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Advance Disposal Fee vs. Disposal Fee: A Monopolistic Producer's Durability Choice Model

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Abstract

This study examines how waste disposal fee collection timing affects the durable goods producer's choice of built-in durability under a monopoly. We categorize the disposal fee policies into two types: advance disposal fee (ADF) policy and disposal fee (DF) policy. We compare an ADF policy with a DF policy using a durable-goods monopoly model. This study shows that a DF policy has two opposing effects on built-in durability. Firstly, the DF policy gives the producer an incentive to increase built-in durability in order to delay the households' disposal and to discount the future payment for the disposal fee. Secondly, the DF policy creates an incentive for consumers to dump waste illegally to avoid the disposal fee, and gives the producer an incentive to reduce built-in durability in order to avoid market saturation and associated future price cuts. As a result, on the one hand, a DF policy can make the producer produce the more durable product compared with an ADF policy; on the other hand, however, a DF policy may increase the amount of waste generated, and lead to an additional environmental damage.

Keywords: disposal fee; advance disposal fee; durable goods; planned obsolescence; illegal dumping

JEL Classification: Q53; Q57; D42; D21

1. Introduction

Many developed countries have incorporated extended producer responsibility (EPR) policies to address waste disposal and recycling of durable goods. In Japan, for example, the Electric Appliance Recycling Law, enacted in 1998, mandates that users pay the disposal fee at the point of disposal for used electric home appliances such as refrigerators and televisions. On the other hand, according to the Automobile Recycling Law promulgated in 2002, users pay the disposal fee at the point of purchase. The former is an example of a disposal fee (DF) policy and the latter an advance disposal fee (ADF) policy. The directive on Waste Electric and Electronic Equipment (WEEE), which came into effect in 2003, requires EU member states to pass a legislation that imposes all recycling and waste management costs of WEEE on the producers of products by introducing an ADF policy. In 2015, United Nations Member States adopted The 2030 Agenda for Sustainable Development that includes Sustainable Development Goals (SDGs). The members of the UN pledged to accomplish 17 goals by the year 2030. Goal 12 states that "Ensure sustainable consumption and production patterns." Policies for this goal should be embraced to improve resource efficiency, reduce waste, and mainstream sustainability practices across all sectors of the economy.

This study considers how waste disposal fee collection timing affects the durable goods producer's durability choice and subsequently, the environment. We compare an ADF policy with a DF policy using a durable-goods monopoly model. From the viewpoint of EPR, the producer, rather than the government, has a responsibility for waste pollution caused by wasted products. In considering EPR policies, the distinction between durable and non-durable goods is crucial because products of higher durability would last longer, thereby reducing the amount of waste generated and the associated environmental burden. In effect, product durability design is essentially a part of design for the environment (DfE).[1]

Our interest is to analyze which policy type, ADF or DF, most effectively reduces waste and environmental damage in the monopolistic producer case, where incentives exist to manufacture less-durable products in order to avoid market saturation and associated future price cuts.[2] We find that a DF policy has two opposing effects on built-in durability

[1] Guiltinan (2009) suggests that planned obsolescence increases the disposal costs of durable goods and brings troublesome environmental consequences.

[2] According to Coase (1972), the built-in durability chosen by a durable goods monopolist is socially insufficient because of the time-inconsistency problem. Consumers expect the monopolist to face a time-inconsistency problem; monopolists lose monopoly power since they have an incentive to sell additional units at a lower price in the future. Planned obsolescence is a device used by the monopolist to ensure that it does not have to lower the good's price in the future. Bulow (1986) formalizes Coase's suggestion by using a two-period model. See also Bond and Samuelson (1984), Waldman (1996),

that an ADF policy does not have. Under a DF policy, households have the incentive to illegally dispose of waste in order to save the payment for waste disposal. This provides an incentive for producers to manufacture goods with lower durability so as to avoid market saturation and associated future price cuts. Conversely, a DF policy also provides an incentive to *increase* built-in durability in order to delay households' disposal and to discount the future payment of the disposal fee. Thus, a DF policy may make a product more durable as compared to an ADF policy; however, a DF policy may also increase the amount of waste and lead to illegal dumping with severe negative environmental consequences.

To the best of our knowledge, only Shinkuma (2007) analyzes the optimal waste disposal policy for durable goods by comparing a DF policy with an ADF policy. He concludes that a DF policy is more desirable because an ADF policy results in excessive disposal and the lifetime of durable goods is shorter than the social optimum. Shinkuma argues that durability of goods is not under the control of producers; instead, products can be repaired at the end of their life and traded in secondhand markets. In this study, we take the approach of focusing on the monopolistic producer's choice of built-in durability, rather than consumers' repairing activity, and reconsider the desirable waste disposal policy under these circumstances.

While we focus on the relationship between the timing of waste policies and the producer's choice of built-in durability, several researchers partially share a common awareness of issues. Regardless of lack of attention on product durability, Fullerton and Kinnaman (1995) and Fullerton and Wu (1998) argue that an ADF policy is preferable because a DF policy results in increased illegal disposal and decreased social welfare.[3] As per Calcott and Walls (2000), a DF policy is undesirable if a recycling market does not function properly. These studies deal with the case of non-durable goods and perfect competition.

Another strand of research examines emissions taxation issues in durable goods industries. Boyce and Goering (1997) demonstrate that the optimal pollution tax may exceed marginal environmental damage under a monopoly seller of durable goods with increasing returns to scale in production and exogenous product durability. Eichner and Runkel (2003) analyze the efficiency-restoring tax-subsidy schemes considering a

Hendel and Lizzeri (1999), Kinokuni (1999), and Kinokuni et al. (2010). Waldman (2003) provides a comprehensive survey of the theory of durable goods.

[3] The issue of illegal dumping is extensively treated in the existing literature. OECD (2001) mentions that a DF policy could increase illegal disposal of waste. Fullerton and Kinnaman (1996) offer evidence that a DF policy leads to illegal dumping. See also Copeland (1991), Aalbers and Vollebergh (2006), and Kirakozian (2016).

relationship between durability and recyclability. Runkel (2003) shows that producers of durable goods have an incentive to delay waste under perfect and imperfect competition. Runkel (2002, 2004) shows that, in a model of a durable goods monopoly with endogenous product durability and constant returns to scale in production, an increase in waste tax enhances product durability and the optimal waste tax is above the marginal environmental damage.[4] These studies do not compare economic effects between an ADF policy and a DF policy.

The remainder of this paper is structured as follows: Section 2 presents a two-period model of a durable goods monopoly, wherein the household is required to pay the disposal fee under an ADF policy or a DF policy. Section 3 shows that a DF policy gives the household an incentive for illegal dumping and that the household's actual payment for waste disposal under a DF policy differs from under an ADF policy. Section 4 derives the equilibrium. Section 5 compares the two policies from the viewpoint of the environment. Section 6 concludes.

2. Basic assumptions

We extend the two-period model for a durable goods monopoly developed by Bulow (1986) to analyze the effect of disposal fee policies on the behavior of a durable goods producer. In our two-period model with durable goods and a numeraire good, the economy is composed of a monopolistic producer, a continuum of identical households with total mass normalized to one, and a local government including a solid waste management (SWM) sector.

In each period, the durable goods producer chooses the amount of the new goods, denoted by q_i $(i = 1, 2)$. The producer also chooses the built-in durability in period 1, denoted by $D \in [0,1]$. Built-in durability D represents the probability that the goods supplied in period 1 will operate in period 2. That is, a portion of the goods produced in period 1, $(1 - D)\ q_1$, is broken at the end of period 1. Thus, the market stock in period i is

$$Q_1 = q_1,\ Q_2 = Dq_1 + q_2.$$

With no loss of generality, we assume there are no production costs. To simplify our analysis, we assume that the fixed cost and marginal cost are zero and the producer can

[4] Kinokuni et al. (2019) reinterpret Runkel's result in the framework of a DF policy and compare the equilibrium of the closed-loop model with that of the open-loop model. Other studies that consider taxation in durable goods industries include Goering and Boyce (1996, 1999), Goel and Hsieh (1999, 2004) and Eichner and Runkel (2005).

choose the durability level without incurring any cost.

At the end of the service life, the used durable goods turn into waste. The SWM sector collects and disposes of the solid waste. Costs for collecting and disposing of the waste are financed by the disposal fee imposed on the household. The disposal process makes no profit, that is, it is a non-profit sector. We also assume that the SWM sector has a linear technology for SWM services. The exogenous disposal cost per unit is denoted by τ.[5]

We investigate two kinds of disposal fee policies: an ADF policy and a DF policy. In the former, the household has to pay the disposal fee at the time of purchasing new goods. In the latter case, the household has to pay the fee at the time of discarding the end-of-life goods. Under an ADF policy, there is a time lag between collecting fees and waste disposal. Any disposal fees collected at the beginning of the first period for units unbroken at the end of that period are carried over to the second period. In our model, we assume that the collected fees, which are factored into the product pricing, are immediately transferred to the SWM sector and the interest income which unused fees yield is refunded to the household at the beginning of the second period.

Under a DF policy, the household has an incentive to illegally dump the end-of-life goods in order to avoid paying the disposal fee. We assume that illegal dumping can be detected by a local government, and the ratio of being accused of illegal dumping is $\rho \in [0,1]$. The fine levied for the crime is denoted by F, and is collected with the detection of illegal dumping.

Identical households live for two periods. The representative household consumes a numeraire good and service flows of the durable goods. It is assumed that the amount of service flows consumed is equal to the stock the household possesses. Denoting consumption of the numeraire good in period i ($i = 1, 2$) by x_i and consumption of service flows of the durable goods in period i by Q_i, the household's per-period utility function in period i, u_i, is assumed to be given by

$$u_i = x_i + Q_i\left(a - \frac{Q_i}{2}\right), \; i = 1,2, \; a > 0. \tag{1}$$

The household gains lump-sum income I at the beginning of the first period. The household's budget constraint in period 1 is

5 The Electric Appliance Recycling Law of Japan and the Automobile Recycling Law of Japan states that the disposal fees shall not exceed the appropriate cost of efficiently implementing activities required for recycling. For example, the disposal cost for a refrigerator is around ¥5,000, that for a liquid crystal television is around ¥3,400, and that for an ordinary vehicle is around ¥10,000-¥18,000 in Japan. These are set by producers.

$$I = x_1 + p_1 q_1 + S + q_1 T_1^{ADF}, \tag{2}$$

under an ADF policy and

$$I = x_1 + p_1 q_1 + S + (1 - D) q_1 T_1^{DF}, \tag{3}$$

under an DF policy. The household's budget constraint in period 2 is

$$R \cdot S + (R - 1) D q_1 T_1^{ADF} = x_2 + p_2 q_2 + q_2 T_2^{ADF}. \tag{4}$$

under an ADF policy and

$$R \cdot S = x_2 + p_2 q_2 + (D q_1 + q_2) T_2^{DF}. \tag{5}$$

under an DF policy. In (2) - (5), q_{i} denotes the amount of the durable goods purchased in period i, p_{i} denotes the sales price of the goods in period i, S denotes savings, and $R > 1$ denotes the gross interest rate. The household's unit cost for waste disposal in period i is denoted by T_i, which differs depending on the type of disposal fee policy. Under an ADF policy, the timing between collecting fees and the expenditure of them is different. Unused fees in period 1 bear interest in period 2. In (4), the income gain from remaining fees is assumed to be refunded to the household in order to close this economy model.

Fig. 1 about here

The chronology of the game is as follows (see Fig. 1). The first period contains stages 1 and 2. In stage 1, the producer chooses its first-period output level of new goods and the built-in durability to maximize overall profit. In stage 2, the household chooses its first-period consumption of the numeraire and new goods to maximize its lifetime utility, subject to its lifetime budget constraint. At the end of the first period, the household discards the end-of-life goods and the SWM sector collects and disposes of the legally collected waste. Under a DF policy, some of the end-of-life goods are illegally dumped and not collected by the SWM sector. If the illegal disposal is detected, the local government levies a fine. The second period contains stages 3 and 4. In stage 3, the producer chooses its second-period output level to maximize second-period profit. In stage 4, the household chooses its second-period consumption of the numeraire and new durable goods to maximize its second-period utility, subject to its second-period budget constraints. As before, at the end of the second period, the household discards the end-of-life goods, the SWM sector collects and disposes of the waste. Under a DF policy, some of the end-of-life goods are illegally dumped, and if detected, the local government levies a fine.

This is a game of complete information. Our model adopts the closed-loop strategies, that is, the producer is unable to pre-commit to future decisions. Therefore, the solution satisfies the properties of the subgame-perfect Nash equilibrium.

3. Disposal fee and advance disposal fee

We examine the difference in the household's costs for waste disposal under an ADF policy and a DF policy. We have assumed that the SWM sector does not benefit from the disposal process.

Under an ADF policy, the household pays the disposal fee, which equals the marginal disposal cost, at the time of purchase of goods. Therefore, under an ADF policy, the household's unit cost for waste disposal in period i is

$$T_i^{ADF} = \tau \equiv T^{ADF},\ i = 1,2. \tag{6}$$

The SWM sector disposes of the collected waste with the disposal fee transferred from the producer.

Under a DF policy, the household pays the disposal fee at the time of discarding the waste good. The SWM sector disposes of the legally collected waste. We assume that the detection probability of any illegal dumping is $\rho \in [0,1]$, the fine levied for that crime is F and θ_i is the ratio of legally collected units to total discarded units. The household's unit cost for waste disposal is

$$T_i^{DF} = \tau\theta_i + \rho(1-\theta_i)F,\ i = 1,2. \tag{7}$$

If households engage in more frequent illegal dumping, the detection probability of the unlawful activity rises. Thus, we suppose that ρ is a decreasing function of θ_i, and is given as follows:

$$\rho \equiv 1-\theta_i,\ i = 1,2. \tag{8}$$

The household determines the ratio of illegal disposal. Substituting (8) into (7) and minimizing T_i with respect to θ_i yields

$$\theta_i = 1-\frac{\tau}{2F} \equiv \hat{\theta},\ i = 1,2. \tag{9}$$

Our analysis is assumed to restrict the interior solution[6]. In (9), it means that a reduction in the disposal fee, associated with a decrease in the marginal disposal cost, would increase the number of households that legally dispose of end-of-life goods through the SWM sector. An increase in the fine for illegal dumping would have the same effect.[7]

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[6] We will discuss conditions of the interior solution of the equilibrium in the end of Section 4.

[7] While (9) implies that illegal dumping cannot be completely prevented unless an infinite fine is imposed, we exclude the case of the infinite fine. Becker (1968), which is a seminal study on the economics of crime, claims that maximum fine should be imposed because a severe punishment deters crime and the fine is a costless transfer. However, a considerable study has attempted to show that extremely heavy penalties may not be socially optimal. For example, Ehrlich (1982) considers the possibility of a legal error and discusses justice as equality under the law; this study suggests a less

Substituting (8) and (9) into (7), the cost for waste disposal paid by the household in period i under a DF policy is

$$T_i^{DF} = \tau\left(1 - \frac{\tau}{4F}\right) \equiv T^{DF}, \ i = 1, 2. \tag{10}$$

An increase in the disposal fee τ has two opposing effects on the household's cost for waste disposal. On the one hand, it reduces disposal costs for those households that choose to illegal dump their waste in order to avoid the higher fee; on the other hand, it increases disposal costs for households that choose to pay the higher fee for legal disposal. From (10), the expected household's payment T_i^{DF} is an increasing function of the disposal fee for $\tau \leq \bar{\tau}$ and reaches the maximum $\tau/2$ when $\tau = \bar{\tau}$. Thus, we have the following result.

Lemma 1. A DF policy reduces the household's expected payment for waste disposal compared to an ADF policy, that is, $T^{DF} < T^{ADF}$.

Under a DF policy, the household that discards the end-of-life goods has two options: paying the regular disposal fee or illegally dumping and incurring the expected cost of the penalty. Therefore, the household's expected payment for waste disposal under a DF policy is lower than that under an ADF policy.

4. The equilibrium

4.1. The equilibrium under an ADF policy

In this subsection, we derive the equilibrium of durable-goods monopoly under an ADF policy. The game is solved by backward induction.[8] We focus on optimization problems of the household and the producer.

In stage 4, the household's maximization problem under an ADF policy is, from (1) and (4),

$$max_{x_2,q_2} \ u_2$$
$$\text{s.t.} \ R \cdot S + (1-R)Dq_1T^{ADF} = x_2 + p_2q_2 + q_2T^{ADF}.$$

Under an ADF policy, the income gain from the remaining fees is assumed to be refunded to the household. The first-order conditions for the household's maximization yield the inverse demand function of the second-period new goods:

$$p_2 = a - (Dq_1 + q_2) - T^{ADF} \equiv p_2^{ADF}(q_1, D, q_2). \tag{11}$$

than maximum fine as the optimal law enforcement. Garoupa (1997) provides a survey on the theory of optimal law enforcement.

[8] The details of the solution are in Appendix.

In stage 3, the second-period maximization problem for the monopolistic producer is

$$max_{q_2}\pi_2 = p_2^{ADF}(q_1, D, q_2)q_2.$$

The maximization of this problem yields the following reaction function:

$$q_2 = \frac{a - Dq_1 - T^{ADF}}{2} \equiv q_2^{ADF}(q_1, D). \tag{12}$$

(12) states that the second-period quantity is a decreasing function in the remaining stock Dq_1.

In stage 2, the household maximizes its lifetime utility subject to the lifetime budget constraint. Assuming a perfect financial market, that is, $\delta = 1/R$, the household's maximization problem is denoted as, from (1), (2) and (4),

$$max_{x_1,q_1}\ u_1 + \delta u_2$$

$$\text{s.t. } I = x_1 + p_1 q_1 + q_1 T^{ADF} + \delta(x_2 + p_2 q_2 + q_2 T^{ADF}).$$

The maximization for the household yields the inverse demand function of the first-period goods as follows:

$$p_1 = a - q_1 + \delta D\{a - (Dq_1 + q_2)\} - T^{ADF} \equiv p_1^{ADF}(q_1, D, q_2). \tag{13}$$

In stage 1, the monopolistic producer chooses not only q_1 but also D, which maximizes its overall profit anticipating the producer's second-period decision given by (12). Therefore, the producer's maximization problem is denoted as

$$max_{q_1,D}\ p_1^{ADF}(q_1, D, q_2)q_1 + \delta p_2^{ADF}(q_1, D, q_2)q_2.$$

$$\text{s.t. } q_2 = q_2^{ADF}(q_1, D).$$

From the producer's maximization problem, we obtain the following equilibrium:

$$q_1^{ADF} = \frac{a - T^{ADF}}{2}, q_2^{ADF} = \frac{a - 3T^{ADF}}{2} \text{ and } D^{ADF} = \frac{4T^{ADF}}{a - T^{ADF}}. \tag{14}$$

When $T^{ADF} = \tau = 0$, $D^{ADF} = 0$, that is, the monopolistic producer practices planned obsolescence.[9] An increased disposal fee decreases the household's willingness to pay for the durable product due to the increased waste cost. Therefore, a rise in the disposal fee reduces each period's output. This gives the producer an incentive to enhance built-in durability since increased durability replaces the output reduction.

4.2. The equilibrium under an DF policy

In this subsection, we derive the equilibrium of durable-goods monopoly under an DF policy. In stage 4, the household's maximization problem under a DF policy is, (1) and (5),

[9] In a seminal study, Coase (1972) shows that a durable-goods monopolist faces the time-inconsistency problem, wherein *ex post* decisions hurt its overall profitability. Low durability is a device to commit, not to overproduce.

$$max_{x_2,q_2}\ u_2$$
$$\text{s.t. } R \cdot S = x_2 + p_2 q_2 + (Dq_1 + q_2)T^{DF}.$$

The first-order conditions for the household's maximization yield the inverse demand function of the second-period new goods:

$$p_2 = a - (Dq_1 + q_2) - T^{DF} \equiv p_2^{DF}(q_1, D, q_2). \tag{15}$$

In stage 3, the second-period maximization problem for the monopolistic producer is

$$max_{q_2}\pi_2 = p_2^{DF}(q_1, D, q_2)q_2.$$

The maximization problem yields the following reaction function:

$$q_2 = \frac{a - Dq_1 - T^{DF}}{2} \equiv q_2^{DF}(q_1, D). \tag{16}$$

In stage 2, the household maximizes its lifetime utility subject to the lifetime budget constraint. Assuming a perfect financial market, that is, $\delta = 1/R$, the household's maximization problem is denoted as, from (1), (3) and (5),

$$max_{x_1,q_1}\ u_1 + \delta u_2$$
$$\text{s.t. } I = x_1 + p_1 q_1 + (1-D)q_1 T^{DF} + \delta\{x_2 + p_2 q_2 + (Dq_1 + q_2)T^{DF}\}.$$

The maximization for the household yields the inverse demand function of the first-period goods as follows:

$$p_1 = a - q_1 + \delta D\{a - (Dq_1 + q_2)\}$$
$$-(1-D)T^{DF} - \delta D T^{DF} \equiv p_1^{DF}(q_1, D, q_2). \tag{17}$$

In stage 1, the monopolistic producer chooses not only q_1 but also D, which maximizes its overall profit anticipating the producer's second-period decision given by (16). Therefore, the producer's maximization problem is denoted as

$$max_{q_1,D}\ p_1^{DF}(q_1, D, q_2)q_1 + \delta p_2^{DF}(q_1, D, q_2)q_2$$
$$\text{s.t. } q_2 = q_2^{DF}(q_1, D).$$

From the producer's maximization problem, we obtain the following equilibrium:

$$q_1^{DF} = \frac{a - T^{DF}}{2},\ q_2^{DF} = \frac{1}{2}\left\{a - \left(1 + \frac{2}{\delta}\right)T^{DF}\right\} \text{ and } D^{DF} = \frac{4T^{DF}}{\delta(a - T^{DF})}. \tag{18}$$

Here, we discuss the interior solution conditions. The interior solution condition of the ADF equilibrium (14) is $\tau \le a/5$ and that of the DF equilibrium (18) is $F < \frac{\delta a}{4+\delta}$. From (9), $\tau < 2F \equiv \bar{\tau}$ guarantees that the fine for illegal dumping is effective. In order to reduce the case classification, we assume that $\bar{\tau} = 2F < a/5$. These conditions are summarized as follows:

$$\frac{\tau}{2} < F < \min\left\{\bar{F}, \frac{a}{10}\right\}. \tag{19}$$

5. Comparison of waste disposal policies

This section examines how the timing of disposal fee collection affects the producer's built-in durability choice. We compare the equilibrium built-in durability under a DF policy with that under an ADF policy.

Proposition 1. When $0 < \delta \leq (a - 2F)/2(a - F)$, the equilibrium built-in durability under a DF policy is always higher than that under an ADF policy. When $(a - 2F)/2(a - F) < \delta \leq 1$, the equilibrium built-in durability under a DF policy is higher than that under an ADF policy for the small disposal fee, and lower than that under an ADF policy for the large disposal fee.

A DF policy has two opposing effects on built-in durability that an ADF policy does not have. Firstly, under a DF policy, the monopolistic producer of durable goods has an incentive to increase built-in durability in order to delay the household's disposal and to discount the future payment for the disposal fee. We call this effect the "payment-discounting effect." Thus, a decrease in the discount factor raises built-in durability under a DF policy. Secondly, under a DF policy, the existence of illegal dumping leads to a reduction in built-in durability. Under a DF policy, the household has an incentive to illegally dump the end-of-life goods with intent to decrease the expected payments for disposal. This incentive makes the producer lower the price and expand production, resulting in reducing the built-in durability in order to prevent a major decline in the product's second-period price. We call this reduction of the built-in durability the "illegal-dumping effect."

Fig. 2 about here

Fig. 2 shows the result of proposition 1. If the discount factor is small, $D^{DF} > D^{ADF}$ since the payment-discounting effect dominates the illegal-dumping effect. If the discount factor is large, the payment-discounting effect dominates the illegal-dumping effect when the disposal fee is small. Only when the discount factor is large and the disposal fee is large, $D^{DF} < D^{ADF}$ holds. In Fig. 2, two opposing effects are balanced out on the boundary line $\widehat{\tau}$, which is derived in Appendix.

From the viewpoint of the producer's profitability, we compare an ADF policy with an DF policy. Both the payment-discounting effect and the illegal-dumping effect have positive impacts on the producer's profit. Under a DF policy, the producer has an incentive to increase built-in durability in order to delay the household's disposal and discount the future payment for the disposal fee. This payment-discounting effect enhances the household's willingness to pay for the product. Illegal dumping reduces the household's payment of the disposal fee. This illegal-dumping effect contributes to an increase in the household's willingness to pay for the product.

Proposition 2. The equilibrium profit for the monopolistic producer of durable goods under a DF is larger than that under an ADF policy.

A purpose of imposing the disposal fee to the household is to reduce solid waste. A rise in the household's willingness to pay for the product enlarges the consumption. In effect, from (14) and (18), $q_1^{DF} > q_1^{ADF}$ always holds and $q_2^{DF} > q_2^{ADF}$ if $T^{DF} < 3\delta\tau/(2+\delta)$.

We assume that the marginal environmental damage is represented by $\gamma > 0$ if waste is dumped illegally.[10] The social cost of waste under an ADF policy is composed of total disposal costs;

$$SCW^{ADF} \equiv \tau(G_1^{ADF} + \delta G_2^{ADF}), \tag{20}$$

where $G_1^{ADF} = (1 - D^{ADF})q_1^{ADF}$ and $G_2^{ADF} = D^{ADF}q_1^{ADF} + q_2^{ADF}$, which is the amount of waste in each period under an ADF policy. Note that τ is an exogenous disposal cost per unit.

Under a DF policy, the household pays a disposal fee of τ with probability θ and illegally dumps end-of-life goods with probability $(1-\theta)$. While the economy saves the disposal cost for illegally dumped waste, the unlawfully dumped waste causes severe damage to the environment.[11] Therefore, the social marginal cost of illegal waste is assumed to be $(\tau + \gamma)$. Thus, the social cost of waste under a DF policy is

$$SCW^{DF} \equiv \{\tau + (1-\hat{\theta})\gamma\}(G_1^{DF} + \delta G_2^{DF}), \tag{21}$$

where $G_1^{DF} = (1 - D^{DF})q_1^{DF}$ and $G_2^{DF} = D^{DF}q_1^{DF} + q_2^{DF}$. The following proposition indicates that, even if a DF policy brings more durable product, the social cost of waste under an DF policy can be larger than that under an ADF policy.

Proposition 3. When the equilibrium built-in durability under an ADF policy is higher than that under a DF policy, an ADF policy leads to smaller social costs of waste. Even when the equilibrium built-in durability under a DF policy is higher than that under an ADF policy and the environmental damage associated with illegal dumping is small, a

[10] Ino (2007), Brécard (2011), and Holland (2012) adopt the assumption with constant marginal environmental damage. We assume that waste generates no external environmental damage if the waste is disposed of legally.

[11] Fullerton and Kinnaman (1995) mention that legal disposal generally results in less environmental damage than illegal dumping.

DF policy may entail higher social costs compared with an ADF policy.

From the standpoint of increasing durability, a DF policy can be superior to an ADF policy. However, a DF policy leads to unlawful dumping, which has two undesirable features. First, illegal waste causes more severe environmental damage than legally disposed waste. Second, it may increase the amount of waste generation compared to an ADF policy since it increases the household's expected payment for waste disposal while expanding the consumption of durable goods.

6. Conclusion

This study considers how waste disposal fee collection timing affects the durable goods producer's durability choice and the environment. We compare an ADF policy with a DF policy using a durable-goods monopoly model. Under an ADF policy, a rise in the disposal fee increases built-in durability, that is, it curbs planned obsolescence, and reduces the amount of waste. Under a DF policy, an increase in the disposal fee curbs planned obsolescence and improves built-in durability by the payment-discounting effect. It also decreases built-in durability and increases waste by the illegal-dumping effect. Illegal dumping brings additional marginal environmental damage γ. If the payment-discounting effect is large and the environmental damage is sufficiently small, there is a theoretical possibility that a DF policy makes social cost of waste smaller than an ADF policy. However, since a DF policy promotes illegal dumping, to argue institutional merits and demerits only by the economic efficiency may not be suitable. Thus, the DF policy generates a legal and ethical problem. As shown in this study, the producer that is able to choose built-in durability has a strong incentive to lobby for the introduction of a DF policy compared with the producer of non-durable goods. The goal of EPR regulations is to hold manufacturers liable for end-of-life their products; however, a DF policy might not a suitable instrument from the viewpoint of EPR.

With our limited knowledge, this study is the first to theoretically consider the relationship between the timing of waste disposal fee collection and the producer's decision on built-in durability. However, this study also suffers from some limitations. We did not consider other types of EPR-like initiatives, such as take-back programs, deposit-refund schemes, and performance standards. These aspects may be included in future research.

Acknowledgments

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Appendix

The derivation of (11)

In stage 4, the Lagrangian for the household's problem is

$$\mathcal{L}_2^{ADF} = x_2 + (Dq_1 + q_2)\left(a - \frac{Dq_1+q_2}{2}\right) + \lambda^{ADF}(RS - x_2 - p_2q_2 - q_2T^{ADF}),$$

where λ^{ADF} is the multiplier. The first-order conditions are given by

$$\frac{\partial \mathcal{L}_2^{ADF}}{\partial x_2} = 1 - \lambda^{ADF} = 0, \tag{A.1}$$

$$\frac{\partial \mathcal{L}_2^{ADF}}{\partial q_2} = a - Dq_1 - q_2 - \lambda^{ADF}p_2 - \lambda T^{ADF} = 0 \ \text{ and} \tag{A.2}$$

$$\frac{\partial \mathcal{L}_2^{ADF}}{\partial \lambda^{ADF}} = RS - x_2 - p_2q_2 - q_2T^{ADF} = 0. \tag{A.3}$$

From (A1) and (A2), we have the second-period inverse demand function (11).

The derivation of (13)

In stage 2, the Lagrangian for the household's problem is

$$\mathcal{L}_1^{ADF} = x_1 + q_1\left(a - \frac{q_1}{2}\right) + \delta\left\{x_2 + (Dq_1 + q_2)\left(a - \frac{Dq_1+q_2}{2}\right)\right\},$$
$$+\mu^{ADF}\{\mathrm{I} - x_1 - p_1q_1 - q_1T^{ADF} - \delta(x_2 + p_2q_2 + q_2T^{ADF})\},$$

where μ^{ADF} is the multiplier. The first-order conditions are given by

$$\frac{\partial \mathcal{L}_1^{ADF}}{\partial x_1} = 1 - \mu^{ADF} = 0, \tag{A.4}$$

$$\frac{\partial \mathcal{L}_1^{ADF}}{\partial q_1} = a - q_1 + \delta D\{a - (Dq_1 + q_2)\} - \mu^{ADF}p_1 - \mu^{ADF}T^{ADF} = 0 \ \text{ and} \tag{A.5}$$

$$\frac{\partial \mathcal{L}_1^{ADF}}{\partial \mu^{ADF}} = \mathrm{I} - x_1 - p_1q_1 - q_1T^{ADF} - \delta(x_2 + p_2q_2 + q_2T^{ADF}) = 0. \tag{A.6}$$

From (A4) and (A5), we have the first-period inverse function (13).

The derivation of (14)

In stage 1, the first-order conditions for the monopolistic producer's profit maximization with respect to q_1 and D are

$$p_1^{ADF} + \frac{\partial p_1^{ADF}}{\partial q_1}q_1 + \delta\frac{\partial p_2^{ADF}}{\partial q_1}q_2^{ADF}(q_1, D)$$

$$+\frac{\partial q_2^{ADF}(q_1,D)}{\partial q_1}\left(\frac{\partial p_1^{ADF}}{\partial q_2}q_1+\delta\frac{\partial \pi_2^{ADF}}{\partial q_2}\right)=0, \tag{A7}$$

$$\frac{\partial p_1^{ADF}}{\partial D}q_1+\delta\frac{\partial p_2^{ADF}}{\partial D}q_2^{ADF}(q_1,D)$$
$$+\frac{\partial q_2^{ADF}(q_1,D)}{\partial D}\left(\frac{\partial p_1^{ADF}}{\partial q_2}q_1+\delta\frac{\partial \pi_2^{ADF}}{\partial q_2}\right)=0. \tag{A8}$$

Using the envelope theorem and substituting (11), (12) and (13) into (A7) and (A8) yields, respectively,

$$a-2q_1+\delta D\big(a-2Dq_1-q_2^{ADF}(q_1,D)\big)-T^{ADF}$$
$$-\delta Dq_2^{ADF}(q_1,D)+\frac{1}{2}\delta D^2q_1=0, \tag{A9}$$

$$\delta\big(a-2Dq_1-q_2^{ADF}(q_1,D)\big)q_1+T^{ADF}q_1$$
$$-\delta q_1q_2^{ADF}(q_1,D)+\frac{1}{2}\delta D{q_1}^2=0. \tag{A10}$$

From (A9) and (A10), we have the equilibrium (14).

The derivation of (15)

In stage 4, the Lagrangian for the household's problem is

$$\mathcal{L}_2^{DF}=x_2+(Dq_1+q_2)\left(a-\frac{Dq_1+q_2}{2}\right)+\lambda^{DF}\{RS-x_2-p_2q_2-(Dq_1+q_2)T^{DF}\},$$

where λ^{DF} is the multiplier. The first-order conditions are given by

$$\frac{\partial\mathcal{L}_2^{DF}}{\partial x_2}=1-\lambda^{DF}=0, \tag{A.11}$$

$$\frac{\partial\mathcal{L}_2^{DF}}{\partial q_2}=a-Dq_1-q_2-\lambda^{DF}p_2-\lambda^{DF}T^{DF}=0 \tag{A.12}$$

$$\frac{\partial\mathcal{L}_2^{DF}}{\partial \lambda^{DF}}=RS-x_2-p_2q_2-(Dq_1+q_2)T^{DF}=0. \tag{A.13}$$

From (A11) and (A12), we have the second-period inverse demand function (15).

The derivation of (17)

In stage 2, the Lagrangian for the household's problem is

$$\mathcal{L}_1^{DF}=x_1+q_1\left(a-\frac{q_1}{2}\right)+\delta\left\{x_2+(Dq_1+q_2^{DF})\left(a-\frac{Dq_1+q_2^{DF}}{2}\right)\right\},$$
$$+\mu^{DF}[\mathrm{I}-x_1-p_1q_1-(1-D)q_1T^{DF}-\delta\{x_2+p_2q_2+(Dq_1+q_2)T^{DF}\}],$$

where μ^{DF} is the multiplier. The first-order conditions are given by

$$\frac{\partial \mathcal{L}_1^{DF}}{\partial x_2} = 1 - \mu^{DF} = 0, \tag{A.14}$$

$$\frac{\partial \mathcal{L}_1^{DF}}{\partial q_2} = a - q_1 + \delta D\{a - (Dq_1 + q_2)\}$$

$$-\mu^{DF} p_1 - \mu^{DF}(1-D)T^{DF} - \mu^{DF}\delta D T^{DF} = 0 \quad \text{and} \tag{A15}$$

$$\frac{\partial \mathcal{L}_1^{DF}}{\partial \mu^{DF}} = \mathrm{I} - x_1 - p_1 q_1 - (1-D)q_1 T^{DF}$$

$$-\delta\{x_2 + p_2 q_2 + (Dq_1 + q_2)T^{DF}\} = 0. \tag{A.16}$$

From (A14) and (A15), we have the first-period inverse function (17).

The derivation of (18)

In stage 1, the first-order conditions for the monopolistic producer's profit maximization with respect to q_1 and D are

$$p_1^{DF} + \frac{\partial p_1^{DF}}{\partial q_1} q_1 + \delta \frac{\partial p_2^{DF}}{\partial q_1} q_2^{DF}(q_1, D)$$

$$+ \frac{\partial q_2^{DF}(q_1,D)}{\partial q_1}\left(\frac{\partial p_1^{DF}}{\partial q_2} q_1 + \delta \frac{\partial \pi_2^{DF}}{\partial q_2}\right) = 0, \tag{A.17}$$

$$\frac{\partial p_1^{DF}}{\partial D} q_1 + \delta \frac{\partial p_2^{DF}}{\partial D} q_2^{DF}(q_1, D) + \frac{\partial q_2^{DF}(q_1,D)}{\partial D}\left(\frac{\partial p_1^{DF}}{\partial q_2} q_1 + \delta \frac{\partial \pi_2^{DF}}{\partial q_2}\right) = 0. \tag{A.18}$$

Using the envelope theorem and substituting (15), (16) and (17) into (A17) and (A18) yields, respectively,

$$a - 2q_1 + \delta D\big(a - 2Dq_1 - q_2^{DF}(q_1, D)\big) - (1-D)T^{DF} - \delta D T^{DF}$$

$$-\delta D q_2^{DF}(q_1, D) + \frac{1}{2}\delta D^2 q_1 = 0, \tag{A19}$$

$$\delta\big(a - 2Dq_1 - q_2^{DF}(q_1, D)\big)q_1 + (1-\delta)T^{DF} q_1$$

$$-\delta q_1 q_2^{DF}(q_1, D) + \frac{1}{2}\delta D {q_1}^2 = 0. \tag{A20}$$

From (A19) and (A20), we have the equilibrium (18).

Proof of Proposition 1

From (6), (14) and (18),

$$D^{DF} - D^{ADF} = \frac{4X(T^{DF})}{\delta(a - T^{DF})(a - \tau)}, \tag{A.21}$$

where $X(T^{DF}) \equiv \{a - (1-\delta)\tau\}T^{DF} - \delta a \tau$. Substituting (10) into $X(T^{DF})$ of (A21) yields

$$X(T^{DF}) = \frac{\tau x(\tau)}{4F}, \tag{A.22}$$

where $x(\tau) \equiv (1-\delta)\tau^2 - \{a + 4(1-\delta)F\}\tau + 4a(1-\delta)F$. The minimum of $x(\tau)$ is $x(2F) = 2F\{a - 2F - 2(a-F)\delta\}$ in the $\tau \in [0, \bar{\tau}]$. When $0 < \delta \leq (a-2F)/2(a-F)$, $x(\tau) > 0$, leading to $D^{DF} > D^{ADF}$. When $(a-2F)/2(a-F) < \delta \leq 1$, $x(\tau) < 0$, resulting in $D^{DF} > D^{ADF}$ for $0 < \tau < \hat{\tau}(\delta)$ and $D^{DF} \leq D^{ADF}$ for $\hat{\tau}(\delta) \leq \tau < \bar{\tau}$, where

$$\hat{\tau}(\delta) \equiv \frac{a + 4(1-\delta)F - \sqrt{a^2 - 8a(1-\delta)(1-2\delta)F + \{4(1-\delta)F\}^2}}{2(1-\delta)}, \tag{A.23}$$

which is the smaller solution of the quadratic equation $x(\tau) = 0$. The derivative of $x(\tau)$ with respect to δ is

$$\frac{\partial x(\tau)}{\partial \delta} = -\tau^2 - 4(a-\tau)F < 0. \tag{A.24}$$

Therefore, $\hat{\tau}(\delta)$ is a decreasing function of δ. Q.E.D.

Proof of Proposition 2

From (10), (11), (13) and (14), the equilibrium profit under an ADF policy is

$$\Pi^{ADF} = \frac{1}{4}(a-\tau)(a-\tau+4\delta\tau) + \frac{\delta}{4}(a-3\tau)^2. \tag{A.25}$$

From (15), (17) and (18) , the equilibrium profit under an DF policy is

$$\Pi^{DF} = \frac{1}{64F^2}(4Fa + 12F\tau - 3\tau^2)(4Fa - 4F\tau + \tau^2)$$

$$+ \frac{1}{64\delta F^2}\{4\delta Fa - 8F\tau - 4\delta F\tau + (2+\delta)\tau^2\}^2. \tag{A.26}$$

The difference between (A25) an (A26) is

$$\Pi^{DF} - \Pi^{ADF} = \frac{\tau^2}{64\delta F^2} Z(\tau), \tag{A.27}$$

where $Z(\tau) \equiv (4 + \delta + \delta^2)\tau^2 - 8(4 + \delta + \delta^2)F\tau + 8(1+\delta)F\{\delta a + 8(1-\delta)F\}$. $Z(\tau)$ is a convex quadratic function and reaches the minimum at $\tau = 4F$. However, $Z(2F)$ is the minimum value in the domain of τ from assumption (19), where

$$Z(2F) = 4F\{2\delta(1+\delta)a + (4 - 3\delta - 19\delta^2)F\}. \tag{A28}$$

Assumption (19) guarantees $Z(2F) > 0$. Thus, $\Pi^{DF} > \Pi^{ADF}$ always holds. Q.E.D.

Proof of Proposition 3

From (14), (18), (20) and (21), the difference between SCW^{ADF} and SCW^{DF} is

$$SCW^{DF} - SCW^{ADF}$$
$$= \tau\{(G_1^{DF} + \delta G_2^{DF}) - (G_1^{ADF} + \delta G_2^{ADF})\} + (1-\hat{\theta})\gamma(G_1^{DF} + \delta G_2^{DF})$$
$$= \frac{\tau}{2\delta} Y(T^{DF}) + (1-\hat{\theta})\gamma(G_1^{DF} + \delta G_2^{DF}), \quad \text{(A29)}$$

where $Y(T^{DF}) \equiv \delta(5-\delta)\tau - (\delta^2 - \delta + 4)T^{DF}$. From (A21) and (A29), $X'(T^{DF}) > 0$ and $Y'(T^{DF}) < 0$. Fig. A1 depicts $X(T^{DF})$ and $Y(T^{DF})$. When $T^{DF} = \frac{\delta a \tau}{\{a-(1-\delta)\tau\}} \equiv \hat{T}$, $X(\hat{T}) = 0$ and $Y(\hat{T}) = \frac{(1-\delta)\delta\{(1+\delta)a-(5-\delta)\tau\}\tau}{\{a-(1-\delta)\tau\}} > 0$ for $\tau < \bar{\tau} < \frac{a}{5}$. When $T^{DF} = \frac{\delta(5-\delta)\tau}{\delta^2-\delta+4} \equiv \bar{T}$, $Y(\bar{T}) = 0$ and $X(\bar{T}) = \frac{(1-\delta)\delta\{(1+\delta)a-(5-\delta)\tau\}\tau}{\delta^2-\delta+4} > 0$ for $\tau < \bar{\tau} < \frac{a}{5}$. Thus, when $\hat{T} < T^{DF} < \bar{T}$, $D^{DF} > D^{ADF}$ but $SCW^{DF} > SCW^{ADF}$ even if the environmental damage by illegal dumping does not exist, that is, $\gamma = 0$. The existence of environmental damage would put upward pressure on SCW^{DF}. Q.E.D.

Fig. A1 about here

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Fig. 1. Sequence of events

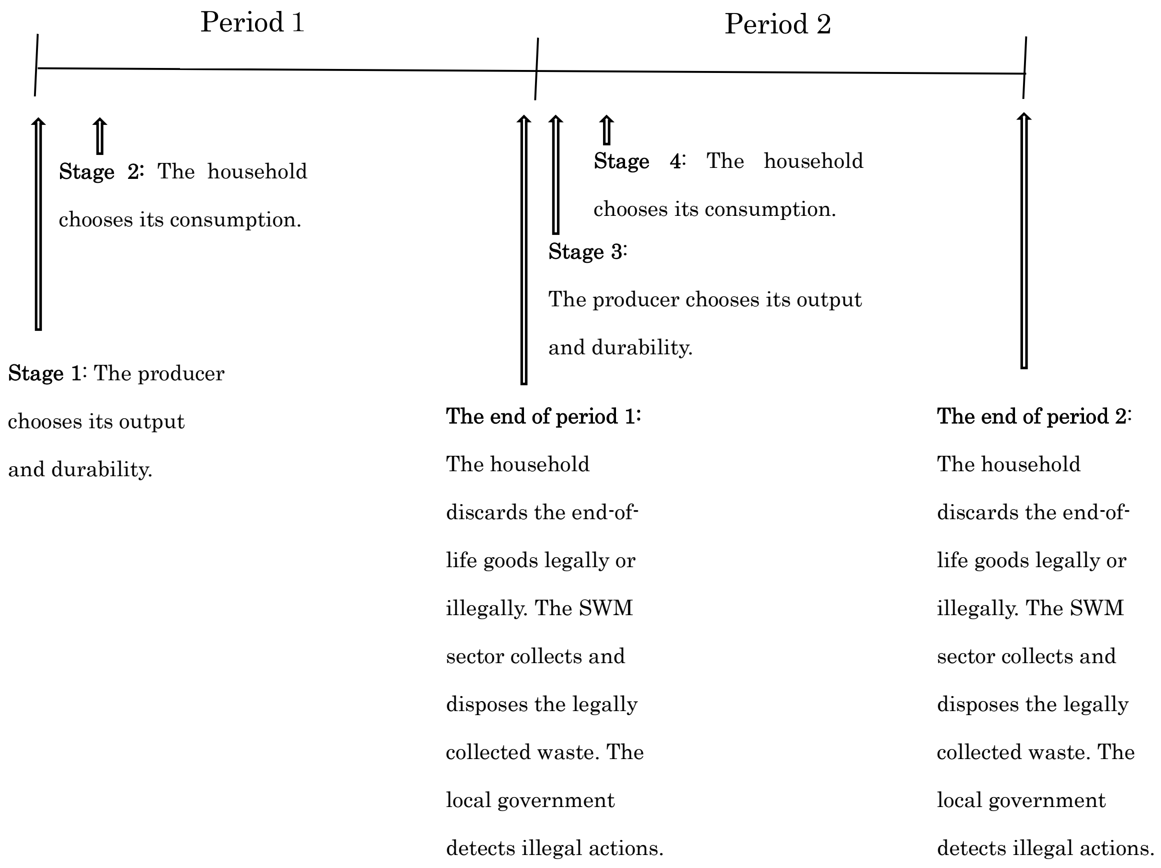

Fig. 2. Comparison of the equilibrium built-in durability

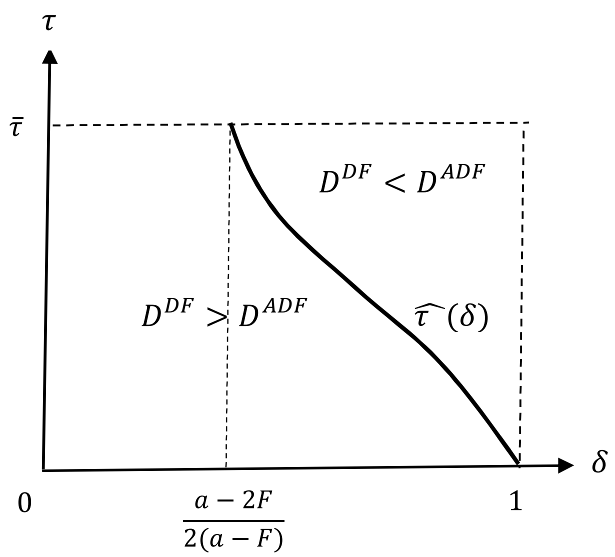

Fig. A1. Illustrative graph regarding proof of proposition 3