste regulation cause manufacturers to increase their equilibrium development time and expenditure, and thus the incremental quality for each new product. As new products are introduced (and disposed of) less frequently, the quantity of e-waste decreases and, even excluding the environmental benefits, social welfare may increase. Consumers pay a higher price for each new product because they anticipate using it for longer, which increases manufacturers' profits. Unfortunately, existing "fee-upon-sale" types of e-waste regulation fail to motivate manufacturers to design for recyclability. In contrast, "fee-upon-disposal" types of e-waste regulation such as individual extended producer responsibility motivate design for recyclability but, in competitive product categories, fail to reduce the frequency of new product introduction.

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1. Introduction

In the electronics industry, firms compete by introducing new products at a blistering pace. This rapid new product introduction is very costly. For example, Apple, Intel, Sony, Nokia, and Motorola reported R&D cost ranging from 4% to 16% of revenue for fiscal year 2006. Moreover, consumers anticipate that the current hot product will soon be surpassed by a new one, which depresses their willingness to pay and hence depresses electronics manufacturers' revenues. This is commonly called "the Osborne effect." The first portable computer, Osborne I, was introduced in 1981 and skyrocketed to $100 million in revenue. However, when founder Adam Osborne revealed that an improved Osborne was under development, sales evaporated and the company went bankrupt (Raymond 1997). Empirical research shows that electronics manufacturers introduce products too rapidly, with poor functionality, because of competitive pressures, and that the increase in profitability following a new product introduction is short lived because manufacturers cannot prevent imitation (Bayus et al. 1997, 2003).

Rapid new product introduction is very costly for the environment, as well as for electronics manufacturers. In the United States alone, consumers scrap approximately 400 million electronic items per year (Daly 2006), which amounts to more than one million tons of so-called e-waste (Schoenberger 2005). Mobile phones, video game consoles, televisions, computers, etc. are typically discarded when the consumer purchases a more technologically advanced version (Sachs 2006). Thus, electronics disposal is propelled by new product introduction. E-waste contains toxic substances that pollute groundwater and air, especially when disposed in an irresponsible manner.

For policy makers, our paper identifies a trade-off between regulations that act as a "fee-upon-sale" and benefit manufacturers and the environment by reducing the equilibrium rate of new product introduction and regulations that act as a "fee-upon-disposal" and motivate design for recycling.

This paper extends the literature on durable goods monopoly with new product introduction, of which Waldman (2003) provides a survey. Most of these papers analyze two-period models with heterogeneous consumers and with an exogenously specified product quality and/or probability that the monopolist introduces a new product (see, for example, Waldman 1996, Fudenberg and Tirole 1998, Kornish 2001). In contrast, in the paper most closely related to ours, Fishman and Rob (2000) assume that consumers are homogeneous in order to endogenize the timing and quality of sequential new product introductions. They find that by artificially shortening the useful life of each product, the monopolist captures more of the value generated by its next new product, which motivates the monopolist to introduce new products more frequently and thus ultimately improves social welfare. Fishman and Rob conclude that regulators should not impose minimum durability standards. All these papers assume that consumers purchase strategically, with rational expectations regarding the monopolist's new product introductions. Empirically, Song and Chintagunta (2003) and Nair (2004) observe that electronics consumers do purchase strategically (based on expected future prices, quality, and availability) and that this reduces manufacturers' profits.

This paper is organized as follows: §§2 and 3 characterize the unique equilibrium new product introduction process in a monopoly and a duopoly setting. Section 4 describes the effects of various e-waste regulations on the new product introduction process, quantity of e-waste, social welfare, consumer surplus, and manufacturer profit. Section 5 quantifies these effects for four different categories of electronic devices. Section 6 describes the effects of various e-waste regulations on design for recyclability. Section 7 explains how all these effects of e-waste regulation are influenced by consumer heterogeneity and the bargaining power of supply chain partners. Section 8 draws conclusions. Proofs are in the e-companion.[1]

2. Monopoly Model Formulation and Equilibrium Properties

We assume that consumers are identical and live forever and normalize the number of consumers to one. Each consumer can use zero or one unit of a durable product but has no use for additional units. Time is continuous and, with an infinite planning horizon, a monopolist introduces a series of new and improved versions of the durable product. The introduction of each new product, starting at time 0, triggers the monopolist to develop the next one. Specifically, when the monopolist introduces a new product, he immediately chooses the development time $\tau \geq 0$ and total development expenditure $x \geq 0$ for the next new product. Then, τ units of time later, the monopolist incurs the development cost x plus a fixed production cost $c > 0$ and introduces a new product with incremental quality $q(\tau, x)$. Instantaneously, the cycle begins again as the monopolist chooses the development time and expenditure for the next new product.

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

We assume that the incremental quality of a new product $q(\tau, x)$ is a twice-differentiable, strictly increasing function of the development time τ and expenditure x

$$q_\tau > 0 \quad \text{and} \quad q_x > 0, \tag{1}$$

and the marginal return on time and expenditure is decreasing

$$\begin{gathered} q_{\tau\tau} < 0, \quad q_{xx} < 0, \\ \lim_{\tau\to\infty} q_\tau(\tau, x) = 0 \quad \text{and} \quad \lim_{x\to\infty} q_x(\tau, x) = 0. \end{gathered} \tag{2}$$

Time and expenditure are complementary

$$q_{\tau x}(\tau, x) \geq 0, \tag{3}$$

but this is dominated by the decreasing marginal return on time and expenditure

$$(q_{\tau x})^2 \leq q_{\tau\tau} q_{xx} \tag{4}$$

and also is dominated in the relative sense that the marginal return from expenditure is more elastic with respect to expenditure than with respect to time:

$$\left|\frac{q_{\tau x}}{(q_x/\tau)}\right| \leq \left|\frac{q_{xx}}{(q_x/x)}\right|. \tag{5}$$

Assumptions (1)–(5) are satisfied by the family of Cobb-Douglas quality functions:

$$q(\tau, x) = x^\alpha \tau^\beta, \text{ with constants } \alpha \text{ and } \beta \text{ satisfying } \alpha \in (0, 1),\ \beta \in (0, 1), \text{ and } \alpha + \beta \in (0, 1]. \tag{6}$$

Cohen et al. (1996, 2000), and references therein provide empirical support for using a standard Cobb-Douglas function (with $\beta = 1 - \alpha$) for the relationship among expenditure, time, and quality in new product development.

For each new product, the monopolist optimally sets the price equal to the maximum price that consumers are willing to pay, so consumers purchase each new product and discard the last version. Consumers have additional utility of $q(\tau, x)$ per unit time from using the new product rather than the last version. Consumers believe that the development time for the *next* new product is $\tilde{\tau}$, so they will be using the current new product for $\tilde{\tau}$ units of time. Therefore, with a discount rate of $\delta > 0$, the maximum price that consumers will pay for the new product is

$$\int_0^{\tilde{\tau}} e^{-\delta t} q(\tau, x)\, dt = q(\tau, x) f(\tilde{\tau}), \quad \text{where } f(\tilde{\tau}) \triangleq (1 - e^{-\delta\tilde{\tau}})/\delta. \tag{7}$$

We assume that the business is potentially profitable for the monopolist; i.e., there exists a constant development time τ_0 such that if the monopolist could publicly commit to development time τ_0, he would earn strictly positive discounted profit:

$$\max_{x\geq 0}[q(\tau_0, x)f(\tau_0) - x - c] > 0. \quad (8)$$

We restrict attention to a pure-strategy, stationary, rational expectations equilibria:

$$(\tau^m, x^m) = \arg\max_{\tau\geq 0, x\geq 0}\{e^{-\delta\tau}[q(\tau, x)f(\tilde{\tau}) - x - c + \pi^m]\}, \quad (9)$$

where $\tilde{\tau} = \tau^m$ and π^m is the optimal objective value in the right-hand side of (9).

In such equilibria, the monopolist chooses the development time τ^m and expenditure x^m for each new product to maximize his infinite-horizon discounted profit π^m, and consumers anticipate the monopolist's choice of development time τ^m.

Our monopoly model differs from the one in Fishman and Rob (2000) in that we assume (1)–(5) and obtain a unique equilibrium.

Proposition 1. *The unique equilibrium* (τ^m, x^m) *is characterized by the first-order conditions*

$$q(\tau^m, x^m) - (x^m + c)/f(\tau^m) = q_\tau(\tau^m, x^m)f(\tau^m), \quad (10)$$

$$q_x(\tau^m, x^m)f(\tau^m) = 1, \quad (11)$$

and the monopolist earns strictly positive profit.

Nevertheless, consistent with Fishman and Rob (2000), we find that, for purposes of maximizing profit, the monopolist introduces new products too quickly and spends too little on R&D for each product. (If the monopolist could publicly commit to increasing the development time for the next new product, customers would anticipate using the current new product for longer and would therefore be willing to pay more for it.) For purposes of maximizing the sum of profit and consumer surplus, the monopolist introduces new products too slowly and spends too little on R&D. (The term $q(\tau, x)/\delta$ in (13) reflects consumers' infinite-horizon discounted utility from the incremental quality improvement of $q(\tau, x)$ in each new generation of the product.)

Proposition 2. *The equilibrium development time and expenditure are strictly lower than the levels that would maximize the monopolist's profit; i.e.,* $\tau^m < \tau^*$ *and* $x^m < x^*$, *where*

$$(\tau^*, x^*) = \arg\max_{\tau\geq 0, x\geq 0}\left\{\frac{e^{-\delta\tau}}{(1-e^{-\delta\tau})}[q(\tau,x)f(\tau) - x - c]\right\}. \quad (12)$$

However, the equilibrium development time is strictly longer than the maximizer of the sum of profit and consumer surplus; i.e., $\tau^m > \tau^{**}$, *where*

$$(\tau^{**}, x^{**}) = \arg\max_{\tau\geq 0, x\geq 0}\left\{\frac{e^{-\delta\tau}}{1-e^{-\delta\tau}}\left[\frac{q(\tau, x)}{\delta} - x - c\right]\right\}. \quad (13)$$

Holding the equilibrium development time fixed, the equilibrium spending is strictly lower than the level that would maximize the sum of profit and consumer surplus.

Whereas Fishman and Rob (2000) equate social welfare with the sum of profit and consumer surplus, in §4, we extend the definition of social welfare to include the environmental, health, and processing costs of e-waste, which increase with the frequency of new product introduction. Our next section shows that competition speeds up new product introduction to the extent that such introduction may become too rapid for purposes of maximizing the sum of profit and consumer surplus. The costs of e-waste make rapid new product introduction even more detrimental to social welfare.

3. Duopoly Model Formulation and Equilibrium Properties

Now consider two firms that take turns introducing new products. At time 0, firm 1 introduces a new product and chooses the development time and expenditure for its next new product. Firm 1 believes that firm 2 is already committed to introducing a new product at time $\tilde{\tau}_2$. Firm 1 intends to see how consumers respond to that product and then imitate its successful features. Therefore, firm 1 chooses a development time of $\tilde{\tau}_2 + \tau_1$ for some $\tau_1 \geq 0$ and also sets development expenditure $x_1 \geq 0$. Let τ_2 denote the actual time that the competitor introduces its new product. A firm cannot observe its competitor's choice of development time until the competitor introduces its new product to the market, so τ_2 might differ from $\tilde{\tau}_2$. Assuming $\tilde{\tau}_2 + \tau_1 \geq \tau_2$, the incremental quality of firm 1's new product introduced at time $\tilde{\tau}_2 + \tau_1$—above and beyond that of firm 2's product introduced at τ_2—is $q(\gamma\tau_2 + (\tilde{\tau}_2 + \tau_1 - \tau_2), x_1)$, where $\gamma \in [0, 1]$ because the development time *after* observing the competitor's new product $(\tilde{\tau}_2 + \tau_1 - \tau_2)$ is relatively more productive than the development time before observing the competitor's new product (τ_2). Thereafter, when firm i (for $i = 1, 2$) introduces a new product, it sets a development time of $\tilde{\tau}_{-i} + \tau_i$ for some $\tau_i \geq 0$ and also sets expenditure $x_i \geq 0$, where $\tilde{\tau}_{-i}$ denotes firm i's belief about the time until its competitor's next new product introduction. As soon as the competitor's product is out on the market, firm i redirects its own development effort to imitate, incorporate, and build upon the most successful features of the competitor's product. Let τ_{-i} denote the actual time until the competitor introduces its new product. Then, assuming $\tilde{\tau}_{-i} + \tau_i \geq \tau_{-i}$, the incremental quality of firm i's product is $q(\gamma\tau_{-i} + (\tilde{\tau}_{-i} + \tau_i - \tau_{-i}), x_i)$.

At a pure-strategy, stationary, rational expectations equilibrium $(\tau_i^d, x_i^d)_{i=1,2}$, each firm i adopts a stationary development time $(\tilde{\tau}_{-i} + \tau_i)$ that fulfills the expectation of consumers and the other firm ($\tau_i = \tau_i^d = \tilde{\tau}_i$, $i = 1, 2$). From the consumers' perspective, $(\tau_i^d)_{i=1,2}$ are expected durations between adjacent new product introductions. On the equilibrium path, as firm i contemplates the choice of τ_i and x_i for a new product, firm i anticipates that the incremental quality of its new product will be $q(\gamma\tau_{-i}^d + \tau_i, x_i)$ and that when its new product is introduced, after development time of $\tau_{-i}^d + \tau_i$, consumers will expect to use the new product for $\tau_{-i}^d + \tau_i^d - \tau_i$ units of time, until the competitor introduces a replacement, according to the equilibrium timing. Therefore, analogous to (7), consumers will pay

$$q(\gamma\tau_{-i}^d + \tau_i, x_i) f(\tau_{-i}^d + \tau_i^d - \tau_i) \tag{14}$$

for firm i's new product. Firm i chooses τ_i and x_i to maximize its discounted profit on the new product, so a duopoly equilibrium is characterized by

$$(\tau_i^d, x_i^d) = \operatorname*{argmax}_{\tau_i \ge 0, x_i \ge 0} \{ e^{-\delta(\tau_{-i}^d + \tau_i)} [q(\gamma\tau_{-i}^d + \tau_i, x_i) \cdot f(\tau_{-i}^d + \tau_i^d - \tau_i) - x_i - c] \} \quad \text{for } i = 1, 2. \tag{15}$$

If $\gamma = 0$, then any solution to (15) constitutes a sequential equilibrium. However, in the case $\gamma > 0$, firm i's choice of τ_i influences its discounted profit on the *next* new product, so a solution to (15) is only a myopic equilibrium; we are not able to characterize a sequential equilibrium. Nevertheless, for purposes of obtaining qualitative managerial insights, even for the myopic case $\gamma > 0$, (15) is a reasonable representation of the competitive process of new product introduction; it incorporates the first-order effect of competition—pressure to rush a new product to market, to have a longer time window in which that product is the best on the market, ahead of the impending new product introduction by a competitor. (Reducing τ_i for the current product allows more time for developing the next new product, which increases its quality. Therefore, for $\gamma > 0$, a forward-looking duopolist's incentive to rush is even stronger than represented in (15).)

By comparing consumers' equilibrium expected time until the next new product is introduced, the argument of $f()$, which is τ^m in the monopoly price (7) versus $\tau_{-i}^d + \tau_i^d - \tau_i$ in the duopoly price (14), one observes that the duopolist has a stronger incentive to introduce new products quickly than the monopolist does. If the monopolist reduces the development time for one product, his optimal development time for subsequent products is not affected and consumers' willingness to pay per unit quality $f(\tau^m)$ is not affected. In contrast, if the duopolist reduces the development time for one product, consumers are able to use that product for longer. That is, the time from purchase until the competitor introduces the next new product increases. Therefore as the duopolist reduces the development time, consumers' willingness to pay per unit quality $f(\tau_{-i}^d + \tau_i^d - \tau_i)$ increases, which tends to allow the duopolist to charge a higher price. Therefore, a duopolist has an additional incentive to rush to stay ahead of its competitor's impending new product introduction.

An implicit but necessary assumption for the duopoly equilibrium to be characterized by (15) is that each duopolist sets the launch date for selling a new product upon initiating the development process for that product and does not shorten or extend its development time in response to subsequent actions by its competitor. Fixing the development time in this manner is common because it generates psychological benefits and increased productivity in the development team (see Cohen et al. 2000 and references therein) and facilitates coordination with suppliers and distributors (Mishra and Bhabra 2001).

To simplify the analysis, we have assumed that each firm plans to introduce *at most one* new product in the time window between new product introductions by the competitor. We prove this assumption is without loss of generality in that the firms choose to take turns introducing new products in equilibrium. Specifically, Proposition EC.1 in the e-companion establishes that the duopoly equilibrium characterized by (15) remains a sequential equilibrium when we extend the strategy space to give each firm the option of arbitrarily introducing many new products in a row, assuming a standard Cobb-Douglas quality function and that $\gamma = 0$.

Unlike in the monopoly model, assumption (8) is not sufficient to guarantee existence of an equilibrium with nonnegative profit.

Proposition 3. *With a Cobb-Douglas quality function, an equilibrium with strictly positive profit for the duopolists exists if and only if $c > c_d^l$, where c_d^l is strictly positive and decreases with δ.*

The intuition is that increasing the fixed cost of production slows down the competitor, which enables each duopolist to charge a higher price for his own new product. Henceforth we assume that an equilibrium with strictly positive profit exists and

$$\frac{q_{\tau x}(\tau, x)}{q_\tau(\tau, x)} + \left| \frac{q_{xx}(\tau, x)}{q_x(\tau, x)} \right| > \frac{q_x(\tau, x)}{q(\tau, x)}, \tag{16}$$

which is a property of all Cobb-Douglas quality functions. These assumptions, with (1), (3), and (4), guarantee that the equilibrium is unique and symmetric.

Proposition 4. *If (16) holds and a profitable equilibrium exists, it is the unique and symmetric equilibrium (τ^d, x^d) characterized by the first-order conditions*

$$q_\tau((1+\gamma)\tau^d, x^d)f(\tau^d) = q((1+\gamma)\tau^d, x^d) - \delta(x^d + c),$$
$$q_x((1+\gamma)\tau^d, x^d)f(\tau^d) = 1.$$

The duopolists introduce new products too quickly in the sense that if they could jointly commit to longer development times, both would earn greater discounted profit. Moreover, unlike the monopolist, the duopolists may even introduce new products too frequently for purposes of maximizing the sum of profit and consumer surplus.

Proposition 5. *The equilibrium development time and expenditure are strictly lower than the levels that would maximize the duopolists' profit; i.e., $\tau^d < \tau^*$ and $x^d < x^*$, where*

$$(\tau^*, x^*) = \arg\max_{\tau\geq 0,\, x\geq 0}\left\{\frac{e^{-\delta\tau}}{1-e^{-\delta\tau}}[q((1+\gamma)\tau, x)f(\tau) - x - c]\right\}. \quad (17)$$

Furthermore, if the quality function is Cobb-Douglas with sufficiently small α or sufficiently large β, then the equilibrium development time and expenditure are strictly lower than the levels that would maximize the sum of profit and consumer surplus; i.e., $\tau^d < \tau^{**}$ and $x^d < x^{**}$, where

$$(\tau^{**}, x^{**}) = \arg\max_{\tau\geq 0,\, x\geq 0}\left\{\frac{e^{-\delta\tau}}{1-e^{-\delta\tau}}\left[\frac{q((1+\gamma)\tau, x)}{\delta} - x - c\right]\right\}. \quad (18)$$

4. Differential Effects of a Fee Upon Sale and Fee Upon Disposal

This section divides various forms of e-waste regulation into two categories: fee upon disposal and fee upon sale. The fee-upon-disposal category includes all regulations that impose a cost on the manufacturer when the consumer disposes of the manufacturer's product. The fee-upon-sale category includes all regulations that impose a cost on the manufacturer at the time that the manufacturer sells a product.

In the fee-upon-sale category, one example is California's Advanced Recovery Fee (ARF). Every consumer must pay an ARF when he or she buys a laptop computer, monitor, or television, and California uses the funds to pay for collection and recycling of all used electronics. The ARF lowers the maximum amount the consumer will pay the manufacturer for a new product and hence lowers the manufacturer's profit from selling the new product in qualitatively the same way as if California charged the manufacturer directly. A second example, Restrictions on Hazardous Substances (RoHS) in the European Union (EU), China, and California require substitution of materials that may be more costly or cause yield problems and require costly testing and documentation of compliance. In our model, such additional costs of producing a new product occur simultaneously with sale of the new product, so we categorize RoHS as a fee upon sale. (Although our model assumes a constant fee, the additional production costs associated with RoHS will decrease over time, as manufacturers learn how to work effectively with substitute materials and optimize their facilities and supply chains around those new work practices.) A third example, "old for new" regulation, requires a firm to collect and process one unit of e-waste when selling a new unit. It is implemented for sales to businesses in most EU countries and for large appliances in Japan.

In the fee-upon-disposal category, individual extended producer responsibility (EPR) makes each manufacturer responsible for collecting and processing its own products at the end of their life. Individual EPR is advocated by many environmental groups, has been implemented in Japan, and is an option for manufacturers in Maine and Washington. Because of the economies of scale in collecting e-waste and the costs of sorting e-waste by manufacturer, the EU, Maine, and Washington have implemented collective EPR, in which used electronics are collected and processed in a single stream and manufacturers share the collective costs. Depending on how those collective costs are allocated among manufacturers, collective EPR may function as a fee upon disposal or as a fee upon sale, as discussed after Proposition 6.

In this section, we assume a positive net cost per unit for collection and recycling at end of product life, and hence assume a positive fee upon sale or fee upon disposal. However, that net cost might be negative (a net profit) for products such as mobile phones that are relatively cheap and easy to collect and that contain valuable metals. Therefore, in the numerical examples in §5, we consider a range of values, both negative and positive, for the fee.

Our fundamental result is that a fee upon sale increases the equilibrium development time, but, under competition, a fee upon disposal does not. Increasing the equilibrium development time increases the marginal return on expenditure and hence the equilibrium expenditure and quality improvement with each new product.

Proposition 6. *In the monopoly model, a fee upon sale or fee upon disposal strictly increases the equilibrium development time τ^m and expenditure x^m and strictly increases the associated quality improvement $q(\tau^m, x^m)$. In the duopoly model, a fee upon sale strictly increases the equilibrium τ^d, x^d, and $q((1+\gamma)\tau^d, x^d)$, but a fee upon disposal does not affect the equilibrium.*

A fee upon sale is equivalent to an increase in the cost c of introducing a new product, which has been shown to increase the equilibrium development time in very different models of new product introduction without strategic consumer behavior (see Souza 2004 and references therein).

In our monopoly model, consumers replace the manufacturer's previous product when she sells a new product, so a fee upon disposal has the same effect on the equilibrium as a fee upon sale. In contrast, in our duopoly model, a manufacturer incurs the fee upon disposal at the time that its *competitor* sells the next new product. That time is not influenced by the manufacturer's choice of development time, so the fee upon disposal does not change the equilibrium. This conclusion relies on our assumption that the manufacturer sets the launch date for a new product when she begins to develop it and does not change the launch date in response to subsequent actions by her competitor. (Commitment to a launch date is common in practice because it increases the productivity of the development team (Cohen et al. 2000) and facilitates supply chain coordination (Mishra and Bhabra 2001).) Furthermore, if one extended the duopoly model formulation to allow for brand loyalty, so that some customers would discard a manufacturer's product only when that manufacturer introduced a new product, then a fee upon disposal would cause some increase in equilibrium development time, in proportion to the fraction of loyal customers. One might think of this as a hybrid of the monopoly and duopoly results given in Proposition 6.

Even with the most stringent of environmental standards for production and recycling, electronics impose significant environmental impacts (Mayers et al. 2005), which can be reduced only by reducing production. Proposition 6 shows that *fee-upon-sale regulations benefit the environment by reducing the rate of new product introduction and, consequently, the quantity of e-waste*. However, in competitive segments of the electronics industry, fee-upon-disposal regulations will fail to significantly reduce the quantity of e-waste.

The greater the fee upon sale is the greater is the reduction in e-waste. Unfortunately, the fee upon sale born by the manufacturer may not reflect the full cost of e-waste. For example, as described in detail in §5, for some types of electronic product, the California ARF is much lower than the cost of collecting, recycling, and/or responsibly disposing of the product. Moreover, in some retail settings, the ARF is not presented to a consumer until she decides to purchase a product at the base sticker price and proceeds to the register. Having already committed herself to acquiring the product, the consumer might be willing to pay the additional ARF, even though she would have decided not to buy the product if she had anticipated its true price (the sum of ARF and base sticker price) from the outset. This enables the manufacturer to maintain a relatively high base price, which effectively reduces the fee upon sale born by the manufacturer. Proposition 6 suggests that to achieve greater reductions in the quantity of e-waste, environmental groups should press for an ARF that reflects the full cost of e-waste and is clearly labeled on all products.

With regard to collective EPR, Proposition 6 suggests that environmental groups should press for the collective cost to be allocated among manufacturers in proportion to *current* sales. Under collective EPR, with cost allocated in proportion to *current* sales, when a manufacturer delays the sales of a new product, it simultaneously delays its cost associated with the regulation. Therefore the regulation functions as a fee upon sale and reduces the quantity of e-waste. This is true even if the collective e-waste costs are aggregated over a long time period. (In practice, aggregating collective e-waste costs over a long period eliminates a perverse incentive for manufacturers to shift their sales to times when the return flow of e-waste and associated collective costs are low.) In contrast, if manufacturers are charged infrequently, based on aggregate sales and aggregate collective costs over a long time period, delaying sales of a new product within that time period will not affect a manufacturer's cost, so the regulation will not function as a fee upon sale. If manufacturers are charged for collective costs as they occur, in proportion to market share aggregated over a long period, the regulation may function only weakly as a fee upon sale. This is easy to see in our simple duopoly model: each firm has half the sales aggregated over a long time period, so that when it introduces a new product, causing consumers to dispose of the last-generation product, it will bear only half the associated e-waste costs; the effective fee upon sale would be doubled if those costs were, instead, allocated based on current sales. In practice, the surge of e-waste caused by a firm's new product introduction may be small relative to current collective costs, which tends to further weaken the effect of collective EPR as a fee upon sale when current costs are allocated in proportion to aggregate sales over a long time period.

Maine, Washington, and an increasing number of EU states are allocating the collective costs of EPR in proportion to each manufacturer's share of the products disposed of by consumers. (Manufacturers' shares are estimated through sampling but may soon be calculated more precisely and cost-effectively by radio-frequency identification.) Collective EPR with disposal-based cost allocation functions as a fee upon disposal and therefore, in competitive product categories, will fail to reduce the quantity of e-waste by reducing the frequency of new product introduction.

Propositions 2 and 5 established that the equilibrium development time is too short to maximize profit, which suggests that a fee upon sale, by increasing the equilibrium development time, may increase profit. The next proposition characterizes conditions under which the derivative of equilibrium profit with respect to c (which is the effect on profit of a "small" fee) is strictly positive.

Proposition 7. *Suppose that the quality function is Cobb-Douglas. A small fee upon sale or fee upon disposal strictly increases the monopolist's profit if and only if*

$$c < c^m_{\text{profit}}. \tag{19}$$

A small fee upon sale strictly increases the duopolists' profit if and only if

$$c < c^d_{\text{profit}}, \tag{20}$$

where the constants c^m_{profit} and c^d_{profit} are strictly positive, strictly decreasing with δ, and, at least for the standard Cobb-Douglas quality function,

$$c^m_{\text{profit}} < c^d_{\text{profit}}. \tag{21}$$

A fee upon disposal strictly decreases the duopolists' profit.

Proposition 7 tells us that if production costs are small relative to R&D costs, then a fee upon sale increases firms' profits. When the production cost c is small, the equilibrium development time is short, and a small increase in c translates into a large increase in development time ($d\tau^m/dc$ and $d\tau^d/dc$ are large). As the equilibrium development time increases, customers pay more for each new product, as they anticipate using it for longer. The resulting increase in revenue is larger than the fee, so profits increase. The regulation is more beneficial for the duopolists than for the monopolist because the duopolists are more rushed by competitive pressures and so have more benefit from slowing down. When the initial c is sufficiently low, imposing even such a large fee that the total resulting fixed cost exceeds the right-hand side of (19) for the monopolist or (20) for the duopolist may increase profit. When the initial c is larger than the threshold, any size of fee will reduce profit. Fee-upon-disposal regulations impose additional costs on the duopolists without the beneficial slow-down in new product introduction and therefore simply reduce the duopolists' profits.

Our next proposition establishes that the effect of a fee upon sale on social welfare depends on the degree of competition in the product category. The social objective is to maximize

$$\frac{e^{-\delta\tau^m}}{1-e^{-\delta\tau^m}}\left[\frac{q(\tau^m, x^m)}{\delta} - x - c - e^{-\delta\tau^m}(k+z)\right], \tag{22}$$

$$\frac{e^{-\delta\tau^d}}{1-e^{-\delta\tau^d}}\left[\frac{q((1+\gamma)\tau^d, x^d)}{\delta} - x - c - e^{-\delta\tau^d}(k+z)\right] \tag{23}$$

in the monopoly and duopoly models, respectively, where k represents the cost to collect, recycle, and/or responsibly dispose of a generation of used electronics, and z represents all environmental and health costs associated with each generation of used electronics. The latter can be reduced but not entirely eliminated through responsible end-of-life processing: Both k and z vary by region and with the quality and efficiency of end-of-life processing (Mayers et al. 2005). The next proposition assumes that k and z are nonnegative constants.

Proposition 8. *In the duopoly model, a fee upon sale strictly increases social welfare. In the monopoly model with Cobb-Douglas quality function, a fee upon sale or fee upon disposal strictly decreases social welfare if $k+z<\bar{k}$ but strictly increases social welfare if $k+z>\bar{k}$ and the fee is not too large. The threshold $\bar{k}$ is strictly positive if $c > c^m_{\text{welfare}}$.*

Proposition 6 implies that a fee upon disposal has no effect on social welfare in our basic duopoly model. However, §6 allows manufacturers to reduce k through design effort and shows that some types of fee upon disposal regulation do improve social welfare.

As most product categories are competitive, the most important insight in Proposition 8 is that imposing a fee upon sale increases social welfare (by causing the duopolists to slow down and make a greater improvement in quality with each new product generation) even in the extreme case $z=k=0$! That improvement in social welfare increases with the environmental, health, and processing costs of e-waste (z and k). However, in product categories dominated by a single firm, imposing a fee reduces social welfare when z and k are small. (In reality, $\bar{k}>0$. We scrutinized the financial statements of many electronics manufacturers and observed in all cases, including those in §5, that $x^m < c$; i.e., their R&D costs less than making and selling a new product. By intermediate arguments in the proof of Proposition 8, $x^m < c$ implies $c \geq c^m_{\text{welfare}}$.) A fee upon sale is less beneficial to social welfare in the monopoly model than in the duopoly model because the monopolist chooses a relatively long development time and relatively high expenditure for each new product, so that a slow-down produces relatively little marginal quality improvement and relatively little reduction in e-waste. Together, Propositions 7 and 8 suggest that policy makers should be wary of a firm with dominant market share seeking e-waste regulations. When $c^m_{\text{profit}} \geq c \geq c^m_{\text{welfare}}$, as in the MP3 player product category (see Figure 2 in §5), such regulations may increase the monopolist's profit at the expense of consumer and social welfare.

The next proposition shows that consumers fare worse under a fee upon sale, regardless of the level of competition. Although the manufacturers bear the direct cost of e-waste regulation, the resulting slowdown in new product introduction delays quality improvements and indirectly (through $f()$) increases the price that consumers pay for each new product.

Proposition 9. *In the duopoly model, a fee upon sale strictly decreases consumer surplus, whereas a fee upon disposal has no effect on consumer surplus. In the monopoly model with Cobb-Douglas quality function, a fee upon sale or fee upon disposal strictly decreases consumer surplus if* $c > c^m_{\text{cs}}$.

In reality, $c > c^m_{\text{cs}}$. (Within the proof of Proposition 9, (EC.55) establishes that $c > c^m_{\text{cs}}$ follows from the realistic condition $x^m < c$ discussed above.)

5. Numerical Examples

In this section, we fit our model to four different categories of electronic products, using financial statements and other public information about market share and the frequency of new product introduction. Then we use our model for each product category to estimate the effect of a fee upon sale on new product introduction, firms' profits, consumer surplus, social welfare, and the quantity of e-waste generated per year. (Specifically, we estimate the mass of all the devices in each product category disposed by consumers in one year.)

Although a majority of product categories in the electronics industry are characterized by competition, we choose to examine two product categories with a dominant innovating firm (MP3 players and workstations) and two categories with competition (video game consoles and mobile phones), in order to assess the interaction effects between competition and e-waste regulation. The Apple iPod claims more than a 70% market share among MP3 players (Hall 2006); therefore, the MP3 product category is best represented by our monopoly model. The workstation category is also best represented by our monopoly model, because introduction of new workstations is driven by Intel's launching of new microprocessors in its Xeon line, and Intel has more than an 85% market share among producers of such microprocessors for workstations (Dignan 2007). Between Intel and workstation end users are the workstation assemblers, such as Sun, Dell, and Hewlett-Packard (HP). The assembler's market is highly competitive and profits are slim. Intel is responsible for a majority of the R&D investment in the workstation product category and captures a majority of the associated profit generated by new product introduction. Therefore, despite the complexity of the workstation supply chain, our simple monopoly model of Intel's new product introduction process is a reasonable approximation. In the video game console market, Sony's Playstation battles Microsoft's Xbox. Committed gamers are the primary target consumers for each new generation of the Sony Playstation and Microsoft Xbox, whereas Nintendo has introduced a line of Wii consoles to appeal to a different demographic—casual or first-time gamers (Casey 2006). Because of this separation in target consumer populations, we fit our duopoly model to represent the competition between Sony and Microsoft. We also take a futuristic view. Currently in the United States, mobile phones are bundled with a service agreement; service providers subsidize the phone purchase and recover revenue through subsequent service charges. However, the industry trend is to unbundle phone sales from service so that, in the near future, U.S. consumers will buy mobile phones at market prices, independently of their choice of service provider (Segan 2007a, b; Holson 2007; Searcey 2007). We fit our duopoly model to this future "unbundled" scenario for the U.S. market, focusing specifically on global system for mobile communications (GSM) phones, and assuming that Nokia and Motorola continue to be the dominant GSM phone suppliers. Unbundling may increase the frequency with which consumers upgrade to a new phone (Spencer et al. 2007) but the magnitude of the change is unknown, so in fitting the duopoly model we assume the same frequency as today.

A brief description of how we fit model parameters for each product categories follows; details are in the e-companion. From industry reports, we have the average time between new product introductions, which we take to be the equilibrium τ. We assume that the quality function is $q(x, \tau) = vx^\alpha\tau^\beta$, where the multiplier v of the Cobb-Douglas function (6) allows for a general number of unit sales per new product (elsewhere in this paper, we have normalized the number of consumers and hence unit sales per new product to 1 for brevity). From financial reports, we have R&D expense as a percentage of revenue, profit margin, and representative unit selling price; we use these data to compute R&D expenditure per new product x and non-R&D cost per new product c. Then, in the system of three equations given by the first-order optimality conditions for τ and x (Propositions 1 and 4) and assumed functional form of the quality function, we solve for the three remaining quality function parameters v, α, and β. In fitting the duopoly model for both the video game console and mobile phone categories, the Cobb-Douglas requirement (6) that $\alpha, \beta \in (0, 1)$ implies that $\gamma \approx 0$; therefore we set $\gamma = 0$, meaning that quality improvement increases with the development time after observing the competitor's latest product. To represent the fee upon sale, we add $N \times \phi$ to the cost c of introducing a new product, taking unit sales per new product N from financial statements and allowing the fee-per-unit sale ϕ to range

Table 1 Input Data and Fitted Model Parameter Values

	Monopoly		Duopoly	
	MP3 player	Workstation	Video game console	Mobile phone (U.S. GSM)
Input data				
New product introduction interval τ (years)	1.0	3.0	1.5	1.5
R&D expense as percentage of revenue	3.0	13.7	8.6	5.7
Operating margin (%)	34.0	32.5	1.5	18.4
Total revenue ($ billion)	8.3	3.6	8.0	32.9
Unit sales N (million)	51.6	7.2	20.0	94.0
Fitted model parameters				
Total non-R&D cost per new product c ($ billion)	5.232	1.936	7.192	24.97
Consumer utility per unit quality per year v (million)	4,934	59.88	698.70	4,836
Quality sensitivity to R&D expenditure α	0.030	0.137	0.086	0.057
Quality sensitivity to development time β	0.361	0.387	0.915	0.946

from −10 to 30. (This covers the range of plausible fees for all four product categories; negative values of ϕ are plausible only in the mobile phone category.) Parameters for each product category are in Table 1. For each level of ϕ, we use the optimality conditions in Propositions 1 and 4 to compute the equilibrium expenditure x, time τ between new product introductions, quality improvement with each new product, quantity of e-waste produced per year, profit for each manufacturer, consumer surplus, and social welfare. Figures 1 and 2 show the percentage change in each of these values, relative to the initial case $\phi = 0$ with

Figure 1 Effects of a Fee Upon Sale on the Equilibrium Time Between New Product Introductions, Quality Improvement per Generation, and Volume of E-Waste Generated per Year

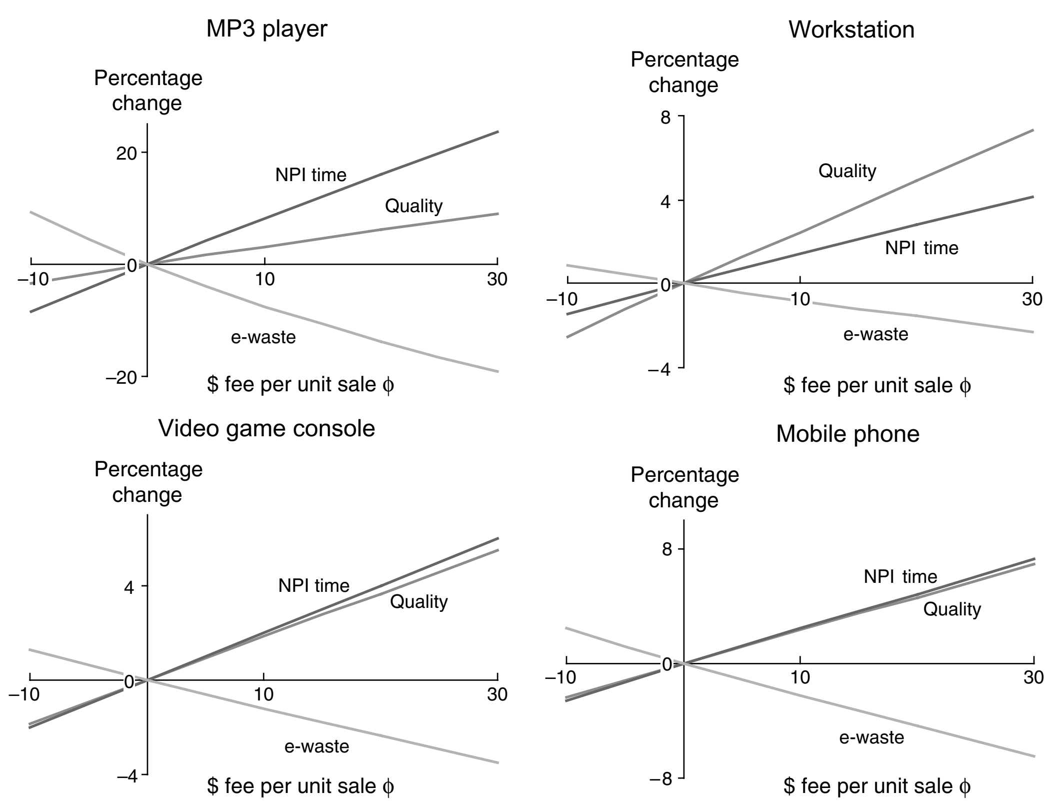
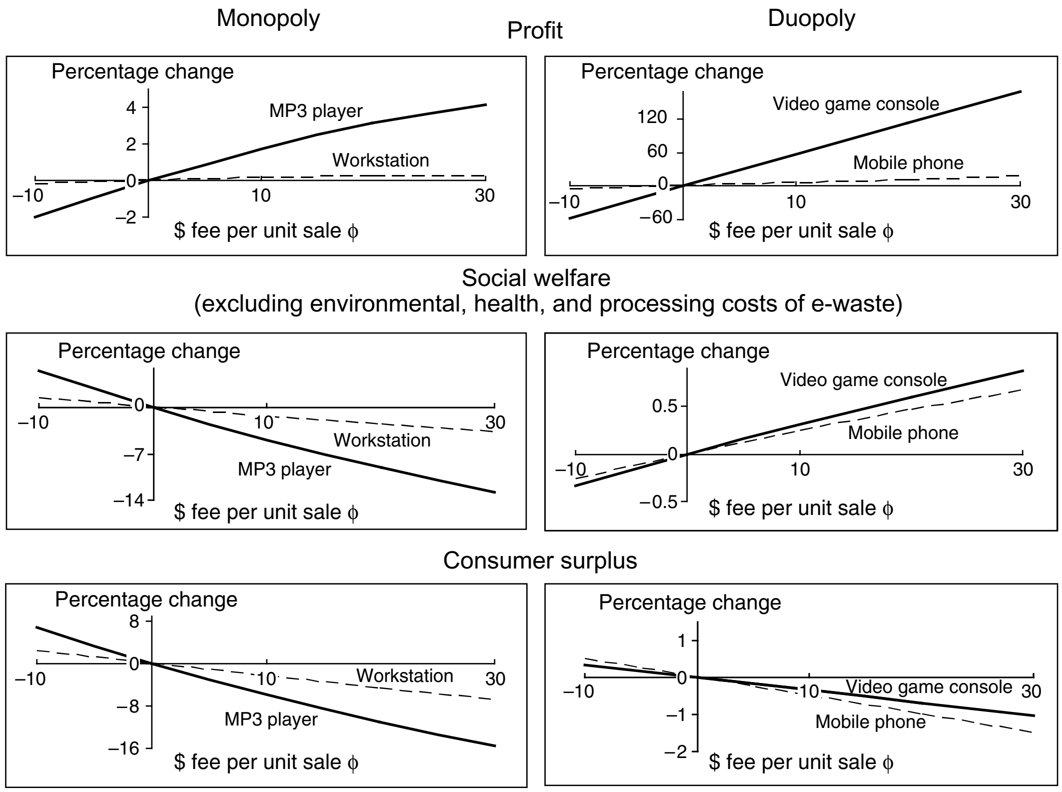


Figure 2 **Effects of a Fee Upon Sale on Manufacturers' Profit, Consumer Surplus, and Social Welfare (Excluding E-Waste Costs)**



Note. Evaluating social welfare at $k = z = 0$ provides a lower bound on the true percentage increase in social welfare with respect to ϕ.

no fee upon sale. As the environmental and health costs of e-waste are highly uncertain and processing costs for e-waste vary widely by region and regulatory regime (Mayers et al. 2005, Martens 2006), we estimate only the equilibrium quantity of e-waste and do not assign a cost to that e-waste. Therefore, in calculating social welfare we set $k = z = 0$ in (22) and (23) and focus solely on the sum of profit and consumer surplus. This provides a lower bound on the actual increase in social welfare with respect to the fee per unit sale ϕ.

For all four product categories, Figure 1 shows a significant increase in the development time and quality for each new product and a corresponding decrease in the quantity of e-waste with respect to ϕ. However, in Figure 2, the categories with and without competition exhibit striking differences in the effects of the fee upon sale on profit, social welfare, and consumer surplus. In the duopoly categories, the percentage increase in profit with respect to ϕ is strikingly large, especially in video game consoles; in the monopoly categories, an increase in ϕ results in a much smaller percentage increase in profit than in the duopoly categories. In the duopoly categories, an increase in ϕ produces a small but significant increase in social welfare (even when we ignore social benefits of eliminating e-waste) and a small loss in consumer surplus; in contrast, in the monopoly categories, an increase in ϕ reduces social welfare (ignoring the social benefits of eliminating e-waste) and reduces consumer surplus by a larger percentage than in the duopoly categories. Note that a fee upon disposal would have precisely the same effects in the monopoly categories as a fee upon sale (with the same discounted fee per unit) but would have no effect in the duopoly categories.

In practice, the fee per unit sale ϕ differs across product categories, as do the environmental, health, and end-of-life processing costs per unit, though the fee is generally *not* identical to the processing cost k or to the total environmental, health, and processing cost $z + k$. In the MP3 player category, Apple has voluntarily adopted a form of individual EPR with incentives for customers to return products. Specifically, Apple provides a 20% discount on purchase of a new iPod when consumers return an old one (Apple 2007). This is equivalent to a ϕ of approximately \$20, for which our model predicts a 2.7% increase in profit for Apple and a reduction in the quantity of e-waste by 760 metric tons per year (assuming 0.12 kg per iPod). In many EU countries, each manufacturer pays a share of the collective cost for processing all used electronics, in proportion to the weight of the electronics it sells, so ϕ is largest for workstations and of moderate size for video game consoles. Among these countries, the efficiency of the collective processing of used electronics differs widely (Martens 2006). Based on the full range of processing costs reported in Martens (2006) and allowing for a workstation to range in weight from 10 kg to 35 kg, and a video game console to range in weight from under 1 kg to 4 kg, the fee per unit sale ϕ for a workstation ranges from \$1 to \$30 and the fee per unit sale ϕ for a video game console ranges from under \$1 to \$9. In California, the ARF for a workstation with a monitor is only \$10, but according to the Sillicon Valley Toxics Coalition (SVTC 2004), the actual cost to process a used workstation responsibly is much larger than \$10 and likely closer to the high-end fee in the EU of \$30. According to our model, in the workstation category, a moderate fee per unit sale ϕ of \$20 eliminates 740 metric tons of e-waste per year (assuming 20 kg per workstation), reduces social welfare (excluding the benefits from eliminating e-waste) by 2.5%, reduces consumer surplus 4.6%, and has negligible effect on profit. In the video game console category, a moderate fee per unit sale ϕ of \$5 eliminates 163 metric tons of e-waste per year (assuming 2 kg per console), increases profit by more than 29%, and has negligible effect on social welfare (excluding the benefits from eliminating e-waste) and consumer surplus. In the mobile phone category, the actual end-of-life processing cost k is very small and might even be negative. Used mobile phones are light and compact, facilitating collection. Each unit contains more than \$1 worth of precious metals and, because of the high rate at which mobile phones are discarded, manufacturers may reuse some components and enjoy sufficient economies of scale to make collection and reuse or recycling profitable (U.S. Geological Survey 2006). In the mobile phone category, assuming ϕ equals \$$-1$, our model predicts an increase of 16 metric tons in the quantity of e-waste produced per year (assuming 0.1 kg per mobile phone) and changes of less than 1% in magnitude in social welfare (excluding environmental, health, and processing costs of e-waste), consumer surplus, and profit. Setting ϕ to \$1 gives the same small magnitude of changes, but with opposite sign.

We conclude that in the mobile phone category, a fee upon sale that reflects the actual end-of-life processing cost has a negligible effect on the quantity of e-waste, profit, social welfare, and consumer surplus. However, in the three other product categories, plausible levels of the fee upon sale greatly reduce the quantity of e-waste and have relatively small but significant implications for social welfare (excluding the benefits from eliminating e-waste) and consumer surplus. In the MP3 player and video game console categories, plausible levels of the fee upon sale greatly increase manufacturers' profits.

6. Design for Recyclability

The Waste Electrical and Electronic Equipment Directive states the EU's motivation for imposing EPR: "The establishment, by this directive, of producer responsibility is one of the means of encouraging the design and production of electrical and electronic equipment which take into full account and facilitate their repair, possible upgrading, reuse, disassembly and recycling." We employ the phrase "design for recyclability" to refer concisely to all such design efforts. The distinction between the fee-upon-sale and fee-upon-disposal categories of regulation of §4 is irrelevant to design for recyclability. Instead, this section considers three specific forms of e-waste regulation that are common (individual EPR, collective EPR, and the ARF) and produces the generalizable conclusion that design for recyclability occurs only when manufacturers bear the specific end-of-life costs for their own products.

Each firm makes an initial investment $I(k)$ in design for recyclability, which reduces the end-of-life processing cost to $k \in (-c, \bar{k}]$. This might reflect a one-time investment in equipment, identifying new suppliers, and developing innovative design features to facilitate reuse, upgrading, disassembly, or recycling. We assume that the function $I()$ is twice-differentiable, decreasing and strictly convex for $k \in (-c, \bar{k}]$, and satisfies $\lim_{k\downarrow -c} I'(k) = -\infty$, $I'(\bar{k}) = 0$, and $I(\bar{k}) = 0$. Proposition 6 implies that the monopoly equilibrium development time τ^m is a strictly increasing function of the end-of-life cost k, but the duopoly equilibrium development time $2\tau^d$ is invariant with respect to k. It follows that a monopolist, but not a duopolist, will underinvest in design for recyclability to commit to a long development time and thus charge a higher price for each new product.

Proposition 10. *Under EPR, the monopolist's optimal end-of-life cost k^m is strictly greater than the level that would minimize the monopolist's total discounted cost*:

$$k^m > \arg\min_{k\in(-c,\bar{k}]} \left\{ I(k) + \frac{e^{-\delta\tau^m}}{1-e^{-\delta\tau^m}} k \right\}.$$

The monopolist invests nothing to reduce the end-of-life cost under an ARF. Under individual EPR or collective EPR with cost allocated according to share of products disposed, each duopolist chooses the end-of-life cost k that minimizes its total discounted cost. However, the duopolists invest nothing to reduce the end-of-life cost under collective EPR with current-sales-based cost allocation or an ARF.

The simplicity of our duopoly model explains the sharp result that allocating the total cost of collective EPR according to share of products disposed rather than current sales turns on perfect incentives for design for recyclability. In our duopoly model, all consumers dispose of the last-generation product precisely when a new product is introduced and manufacturers take turns in introducing new products, so their products are never mixed upon disposal. Under current-sales-based collective EPR, each duopolist, when he introduces a new product, pays the end-of-life processing cost for the competitor's latest product, so the competitor has no incentive to reduce the end-of-life processing cost. Under disposal-share-based collective EPR, each duopolist bears the end-of-life processing costs for his own products exactly as he would under individual EPR. In reality, many manufacturers' products from various categories are mixed in the return stream. The realistic interpretation of Proposition 10 is that, to the extent that a manufacturer's share of products disposed varies significantly over time and differs from his share of sales, allocating the cost of collective EPR based on share of products disposed rather than current sales will increase the manufacturer's incentive to design for recyclability.

An ARF gives no incentive to either the duopolists or the monopolist to reduce end-of-life cost. (We assume that the ARF is a constant, as in California. Conceivably, the ARF could be a general function of material content and other elements of design that determine the end-of-life cost, in order to provide appropriate design incentives. However, electronics and their design process are so complex that regulators cannot effectively specify such a function (Sachs 2006).)

As the electronics industry is competitive in most product categories and manufacturers' products are mixed in the return flow, Proposition 10 suggests that only individual EPR can give socially optimal incentives for design for recyclability.

We have focused on a one-time investment that reduces the end-of-life processing cost for all future generations of new products. In reality, a firm may also have the option of reducing a specific new product's end-of-life processing cost by increasing the development expenditure and/or time for that specific product. The results in Proposition 10 hold for such generation-specific expenditures. With regard to adding development time to reduce a new product's end-of-life processing cost under individual EPR, the duopolists choose a shorter development time than would maximize profit and the sum of profit and consumer surplus (analogous to Proposition 5). No such clear result holds for the monopolist under EPR. Under an ARF, manufacturers will not add development time to reduce a product's end-of-life processing cost.

7. Heterogeneous Customers and Multiple Firms in the Supply Chain

Up to this point, we have assumed that consumers are identical in their valuation of each new product, so a firm sets its price equal to the maximum price qf that consumers are willing to pay. (For brevity, q refers to the equilibrium incremental quality of a new product and f to the associated time-value defined in (7).) However, with heterogeneous customers, we know from Coase (1972) and Gul et al. (1986) that a firm will reduce its price over time to sell to consumers with lower and lower valuation of a new product. Anticipating future price reductions, consumers will pay less for the new product. As a result, with heterogeneous customers, a firm captures as revenue only a fraction of consumers' value for the new product. Following Gul et al. (1986), for our unit mass of consumers, let $u\colon [0,1] \to R_+$ denote utility per unit of quality improvement q per unit time, where u is nonincreasing, left-continuous, Lipschitz at 1, and satisfies $\int_0^1 u(y)\,dy = 1$. Also suppose that $u(1)qf > c$, meaning that all consumers value the new product at more than its production cost; this is needed to ensure existence of a unique equilibrium (Gul et al. 1986). Suppose that the firm marks down its price sufficiently rapidly to sell to all prospective consumers before the next new product is introduced and produces in a single lot at the time of new product introduction. Theorem 1 of Gul et al. (1986) implies that the firm earns discounted revenue of θqf on each new product, where the constant $\theta \in (0,1]$ depends *only* on the distribution of consumer utility u, the time between markdowns and the discount rate δ. In the extreme case that $u(y) = 1$ for all $y \in [0,1]$ (consumers are homogeneous), $\theta = 1$. In general, as conjectured by Coase (1972), θ decreases to $u(1)$ as the time between markdowns converges to zero. The e-companion shows how to compute θ for general values of the time between markdowns, u and δ.

We have also assumed that a single firm develops, produces, and sells each new product. In reality, a firm might develop an innovative component, then contract with other firms to assemble and sell a new product differentiated by that component. The innovating firm will bear its entire R&D expenditure x but capture only a fraction $\theta(qf - c)$ of the resulting total supply chain profit, where $\theta \in (0,1]$ and c incorporates any e-waste fee, in addition to the cost of producing and selling the product. Insofar as the innovating firm is in a strong bargaining position vis-a-vis its supply chain partners, the value of θ will be relatively large. (In the workstation example from §5, assemblers HP and Sun are directly responsible for e-waste costs under most regulatory regimes, and innovator Intel captures a large share θ of the supply chain profit.)

As explained in detail in the next three paragraphs and proven in the e-companion, almost all our analytic results hold for general $\theta \in (0, 1]$ in both the fractional-revenue case (consumer heterogeneity) and the fractional-profit case (multiple firms in the supply chain). However, a reduction in θ tends to weaken the increase in development time, social welfare, and profit caused by a fee upon sale and, in the fractional-profit case, to reduce investment in design for recyclability under individual EPR.

All propositions in §§2 and 3 remain true for general $\theta \in (0, 1]$. In both the monopoly model and the duopoly model, the unique equilibrium time between new product introductions decreases with θ, which means that customer heterogeneity and multiple firms in the supply chain cause a slow-down in new product introduction.

All propositions in §4 hold as stated for general $\theta \in (0, 1]$, with one exception: a fee upon sale is no longer guaranteed to increase social welfare in the duopoly model, as stated in the first part of Proposition 8. A fee upon sale increases social welfare when θ is large but may decrease social welfare when θ is small and the production cost c is large. The intuition behind this result is that when c is large and θ is small, the equilibrium time between new product introductions is already relatively long, so the further slow-down caused by the fee upon sale contributes less to social welfare. In Proposition 7 the thresholds c^m_{profit} and c^d_{profit} increase with θ. The intuition for this parametric shift is that the innovating firm, forced to share revenue with heterogeneous consumers or to share profit with supply chain partners, captures less of the social value generated by the slow-down in new product introduction. Even though heterogeneity enables consumers to capture more of that value, Proposition 9 holds: a fee upon sale decreases consumer surplus.

Proposition 10 in §6 holds for general $\theta \in (0, 1]$. However, in the duopoly model with fractional profit (multiple firms in the supply chain) and $\theta < 1$, individual EPR fails to give socially optimal incentives for investment to reduce the end-of-life processing cost. The duopolist pays only a fraction θ of the end-of-life cost but bears the full investment to reduce that cost. Consequently, as θ decreases, the duopolist invests less in design for recycling. In contrast, the monopolist's investment is not necessarily monotone in θ.

8. Conclusions

This paper shows how e-waste regulation affects new product introduction, the quantity of e-waste, manufacturers' profits, consumer surplus and social welfare, depending on the level of competition and on whether a manufacturer incurs cost associated with the regulation when selling a new product versus when consumers dispose of that product. Table 2 provides a summary.

The only known means to reduce all the various environmental impacts of the electronics industry is to reduce the quantity of electronics produced and disposed. Mayers et al. (2005) show that collection and recycling of e-waste reduces some pollutants (e.g., lead leaching into groundwater) but increases others (e.g., greenhouse gases and smog). Therefore, our most important finding is that fee-upon-sale

Table 2 Effects of E-Waste Regulation Depend on When Manufacturers Are Charged and the Level of Competition

<table>
<tr><th>Type of regulation</th><th>Market structure</th><th>NPI time, expenditure, and quality</th><th>Quantity of e-waste</th><th>Manufacturer profit</th><th>Consumer surplus</th><th>Social welfare</th></tr>
<tr><td rowspan="2">Fee upon sale</td><td>Duopoly</td><td rowspan="3">Increases</td><td rowspan="3">Decreases</td><td rowspan="3">Increases if and only if production cost is small relative to R&D cost</td><td rowspan="3">Decreases</td><td>Increases</td></tr>
<tr><td>Monopoly</td><td rowspan="2">Decreases if and only if e-waste costs are small</td></tr>
<tr><td rowspan="2">Fee upon disposal</td><td>Monopoly</td></tr>
<tr><td>Duopoly</td><td>No change</td><td>No change</td><td>Decreases</td><td>No change</td><td>No change[a]</td></tr>
</table>

[a]If a manufacturer's fee upon disposal is linked to the actual end-of-life processing cost for its own products, the manufacturer will design for recyclability, which increases social welfare.

types of e-waste regulation (including ARF, collective EPR with current-sales-based cost allocation and RoHS) reduce the quantity of electronics produced and disposed by reducing the frequency of new product introduction. In contrast, in competitive product categories, fee-upon-disposal types of e-waste regulation (including individual EPR and collective EPR with disposal-based cost allocation) fail to reduce the frequency of new product introduction.

In our duopoly model, a fee upon sale strictly improves social welfare because of the slow-down in new product introduction. The greater the environmental, health, and processing costs for e-waste, the greater is that improvement in social welfare. In our monopoly model, both fee-upon-sale and fee-upon-disposal regulations reduce the frequency of new product introduction, which decreases social welfare when the environmental, health, and processing costs for e-waste are small, but increases social welfare when those costs are large.

One might think that a fee upon sale would be detrimental to consumers and manufacturers. Consumer surplus is indeed reduced, but that effect is very small in all product categories examined in §5. In contrast, especially in competitive product categories, manufacturers' profits increase significantly. Profits rise because, as manufacturers introduce new products less frequently and with higher quality increments, consumers become willing to pay more for each new product. That is, a fee upon sale reverses the "Osborne effect." In contrast, fee-upon-disposal regulations reduce manufacturers' profits.

As industry resistance has been a primary barrier to U.S. federal regulation of e-waste, these results suggest that environmental groups should press for a fee-upon-sale type of e-waste regulation as the path of least resistance. More specifically, in the case of an ARF, environmental groups should press for a large ARF that reflects the full cost of e-waste and is clearly labeled on all products. In the case of collective EPR, environmental groups should press for the collective e-waste costs to be allocated among manufacturers in proportion to current sales. Collective EPR is already in place in the EU, Maine, and Washington, but the rules for cost allocation differ widely among states and are subject to change (Sander et al. 2007). Currently, most environmental groups argue that each manufacturer should be individually responsible for processing its own products at the end of a product's life to motivate design for recyclability. Indeed, in our duopoly model, individual EPR provides socially optimal incentives for design for recyclability and, of all the different types of e-waste regulation considered in this paper, is the only type to do so. Unfortunately, individual EPR, as a form of fee upon disposal, decreases manufacturers' profits and fails to reduce the quantity of e-waste.

For analytic tractability, we have made strong modeling assumptions that influence some of our results. In reality, unlike in the models formulated in §§2 and 3, consumers differ in their willingness to pay for new electronic devices, and an innovating firm has multiple supply chain partners. This weakens the effect of a fee upon sale on development time, profit, and social welfare, such that if environmental, health, and processing costs of e-waste are small and production costs are large, a fee upon sale is no longer guaranteed to increase social welfare, as reported in Table 2 for the duopoly model. Moreover, investment in design for recyclability under individual EPR may be lower than is socially optimal. Whereas product disposal in our models is driven entirely by technological obsolescence, in reality consumers dispose of some electronic devices because of functional failure. Therefore, a fee upon disposal might reduce the quantity of e-waste by motivating manufacturers to design for durability and thus postpone the fee.

In summary, for environmental groups and policy makers, this paper identifies a trade-off among existing forms of e-waste regulation. The ARF, collective EPR with current-sales-based cost allocation, and RoHS slow the rate of new product introduction and thus reduce the quantity of e-waste. Individual EPR motivates manufacturers to design for recyclability. RoHS mandates design for recyclability but is limited by regulators' understanding of design possibilities. A challenge for future research is to invent a form of e-waste regulation that optimally induces electronics manufacturers to both slow R&D *and* design benign products.

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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