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Price Setting for Green Design

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Abstract—Although much has been said about promoting industrial ecology, little has been done to specify how to incorporate the broad goals of promoting environmental friendliness into a model of profit maximizing behavior for the firm. We outline such a model for products that can be repaired, remanufactured, or recycled. One way to promote optimal product use is to set a price that declines each time the product is reused. Another is a deposit fee that declines with each use. This simple model encourages the firm to find if products as reusable, remanufacturable, or recyclable and focuses on interactions between the firm and the consumer.

I. INTRODUCTION

Ayres [1] suggested that an industrial economy can be thought of in ecological terms. In nature, each plant or animal uses available food and energy to grow; its growth and discharges are used as food for other animals. There is no toxic or even undesired wastes in the system. In contrast, all industrial societies face increasing problems with disposing of waste, particularly hazardous waste. At the same time, industrial societies are concerned about running out of raw materials in the future. Rather than wallowing in its discharges, Ayres and Allenby and Graedel [2] propose that industrial economies think about how to make the discharges and discarded products of each industry into inputs for other industries or the natural environment so that there is no waste.

While these ideas have received a good deal of attention and praise, we have been unable to find published research on how to incorporate these broad goals into the operations of a profit maximizing firm. Unless models and guidelines are developed to accomplish this goal, free market, industrial economies will be seen as incompatible with industrial ecology.

We do not address the more general issue of how to accomplish the goals of industrial ecology or even whether those goals are all desirable. Rather, we have started with a modest model of how a firm can think about products with the potential for reuse, remanufacture, and recycling and how such products should be "sold." The current industrial structure sells products to consumers who then transform them into waste to be disposed of. Interactions between producer and consumer are limited to the point of sale. Reuse, remanufacture, and recycling of products requires a more extensive interaction between consumer and producer. A new market structure is required to accommodate this interaction.

A model quantifying the benefits of green engineering must examine a pair of major issues regarding product "greenness". First, it must estimate the benefits of incorporating reuse, remanufacturing, and recycling into the design

of a green product. Second, it must quantify the conditions under which "green" practices become profitable.

This paper will describe a model for a green product which by design can have its components or entire assembly used more than once. The model examines the implications of choices concerning quality, pricing, and reuse. Examples are added to clarify the nature of the model, relying on three different classes of green products.

Life Cycle Modeling of Manufacturing Processes

The typical current path for a manufactured product's life cycle is shown in Figure 1. Raw materials are processed, fabricated, assembled and then sold to consumers. After transfer/use, the remains are disposed of. The total social cost of this product is the sum of costs at each stage. The consumer rather than the manufacturer faces disposal costs and so the manufacturer is unconcerned about this stage. Standard economic theory describes this economy, develops prescriptions for profit maximization, and points to a possible social problem because the manufacturer does not bear disposal costs.

Figure 2 allows products to be reused, repaired, remanufactured, or recycled. If there were no disposal, this model would fit the industrial ecology ideal; if disposal is reduced, there should be some gains in pollution prevention and green design.

Reuse refers to using the product again without modification, e.g., a refillable bottle or rental car. Repair entails only simple fixes done in the retail store, e.g., alterations made in rented tuxedos. Remanufacture requires a trip to the factory where some components are replaced, e.g., automobile fuel pumps, disposable cameras, and toner cartridges. Finally, recycled products are ones where the materials are made back into feedstocks, e.g., lead batteries and steel refrigerator parts.

Fig. 1: Standard Product Life Cycle

Fig. 2: Green Product Life Cycle

Manufacturers can alter the fate of a product, from disposal to reuse, repair, remanufacturing, or recycling by altering design, choice of materials, quality of manufacturing, and the terms of sale. Since manufacturers presently do not bear disposal cost and do not have access to the product after consumer use, there is little or no incentive to design products for reuse rather than disposal.

Until a used product attains the status of an antique or family keepsake, no one prefers used to new products. Any product perceived to be of lower quality than a new product is likely to fail in the market, unless it is much cheaper than its new counterpart. Thus consumers should not be able to distinguish any drop in quality for used products. At the same time, the manufacturer probably needs to know the number of times each product has been used to make the proper decisions about what must be done before the product is resold. Each product can be marked in a way that consumers cannot interpret. Alternatively, manufacturers can test each product to determine what repairs or new components are needed, e.g., checking a soft drink bottle for cracks and chips.

A product might be designed so that any one of these steps could be performed. For example, if a rental car is in a severe crash, it would be recycled. If some of the parts were not crushed, they could be remanufactured, repaired, or simply reused. In the following model, we assume that a product is returned to the manufacturer and is subject to a standard procedure. A model with a richer array of repair alternatives does not give qualitatively different results.

II. DEFINITION OF THE MODEL

The model has two components of product cost (C_i): Manufacturing cost M_i and turnaround cost T_i . The initial cost of manufacturing is M_1 . In each period after initial manufacture, the manufacturing cost is $(1 - k)M_1$, where k might be thought of as the proportion of a product's components that can be reused ($0 \leq k \leq 1$). Turnaround cost, the cost of processing a returned product, is assumed to be constant.

We assume that a product is sold and returned in a sufficiently short period that the interest rate (or opportunity cost of the capital) can be treated as zero.

Under these assumptions the costs can be written:

$$C_1 = M_1$$

$$C_i = M_i + T$$

or,

$$C_i = (1 - k)M_1 + T$$

Within this model, a perfectly reusable product is characterized by $k = 1$ (all components reusable). The quality of design, choice of materials, quality of manufacturing, and number of uses determine the value of k . Note that at the end of a product's life, we assume the cost of disposal is just equal to the value of recycled materials.

The lifetime cost of a product, C , is the sum of the costs incurred in initial manufacturing and through the various cycles, as shown in (1). The final time a product is returned, the manufacturer incurs the turnaround cost before discovering that the product must be recycled rather than remanufactured.

$$C = C_1 + C_2 + \dots + C_n + T$$

$$C = M_1 + (n-1)(1-k)M_1 + (n-1)T + T$$

$$C = [n - nk + k] M_1 + nT \quad (1)$$

Although many remanufactured products sell for a lower price than new products, reused or repaired products sell for new product prices. For example, Hertz doesn't vary its price with the age or mileage of rental cars. The strategy is to offer used products "as good as new" with new product prices. We assume that price does not vary with the number of uses.

Assuming a competitive market, the total revenue will equal the total costs (including a return on equity). For a product sold n times at price p , the equilibrium price is shown in (2).

$$\Pi = \text{Total Revenue} - \text{Total Cost} = 0$$

$$\Pi = np - [n - nk + k] M_1 - nT = 0$$

$$p^* = (1/n) [(n - nk + k) M_1 + nT] \quad (2)$$

Consider a remanufactured product such as a disposable camera. Most of the expensive components can be reused at little cost. Table I shows a hypothetical schedule of costs for such a product, assuming that $k = 0.8$, $M_1 = 18$, $T = 2$, and $n = 2$. For space considerations, turnaround costs have been included for the $(i+1)$ th period on each line (i.e. the turnaround cost shown for use 1 is really the turnaround cost from use 1 to use 2, and similarly that on the last line the turnaround cost listed is that cost which is incurred to get the product back at the end of its life when no further modifications will be made). The total and lifetime cost columns represent the additional cost incurred at use i and the cumulative sum of these costs up to i , where turnaround costs actually are added from the previous row. The price column shows what the price would need to be for each number of uses, i.e. if it were designed to be used only 4 times the price would need to be 9.5, using (2).

TABLE I
COST AND PRICE SCHEDULE FOR SAMPLE GREEN PRODUCT

Use	Man Cost (M)	Turn Cost (T)	Tot Cost(i)	Lifetime Cost	Price (p)
1	18	2	18	18	18
2	3.6	2	5.6	23.6	11.8
3	3.6	2	5.6	29.2	9.733
4	3.6	2	5.6	34.8	8.7
5	3.6	2	5.6	40.4	8.08
6	3.6	2	5.6	48	8

As shown above, this model also generalizes to the classic single-use product in a perfectly competitive market by substituting $n=1$ and $T=0$ (row 1 of Table I).

Quality Improvement

Now consider the effect of creating a better product (i.e. spending more on its initial manufacture such that future recycling expenditures will be less). Let δ represent the increase in the recyclability factor as a result of initially building in an additional ϵ value. Consider the following adjustments to the original life cycle model.

$$C_1^* = M_1 + \epsilon$$

$$C_i^* = [1 - (k + \delta)](M_1 + \epsilon) + T$$

$$C^* = (M_1 + \epsilon) + (n-1)T + (n-1)(1 - k - \delta)(M_1 + \epsilon) + T$$

From (1),

$$C = [n - nk + k] M_1 + nT,$$

thus

$$C^* = C + \epsilon(n - nk + k + \delta - n\delta) - [\delta(n-1)] M_1.$$

The cost of the product with quality improvement (C^*) will be less than the cost of the standard product (C) as long as the value $C^* - C < 0$, or when

$$\epsilon(n - nk + k + \delta - n\delta) < \delta M_1(n-1)$$

$$\epsilon(n - nk + k) < \delta(M_1 + \epsilon)(n-1).$$

The solution is optimal at equality, and values where

$$\delta = \frac{\epsilon(n - nk + k)}{(M_1 + \epsilon)(n-1)} \quad (3)$$

will represent solution paths where delta-epsilon combinations are optimal and costs are lowest to the manufacturer. Note that this equation describes an isoprice condition for the various delta-epsilon combinations (Table I is the case where delta and epsilon = 0).

Equation (3) defines the required change in the recyclability factor for increased initial manufacturing cost. Table II shows how this condition relates to the example in Table I, and assumes $k=0.8$, $M_1=18$, $T=2$, $n=6$, $\epsilon=2$, and $\delta=0.04$, where δ is determined from (3).

TABLE II
COST AND PRICE SCHEDULE FOR PRODUCT WITH QUALITY IMPROVEMENT

Use	Man Cost (M)	Turn Cost (T)	Tot Cost(i)	Lifetime Cost	Price
1	20	2	20	20	20
2	3.2	2	5.2	25.2	12.6
3	3.2	2	5.2	30.4	10.133
4	3.2	2	5.2	35.6	8.9
5	3.2	2	5.2	40.8	8.16
6	3.2	2	5.2	48	8

Modeling Moral Hazard

The price of a recyclable product is the sum of lifetime costs divided by the intended number of uses. As seen in Tables I and II, the price charged at each use (and more generally, the total lifetime revenue) does not cover the lifetime costs until use n . Thus the manufacturer relies heavily upon the return of the product to ensure their perfectly competitive zero-profit condition. If a product is either not returned or damaged beyond cost-efficient repair, the manufacturer gets negative profit (equal to lifetime costs up to i minus lifetime revenues). This scenario creates and defines the moral hazard of the market because the company is in danger of losing the remaining unrecouped costs at every sale in its lifetime.

Part of the moral hazard problem is the fact that the producer must optimize for a certain number of uses of the product based on its cost structure and the recyclability of its components. Thus, there is an inefficiency when the customer fails to return the product in a recyclable condition (or does not return it at all) at some point $i < n$.

The underlying problem is that of incentive differences. The disposable camera maker plans to sell it a total of 5 times and sells it each time with only an implicit contract. Using incentive compatibility we see that the ideal scenario exists where the manufacturer gets the camera not only returned to them, but in remanufacturable condition, and they always find buyers who are looking for a camera that will provide reliable operation and good pictures. The potential for problem, for example, occurs when the consumer actually buys the disposable camera for a child in lieu of a more expensive camera, the child breaks it beyond repair, and the consumer returns the camera anyway. The consumer of course still sees value in this transaction since the value of the disposable camera (in the form of a relatively low price) is compared to the cost of the child breaking a more expensive (non-disposable) camera. Although the consumer does not get film back from the manufacturer, the manufacturer incurs both the lifetime cost up to use n , as well as the turnaround cost when returned and only receives $i \cdot p$ in revenue, and when $i < n$ this is a loss.

To correct this inefficiency, similar to a regulated market scenario, there need to be incentives to move both sides towards the equilibrium. We consider alternatives which motivate the "renter" into returning the product so that it can be refurbished and then resold. This is done in the form of a deposit (D), by making the renter pay additional costs up front to the owner, who uses the additional money in some form to

cover the replacement value of the product if not returned intact. Intact will refer to the case where the product needs no additional work (other than that which would normally be required) to turn it around for the next time of sale. This also has the desired effect of making the renter realize the intended lifetime and future value of the product. Although the renter may still misuse the product, he pays for it by losing the deposit.

In general, the value of the deposit is related to the residual value of the product at each time of sale. That is, the deposit will reflect the remaining unrecovered costs in the stream of costs of the product in its lifetime. Thus, in the beginning, the deposit will be relatively high, and at the end, the deposit will be zero. It is noted that this discrepancy in deposit costs acts as a strong signal to the renter, because these deposit costs cannot be kept a secret, and the consumer can then choose amongst available substitutes for the optimal cost product to suit their needs and budget. Further, the variance in deposits reinforces the reasons for having the deposit, making the renter realize the residual value.

The expression for the cost of the deposit is derived as follows. For all sales before i , the producer will receive deposits at the time of sale and will return these deposits at time of return. However, the producer wants to guarantee the ability to break even if the renter does not return the product intact, and charges the renter a deposit at each i which would recoup all previous costs. Thus, the profit function at i is

$$\Pi = ip - \sum_{k=1}^i C_k + \left[\sum_{k=1}^{i-1} D_k - \sum_{k=1}^{i-1} D_k \right] + D_i$$

where the $i-1$ terms (referring to the deposits which are received and returned prior to sale i) cancel each other and become zero. Thus, setting profit to zero and solving,

$$D_i = \sum_{k=1}^i C_k - ip \quad (3)$$

Since all deposits are generally paid and returned it can be shown that if deposits defined by (3) apply, the case related to (2) prevails.

This system fairly represents the residual value to both parties. In this case, the manufacturer gets a deposit equal to the difference of the sum of the lifetime costs so far and the purchase price. Thus, the firm is protected against loss or damage of the product. In addition, the consumer is not unfairly charged for how the remaining lifetime revenues and costs would affect the price (although the price is determined by dividing lifetime costs over a planned number of uses). This system represents a tradeoff which should be equitable for both parties.

However, deposits are falling over a product's lifetime, so under this deposit system, demand should actually be going up for a product as it is recycled, all else held constant (especially consumer preference and substitution).

There is another form of moral hazard: The consumer might decide to keep a camera for two years. During this period, the manufacturer has a nonperforming asset. If the deposit is equal to the manufacturer's investment in the camera,

the incentives to consumer and manufacturer are precisely correct.

Profit Potential and Secondary Markets

Given the benefits, it is possible for both the manufacturer and a secondary remanufacturing market to share the profits of green design. Although we have assumed a perfectly competitive world, it is clear that green design practices will only be undertaken when there is some economic benefit to the manufacturer. In pure competition, the first manufacturer to design a remanufactured product would make an economic profit. That profit would fall to zero as others imitated. There is no economic profit at equilibrium. The methods of green remanufacturing processes are not private to the producer—in fact, many industries have been formed which take advantage of these more environmentally friendly design processes.

Consider the secondary market for remanufactured laser printer toner cartridges, which relies on buyers of new cartridges to feed its operations. After a new cartridge is bought (average cost for a new cartridge is \$100) and used ("use" in this case generally refers to depleting the toner supply), a remanufacturer will pay \$2 for a depleted cartridge. They then invest, on average, \$12 in remanufacturing costs before reselling the same toner cartridge at OEM specification for \$50 (the assumed price).

Excluding overhead costs, which are low in these industries, Table III shows the lifetime profit potential for a single cartridge which is remanufactured 20 times (although greater than 20 reuses is not uncommon) from the perspective of the remanufacturer, who does not sell the original cartridge. Note that several lines have been removed for illustration.

Assume now that the original toner cartridge manufacturer performed the same function as the secondary market, i.e. that the manufacturer established return pathways for used cartridges and made the necessary improvements at every turn to resell the cartridge. Given a retail price of a new cartridge is \$100, assume an initial manufacturing cost of \$40 (recall that we are knowingly excluding overhead costs). Using the same secondary market remanufacturing cost of \$12, then 70% (\$28/\$40) of the cartridge can be reused without cost at each turn, and we see that k is 0.7 for this product. We also reuse \$2 as a turnaround cost. Table III represents the cost and price schedule

TABLE III
PROFIT POTENTIAL IN SECONDARY REMANUFACTURING MARKETS

Use	Reman Cost	Turn Cost	Tot Cost	Lifetime Cost	Lifetime Rev	Lifetime Profit
1	12	2	14	14	50	36
2	12	2	14	28	100	72
3	12	2	14	42	150	108
4	12	2	14	56	200	144
5	12	2	14	70	250	180
10	12	2	14	140	500	360
15	12	2	14	210	750	540
20	12	2	14	280	1000	720

for the cartridge which originally sold one time for \$100, but which now is sold 20 times. Recall that the price column actually denotes what the optimal price should be given that the cartridge is planned for i uses, from (2).

Table IV shows the degree to which price is affected by the planned number of remanufactures of a toner cartridge. We start with the original price of the cartridge (recall the turnaround cost on line 1 actually refers to the turnaround incurred after use 1), and the optimal price after 5 turns quickly falls to about half of the original price. This analysis motivates the derivation of the relationship between price changes and number of reuses in the model. By taking the partial derivative of (2) with respect to n :

$$\frac{\partial p}{\partial n} = \frac{n(M_1 - kM_1 + T) - [(n - nk + k)M_1 + nT]}{n^2}$$

which simplifies to

$$\frac{\partial p}{\partial n} = \frac{-kM_1}{n^2} \quad (5)$$

Equation 5 shows the rapid decline in price associated with the number of uses of the product. By extension, note that a similar relationship would hold by substituting increases in product quality (the delta-epsilon model posed above) into the numerator, which would increase the rate of price decline over time.

Clearly, there is great potential for profit in this market. However, few cartridge manufacturers seem to be currently partaking in this venture. Part of the reason must deal with the public's perception of recycled goods in general. Consumers think that a non-virgin product is inferior. But a manufacturer could adjust for this difference by guaranteeing that all cartridges purchased (regardless of how many times they have been used) will meet original specifications.

TABLE IV
COST AND PRICE SCHEDULE FOR REMANUFACTURED TONER CARTRIDGES

Use	Man Cost (M)	Turnaround	Tot Cost(i)	Lifetime Cost	Price
1	40	2	40	40	40
2	12	2	14	54	27
3	12	2	14	68	22.667
4	12	2	14	82	20.5
5	12	2	14	96	19.2
6	12	2	14	110	18.333
7	12	2	14	124	17.714
8	12	2	14	138	17.25
9	12	2	14	152	16.889
10	12	2	14	166	16.6
15	12	2	14	236	15.733
20	12	2	14	308	15.4

Disposal

There are 3 classes of products in which this research is relevant. First are reusable or remanufacturable products, which are returned to the manufacturer after each use. Examples of this class of product are disposable cameras and rental goods. Second are consumable products, which are bought and partially consumed and typically returned to their manufacturer, such as photocopiers. Finally, there are dissipative products, which are either completely consumed or at least not returned to the manufacturer, such as gasoline.

In all cases, there is an eventual question of how the product will be disposed which is typically excluded from the design process. This typically leads to the selection of materials which lead to the lowest manufacturing cost without regard for the harm which the chosen materials will do to the environment.

Full cost accounting represents a shift from the standard methods of cost accounting to one which includes the liability to a firm for disposing of its products. Social costs need to be evaluated at time of design and made part of the decision-making process of the firm.

The questions of disposal and environmental fate, however, should be central to the design process. Although some optimization should be done to minimize product cost, such minimization should include the social cost of disposing of the component materials in the future, including any additional charges for toxic materials. This procedure internalizes everything for designers, allowing them to select products which minimize total lifetime costs as we have previously defined them, but now including disposal cost. This paradigm shift would allow designers to see the marginal effects of selecting material X over material Y, especially the increase in lifetime costs, including disposal.

In any case, product designers must consider industry-environment interactions that are largely outside the process designer: choice of materials, product packaging, environmental impacts during product use, and optimization of product recycling [2].

Reconsider the original lifecycle model with the addition of R , the cost of disposing of non-recyclable components at each turn, and E , the environmental cost of disposal at the end of its lifetime,

$$\begin{aligned} C_1 &= M_1 \\ C_i &= (1-k)M_1 + T + R \\ E &= \sum_{i=1}^m w_i (B_i + X_i) \end{aligned}$$

where w_i is the weight or volume of material i , m is the total number of component materials in the product, B_i is the base disposal cost of properly disposing of a material (typically seen as a landfill cost by weight), and X_i is the toxicity surcharge for disposing of material i , potentially zero.

We assume that R is related to both the degree to which the product is recyclable, defined as k , and the weight of the portion of the product disposed of at turn i . So assume the following equation represents the total disposal cost.

$$R = (1 - k) \sum_{i=1}^m w_i (B_i + X_i) = (1 - k)E$$

Consequently, the lifetime cost is:

$$C = [n - nk + k] M_1 + nT + (n-1)(1-k)E + E$$

with the associated price

$$p^* = \frac{1}{n} [(n - nk + k)(M_1 + E) + nT] \quad (6)$$

The utility of such a model is in allowing the green product designer to see the tradeoffs between using various (potentially toxic) substances at the materials selection phase of the design process. For example, if lead is one of the component materials (which has known toxicity), the designer can see the cost effects of switching to a different material of higher usage cost but lower environmental cost. Varying companion models can be generated which would show all materials which could be substituted resulting in the same overall cost. This could be accomplished with only knowledge of the volume of material required and associated environmental costs.

Consider for example the toner cartridge example used above, but now include the knowledge that the base end-of-life disposal cost component for the whole cartridge is \$5 ($B=5$), and that the cadmium-plastic shell which weighs 7 ounces has an added toxicity charge X of 1 dollar per ounce. Thus, there is a \$12 disposal cost at the end of the cartridge's lifetime, and by the definition of R , a \$3.60 disposal charge per period. This scenario is represented in Table V. Note that the addition of the "disposal" period changes the placement of the Turnaround Cost for each period to a more straightforward presentation.

The first difference to note with the addition of disposal considerations is that the optimal price has increased only from \$15.40 to \$19.42. In short, the positive disposal costs incurred at the end of the life of the product are paid for over the 20 uses of the product. This model shows a more complete picture of the lifetime cost of the product, and now several points can be made. First of all, the designer could see the true cost of a product given information about the actual materials which will be used in its manufacture. This knowledge further allows the designer to reduce the lifetime cost by

TABLE V
GREEN PRODUCT INCLUDING DISPOSAL

Use	Man Cost	Turn- around	Disp (R)	Base Disp	Toxic Cost	Cost(i)	Life Cost	Price
1	40	0	0	0	0	40	40	40
2	12	2	3.6	0	0	17.6	57.6	28.8
3	12	2	3.6	0	0	17.6	75.2	25.07
4	12	2	3.6	0	0	17.6	92.8	23.2
5	12	2	3.6	0	0	17.6	110.4	22.08
10	12	2	3.6	0	0	17.6	198.4	19.84
15	12	2	3.6	0	0	17.6	286.4	19.1
20	12	2	3.6	0	0	17.6	374.4	18.72
Disp	0	2	0	5	7	14	388.4	19.42

switching to other materials. In this example, if the designer is able to remove all plastic from the cartridge (eliminating the toxicity charge), he can spend \$12 more on the substitute material without increasing the current price. Of course, any cost increase of less than the toxicity charge effect on the substitution will lead to lower lifetime cost and price.

CONCLUSIONS

This model serves several purposes. First of all, it creates a generalized system for accounting for costs in a manufacturing setting. It further supports the lifecycle nature of a green product, and shows the optimal price solutions for all cases. Extensions of the basic model also provide strong tools to designers to see exactly what the tradeoffs in this system are between increased lifetime costs and product price.

Finally, the model accounts for the inclusion of disposal costs of a product over its lifetime, and generalizes new optimal solutions based on these additional costs. Once again, it serves as a tool to show the tradeoff between reducing disposal costs and product price.

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