Remanufacturing
(Preliminary. Comments are welcome.)

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Abstract

Remanufacturing is a form of recycling where used durable goods are refurbished to a condition comparable to new products. With reduced energy and resource consumption, remanufactured goods are produced at a fraction of the original cost and with lower emissions of pollution. However, remanufacturing-oriented designs generally raise initial production costs. Because the benefits of such designs are not totally internalized, technology choices are socially suboptimal.

This paper presents a theoretical model of remanufacturing where a duopoly of original manufacturers produces a component of a final good. In this primary market, competition *à la* Bertrand with threat of entry keeps prices at the minimal production costs. The specific component needing to be replaced during the lifetime of the final good creates an aftermarket where remanufacturing activities substitute perfectly new good productions. Consumers generally prefer to purchase a replacement product remanufactured by the original manufacturers, but would consider the services of independent remanufacturers as an alternative.

The market segmentation brings profit opportunities to the original manufacturers that can engender investments in remanufacturable original products. An environmental regulation that constrains a minimum level of remanufacturability supports an increase in the original product price. Therefore, if original manufacturers can reach new margins by increasing their remanufacturing activities, they would cooperate to the application of such a regulation.

The main result coincides with the *Porter Hypothesis* which stipulates that industries respecting environmental regulations can see their profits increase.

Keywords: remanufacturing, competition, environmental regulation, Porter Hypothesis, public choice.

JEL classification: H23, L10, L51, Q53, Q58

1 Introduction

Remanufacturing is a specific type of recycling where used durable goods are repaired to a condition like new. Both remanufacturing and recycling avoid post-consumption waste while reducing the use of raw materials. However, recycling is an energy intensive process that conserves only material value. In attempting to meet multiple environmental objectives, remanufacturing can be a more suitable option; it preserves most of the added-value by giving a second life to the product and, typically, reduces the use of energy by eliminating production steps.

Recycling or remanufacturing oriented designs generally raise initial production costs. There is a reduced incentive for such designs because the benefits are not totally internalized and choice of production technology is suboptimal. Take-back regulation internalizes product life cycle costs by making manufacturers responsible for disposal. Waste costs are then reflected in market prices and encourage the development of recyclable goods [Toffel and al. 2008]. Consumption and production taxes, subsidies to green designs as well as subsidies to the demand for recyclable material input also create strong incentives for greener designs [Fullerton and Wu 1998; Eichner and Pethig 2001; Eichner and Runkel 2005]. This has lead governments to introduce recycling oriented regulations. The European Union's Directive on Waste Electrical and Electronic Equipment in 2005 is an example of take-back regulation. The European Union's End of Life Vehicle Directive introduced in 2006 stipulates that every new vehicle must have recyclable content of 85 percent (95 percent by 2015). In the United States, goods purchased by federal agencies must respect the Electronic Product Environmental Assessment Tool issued in 2007 that regulates product design and imposes products to have reusable or recyclable content of 65 percent[1].

Similarities between recycling and remanufacturing are such that their corresponding public interventions use comparable mechanics. Webster and Mitra (2007) and Mitra and

[1]For more details on the different regulations see Toffel and al. (2008).

Webster (2008) have pointed out that take-back regulations as well as subsidies can encourage remanufacturing activities. Furthermore, because recyclable and remanufacturable products present common characteristics in their conception [Steinhilper 1998], regulations aimed at either recycling or remanufacturing may interchangeably foster one activity or the other.

Unlike recycling, the beneficial effect of remanufacturing on environment is complementary to industrial performances. While remanufactured products are sold at 60 to 70 percent of the new products' price, their production counts for only 35 to 60 percent of the original costs [Giuntini and Gaudette 2003]. Therefore, when new products can be substituted with remanufactured ones, *original manufacturers* (OMs) may undertake profitable remanufacturing initiatives. Xerox, Kodak, Ford Motor Company and Mercedes-Benz are examples of corporations that could reduce their production costs with voluntary product recovery [Toffel 2004]; and they are part today of a 60-65 billion dollar industry according to the sources. Over the years, profitability concerns have made remanufacturing a hot topic in the engineering and managerial worlds, witness the flourishing literature on reverse logistic, stock planning, material demand and return, and case studies[2]. Nonetheless, there is only a handful of economic studies that consider the effect of public interventions on remanufacturing [Webster and Mitra 2007; Mitra and Webster 2008].

In this framework, the car parts industry is of particular interest. Combined, alternators and starters represent 80 percent of remanufactured products [Kim and al. 2008]. Valeo and Bosch are the two most important alternator producers in Europe. They started remanufacturing activities in the early 90's, following the announcement of a legislation prohibiting production, sale and use of asbestos[3]. This technological constraint has made alternators remanufacturing commercially viable.

A study by Debo and al.(2005) analyzes the technology selection for remanufacturable

[2] See for instance Ferrer (1997), Kiesmuller and Laan (2001), Majumder and Groenevelt (2001), Lebreton and Tuma (2006), Ferrer and Swaminathan (2006), Chung and We (2008).

[3] This legislation was issued in 1997 in France where Bosch and Valeo are located. The European Union followed in 1999 [European Commission 1999].

goods when a higher remanufacturability may invite entry by *independent remanufacturers* (IRs) attracted by lower remanufacturing costs[4]. Stronger competition on the remanufacturing market pulls down prices and OMs show lower interest in costly technology of production. Therefore, governmental interventions promoting competition on the aftermarket negatively influence the level of remanufacturability. This corroborates the observation of Ferrer (2000) which says that remanufacturing is viable only if the remanufactured product is priced above its marginal cost.

Studies that observe the effects of competition on the remanufacturing market generally omit to discuss the implication of competition on the primary market where they assume a monopolistic original manufacturer[5]. The current paper proposes a theoretical model of remanufacturing inspired by Debo and al. (2005) and framed on the particularities that characterize the alternator industry. A duopoly of OMs compete *à la* Bertrand on the primary market and *à la* Cournot on the aftermarket where consumers of remanufactured products may alternatively use the services of competitive IRs. The model pins down the different incentives in the technology selection determining the level of remanufacturability and explores the consequences of environmental regulations. Particularly, it explains why original alternator manufacturers refrained from adopting a voluntary withdrawal of asbestos in their production in order to launch profitable remanufacturing activities.

The main result shows that the introduction of environmental regulations imposing a minimum level of remanufacturability could be beneficial to firms. In absence of public intervention, the threat of entry on the primary market imposes the support of all the costs of remanufacturing-oriented technologies on OMs, while environmental benefits are share by

[4]Because remanufacturability gives the products a positive value at the end of their life, OMs have the incentive to offer remanufacturable products when the end of life value is reflected in the original product price.

[5]See for instance Mitra and Webster (2008), Debo and al. (2005) and Majumder and Groenevelt (2001). Heese and al. (2005) study a duopoly that compete on the primary market. In their model, new products have a positive initial remanufacturability level. Hence the first mover in launching take-back strategy can deter the competitor by offering a new product with a lower price that includes a discount for the consumer who will return the used product.

all. Consequently, OMs can gain additional profits when the regulation justifies a raise in the original product price that reflects the cost of remanufacturability. This result is in line with the Porter Hypothesis stating that environmental regulations may increase profits in the regulated industries.

2 The Model

An oligopoly of two identical original manufacturers (OMs) produce an intermediate good m (the alternator), which enters as a component of a final consumption good (the vehicle). This constitutes the primary market and the component's first life. Matching the fact that the same car gets through two or three alternators [Kim and al. 2008], the lifetime of the two products is respectively l and L, with $l < L$. Consequently, consumers of the final good have to replace the specific component b times, where $b = (l/L) - 1$. This creates an aftermarket.

The alternator's original life aims specifically at the new vehicle industry with one alternator per vehicle. Used alternators can be remanufactured several times and, by using exclusively new alternators, the new car industry generates the maximum amount needed for the replacement market. This situation prevents original good productions to be driven by profitable remanufacturing activities, unlike in Debo and al. (2005).

When they originally produce a remanufacturable component, OMs participate in the aftermarket by recovering and remanufacturing used products. On this market, however, they face the competition of independent remanufacturers (IRs).

2.1 Technology and pollution

OMs control the level of remanufacturability q, a technology choice corresponding to the ease with which a used product can be remanufactured[6] and leading to decreasing unit

[6] In most models [see for instance Debo and al. 2005; Majumder and Groenevelt 2001; Ferrer and Swaminathan 2006] the level of remanufacturability is the percentage of remanufacturable used products.

remanufacturing cost $c_r(q)$. However, designing the original product to make it more remanufacturable generates additional costs and it is assumed that $c_m(q)$, the initial production cost, is increasing and convex.

IRs also face a decreasing remanufacturing cost function $c_s(q)$. However, they detain only partial information on the original product conception and hence, for any q, meet larger remanufacturing costs than the OMs; that is:

$$c_s(q) - c_r(q) \geq 0; \quad \text{and asymptotically:} \quad \lim_{q \to \infty} c_s(q) = \lim_{q \to \infty} c_r(q) = 0. \tag{1}$$

According to the literature on remanufacturing, the cost variation associated with a larger level of remanufacturability is mostly due to a reduction in energy and raw material consumptions, and is hence environmentally desirable. Particularly, Steinhilper (1998) shows that on average remanufactured alternators and starters require 14% of the energy and 12% of the material necessary for the production of new ones. Furthermore, lower remanufacturing costs for the OMs denote better use of material and energy. Therefore a social planner showing environmental concerns will manifest preference for products remanufactured by OMs.

2.2 Demand functions

The demand for the component is segmented in two types: the demand for new and for remanufactured products.

The demand for new products m is driven by the final good producers. It is assumed that any variation in the original component price represents a small share of the final good production cost and, hence, the demand for m stays inelastic for a large reasonable range of

While the share of un-remanufacturable cores can exceed 30% for certain products, it is less than 15% for alternators [Kim and al. 2008]. In the present model, this number is assumed to be negligible so that the alternator/vehicle ratio stays equal to 1.

prices (or until a certain choke price). For simplicity, m is normalized to 1.

The demand for remanufactured products comes from consumers needing to replace the defective part. Variables r and s designate the demand for components remanufactured by the OMs and the IRs respectively. The following set-up describes the demand for OMs' remanufactured products which depends on the difference in price and the difference in perceived quality between OMs and IRs' services. Consumers are differentiated with respect to $\theta + x$, their willingness to pay for a new replacement product. People are uniformly distributed over $\theta \in [0, 1]$, variable that also refers to the type of the individual. The constant x indicates that even the individual from the lower bound is willing to pay a positive amount for a replacement product. For each of the b replacement periods, the number of potential consumers is exactly equal to one, the number of final goods on the market.

When remanufacturing used products, OMs provide the properties and warranty of new goods while IRs supply products of lower quality. As a result, consumers will not differentiate original products from the ones remanufactured by the OMs, but they will express lower willingness to pay for IRs' products. More precisely, an individual of type θ has willingness to pay $(1 - \delta)\theta + x$ for IRs' services, where $\delta \in [0, 1]$ reflects the perceived depreciation of lower quality goods compared to new ones. The parameter δ is the same for all individuals. Figure 1 illustrates the willingness to pay for the two differentiated products.

At each period, people maximize their consumer surplus by solving the following problem:

$$\max[\theta + x - p_r, (1 - \delta)\theta + x - p_s, 0],$$

which corresponds to the choice of purchasing a product coming from an OM, an IR or no product at all. The selling price of products remanufactured by OMs and IRs are respectively p_r and p_s. Because the component price represents a small fraction of the final good value, $x \geq p_s$ allows to mimic the inelastic aftermarket and insures that everyone consumes a replacement good; that is: $r + s = 1$.

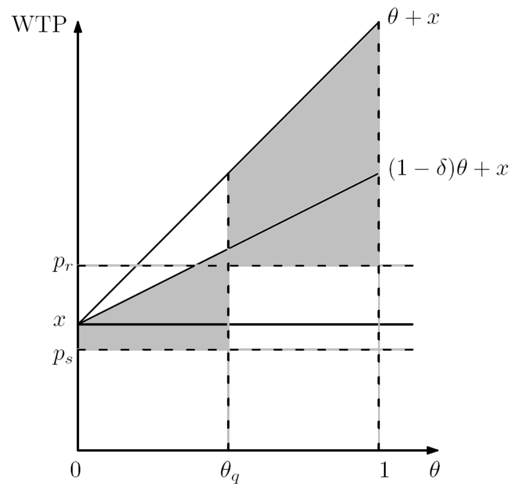

Figure 1: Willingness to pay and consumer surplus

The set of consumers buying remanufactured products from the OMs is defined by θ such that $\theta + x - p_r \geq (1-\delta)\theta + x - p_s$. This condition can be written as:

$$\theta \geq \frac{p_r - p_s}{\delta}$$

In Figure 1, given prices p_r and p_s, individual θ_q is indifferent between the two products, individuals of types $\theta \in [\theta_q, 1]$ prefer OMs' services while the others, $\theta \in [0, \theta_q]$, content themselves with lower quality goods. The shaded area corresponds to the total consumer surplus at each replacement period.

Given uniform distribution for θ, the demand for products remanufactured by the OMs at each period is $r = 1 - (\frac{p_r - p_s}{\delta})$ so that the inverse demand function is:

$$p_r = \delta(1-r) + p_s. \tag{2}$$

For any positive value, parameter δ depicts the alternator industry where the observed OMs' prices are from 25 to 200 percent higher than their competitors' [Kim and al. 2008]. This premium adds an incentive to the OMs, but stays unexplored in Debo and al. (2005) where only IRs participate in the aftermarket.

2.3 Industrial structure

Competition in the industry is described by the following four stage game. In the first stage, the two identical OMs produce the original component and control its level of remanufacturability q. Two different competitive environments will be considered in determining q: a Cournot competition and a collusive game. In the second stage, OMs set the original product's prices and quantities p_{mi} and m_i. They face the threat of an outsider that would seize any profit opportunities originating from the original market but who stays blind on what occurs on the remanufacturing market[7]. In the third stage, OMs compete *à la* Cournot to set quantities r_i on the aftermarket; reflecting the alternator industry, they dispute the profit generated by their price premium. In the final stage, IRs compete perfectly and their remanufactured good's price is established. They are constrained by the engagement to remanufacture all the used products they receive from their suppliers. In other words, they cannot discriminate between products that have different level of remanufacturability.

OMs have perfect knowledge of each other. Their decisions in each stage are taken and applied simultaneously. They also detain perfect information on IRs' behavior.

[7]Two arguments are proposed in order to explain this behaviour. The first one assumes that reputation is an important factor in being considered as an OM and, therefore, new entries cannot compete with OMs on the aftermarket. The second point considers that incumbents face less risk and are more willing to accept delayed profits.

3 The optimization problem

Under the market clearing conditions, $m_1+m_2=1$ and $r_1+r_2=r$. The OMs' profit function depends on both their activities on the primary market and the remanufacturing market:

$$\pi_i = (p_{mi} - c_m(q_i))m_i + \underbrace{\sum_{t=1}^{b} \beta_l^t [(p_r - m_i c_r(q_i) - m_j c_r(q_j))r_i]}_{R_i(r_i, r_j, m_i, m_j, q_i, q_j)} \text{ for } i = 1, 2 \text{ and } j \neq i$$

where $p_r = \delta(1-r) + p_s$ from equation (2) and where $0 < \beta_l < 1$ is the discount factor associated with the length of time l. The first term is the total net profit from the original market while $R_i(r_i, r_j, m_i, m_j, q_i, q_j)$ corresponds to the discounted profit from all the remanufacturing periods. Because used products randomly go to any remanufacturer, the remanufacturing cost depends on the technology selection of each OM and is weighted by their respective participation on the original market.

3.1 Prices and quantities

With backward resolution, the final stage is solved first. IRs are perfectly competitive and the selling price p_s is set at the average unit cost of production:

$$p_s = m_i c_s(q_i) + m_j c_s(q_j). \tag{3}$$

In the third stage, each manufacturer i maximizes its profit on the aftermarket by choosing its supply of remanufactured products r_i, and by taking the supply choice of its opponents r_j (for $j \neq i$) as well as the levels of remanufacturability (q_i, q_j) as given. They also consider

IRs' behavior through equation (3). The OMs maximization problem at this stage is:

$$\begin{aligned} \max_{r_i \geq 0} R_i &= \sum_{t=1}^{b} \beta_l^t [(\delta(1-(r_i+r_j)) + m_i(c_s(q_i) - c_r(q_i)) + m_j(c_s(q_j) - c_r(q_j)))r_i] \\ \text{for } i &= 1,2 \text{ and } j \neq i \end{aligned}$$

and the first order condition is:

$$\frac{\partial R_i}{\partial r_i} = 0 \Longleftrightarrow \sum_{t=1}^{b} \beta_l^t [\delta - \delta r_j - 2\delta r_i + m_i(c_s(q_i) - c_r(q_i)) + m_j(c_s(q_j) - c_r(q_j))] = 0. \quad (4)$$

With the assumption that manufacturers are identical, $r_i = r_j$ and the symmetric Nash equilibrium for the supply of remanufactured products is defined by:

$$r_i^*(m_i, m_j, q_i, q_j) = \frac{\delta + m_i(c_s(q_i) - c_r(q_i)) + m_j(c_s(q_j) - c_r(q_j))}{3\delta}. \quad (5)$$

Here, the role of IRs is mainly figurative while their price is driven by the OMs' choice of remanufacturability (equation 3). Also, they only have a residual participation in the aftermarket; the demand for their products depends on OMs' supply decisions with $s^* = 1 - 2r_i^*$. The choice of $2r_i^*$ also corresponds to OMs' aftermarket share.

The second stage mirrors the alternator industry. The two OMs compete *à la* Bertrand on the primary market where the threat of entry keeps the component price p_m at the minimum production cost; that is:

$$p_{m1} = p_{m2} = c_m(0). \quad (6)$$

Offering a common original price, the market is equally shared among OMs with $m_i = 1/2$. The outsider, by proposing the lowest level of remanufacturability, can deter competitors that would set a higher price. Note that in spite of that restriction, OMs may still optimally choose a positive level of remanufacturability and, consequently, bear deficit on the primary market ($p_m - c_m(q) = c_m(0) - c_m(q) \leq 0$).

Two situations are considered for the determination of q_i and q_j in the first stage. The first case reflects the free-riding problem that occurs when an original component produced by i randomly goes to any remanufacturer. The second case considers the possibility of collusion in the industry where q is the result of an agreement between the OMs. These situations are explicitly formulated in subsections 3.3 and 3.4.

Before solving for the choice of remanufacturability, an important assumption on the technology selection is introduced in the coming subsection.

3.2 Assumption on technology selection

At this step, only the first stage remains and everything depends on the technology selection (q_i, q_j) taken as given. The profit function is:

$$\pi_i^* = (c_m(0) - c_m(q_i))\frac{1}{2} + \underbrace{\sum_{t=1}^{b} \beta_l^t [\delta r_i^*(q_i, q_j)^2]}_{R_i(q_i,q_j)}. \tag{7}$$

where the optimal supply of remanufactured products is reduced to:

$$r_i^*(q_i, q_j) = \frac{\delta + c_s(q_i) - c_r(q_i)}{6\delta} + \frac{\delta + c_s(q_j) - c_r(q_j)}{6\delta} \tag{8}$$

A variation in q affects the profit through two channels: i) the original production cost c_m; ii) the total net revenue of remanufacturing activities $R_i(q_i, q_j)$. OMs know that when selecting the original product technology, their profit depends importantly on their *technological advantage* over the IRs: $c_s(q_i) - c_r(q_i)$. Looking at comparative static:

$$\frac{\partial r_i^*}{\partial q_i} = \frac{c_s'(q_i) - c_r'(q_i)}{6\delta}, \tag{9}$$

which says that OMs' total remanufacturing revenue varies in the same direction as the OMs' advantage when the level of remanufacturability increases.

It is supposed that when OMs comply for small levels of remanufacturability, they have access to a wide choice of different technologies and they shape the original product in order to suit their own facilities or assembly lines. Consequently, for q small enough, OMs endogenously pick a technology where their unit cost decreases more than their competitors'[8]; that is: $c_s'(q) - c_r'(q) \geq 0$. As the original product tends to higher levels of remanufacturability, the choice of technologies lessens and $c_s'(q) - c_r'(q)$ decreases until IRs get the edge with $c_s'(q) - c_r'(q) \leq 0$. This situation occurs for instance when a larger q eliminates disassembly or reassembly steps originally costlier for IRs[9]. Precisely, with $\widehat{q} < \widetilde{q}$, it is assumed that:

$$c_s'(q) - c_r'(q) \begin{cases} \geq 0 \text{ for } q \text{ small} \\ = 0 \text{ for } q = \widehat{q} \\ \leq 0 \text{ for } q \text{ large} \end{cases} \quad \text{and} \quad c_s''(q) - c_r''(q) \begin{cases} < 0 \text{ for } q \text{ small} \\ = 0 \text{ for } q = \widetilde{q} \\ > 0 \text{ for } q \text{ large} \end{cases} \tag{10}$$

3.3 The competitive case

Each manufacturer i maximizes its profits by choosing the level of remanufacturability q_i taking the technology choice of the others q_j $(\forall j \neq i)$ as given and considering the optimal supply of remanufactured products $r_i^*(q_i, q_j)$. Used products are randomly dispatched among remanufacturers (both OMs and IRs) and, therefore, the technology selection of i is subject to free-riding. The share of products that carry the technology choice of i is $1/2$ and, hence, influences only $1/2$ of the remanufacturing cost functions while the rest is the result of q_j.

[8] This may also be related to some industrial strategies. For instance, in the toner cartridge industry, some firms have added an electronic key in their remanufacturable cartridges that must be reset by the OM. This leads to an increase in the relative remanufacturing cost of IRs [Majumder and Groenevelt 2001].

[9] By the mean value theorem, $c_s'(q) - c_r'(q) \leq 0$, for at least some q, is an essential condition for the respect of equation (1).

The maximization problem becomes:

$$\max_{q_i \geq 0} \pi_i^* = (c_m(0) - c_m(q_i))\frac{1}{2} + \sum_{t=1}^{b} \beta_l^t \left[\delta r_i^*(q_i, q_j)^2\right]$$
$$\text{s.t. } r_i^*(q_i, q_j) = \frac{\delta + c_s(q_i) - c_r(q_i)}{6\delta} + \frac{(\delta + c_s(q_j) - c_r(q_j))}{6\delta},$$

and the first order condition is:

$$\frac{\partial \pi_i^*}{\partial q_i} = 0 \Longleftrightarrow -\frac{c_m'(q_i)}{2} + \sum_{t=1}^{b} \beta_l^t \left[\frac{2\delta(c_s'(q_i) - c_r'(q_i))}{6\delta} r_i^*(q_i, q_j)\right] = 0$$

where the marginal cost of a higher level of remanufacturability is equal to the marginal revenue generated by it when choices of others are taken as fixed. With the assumption that manufacturers are identical, $q_i = q_j = q_{fr}$ where the subscript fr stands for the free-riding case. The symmetric Nash equilibrium q_{fr}^* is defined by:

$$-c_m'(q_{fr}^*) + \underbrace{\sum_{t=1}^{b} \beta_l^t \left[\frac{2(c_s'(q_{fr}^*) - c_r'(q_{fr}^*))}{3} r_i^*(q_{fr}^*)\right]}_{R'(q_{fr}^*)} = 0. \tag{11}$$

In presence of a corner solution ($q_{fr}^* = 0$), the component m is not remanufacturable. In this case, $r_i^*(0)$ corresponds to the supply of new goods destined to the aftermarket while IRs offer repairing and not remanufacturing services. Also, the production cost equals the one that prevails on the original good market: $c_r(0) = c_m(0)$.

3.4 When consensus on q is tolerated

Although an agreement on the level of remanufacturability could be interpreted as a cartel strategy, this could be tolerated by governments seeking environmental objectives without the application of environmental regulations. While it is previous to tell that this kind of consensus exist, the industry offers poles where manufacturers and remanufacturers can meet[10].

Knowing that the optimal supply of remanufactured products depends on a unique level of remanufacturability, $r_i^*(q_i, q_j) = r_i^*(q)$ and OMs internalize the free-riding behavior by choosing the level of remanufacturability q_c^* that maximizes one of the identical individual profit functions. The subscript c refers to the consensual optimum.

$$\max_{q \geq 0} \pi_i^* = (c_m(0) - c_m(q))\frac{1}{2} + \sum_{t=1}^{b} \beta_l^t [\delta r_i^*(q)^2] \tag{12}$$
$$\text{s.t. } r_i^*(q) = \frac{\delta + c_s(q) - c_r(q)}{3\delta}.$$

The first order conditions is:

$$\frac{\partial \pi_i^*}{\partial q} = 0 \Longleftrightarrow -\frac{c_m'(q_c^*)}{2} + \underbrace{\sum_{t=1}^{b} \beta_l^t \left[\frac{2(c_s'(q_c^*) - c_r'(q_c^*))}{3} r_i^*(q_c^*) \right]}_{R'(q_c^*)} = 0. \tag{13}$$

Result 1 *Private agreement on the level of remanufacturability leads to a higher level of remanufacturability, larger remanufacturing activities and higher profits:*

$$q_{fr}^* \leq q_c^*, \;\; r_i^*(q_{fr}^*) \leq r_i^*(q_c^*) \;\; and \;\; \pi_i^*(q_{fr}^*) \leq \pi_i^*(q_c^*).$$

Proof: The optimal choice of q_{fr}^* and q_c^* are determined by equations (11) and (13). In case of collusion, the free-riding solution, q_{fr}^*, is not optimal and $-c_m'(q_{fr}^*)/2 + R'(q_{fr}^*) \geq 0$. From the second order condition, it is known that the marginal cost grows faster than the marginal revenue: $-c_m''(q)/2 + R''(q) \leq 0$. Therefore, an increase from q_{fr}^* to q_c^* is required to respect the optimal condition (13). This leads to the conclusion that, indeed, the level of

[10] For instance the international Automotive Parts Remanufacturers Association (see http://apra.org/) or the United States Council for Automotive Research (see www.uscar.org).

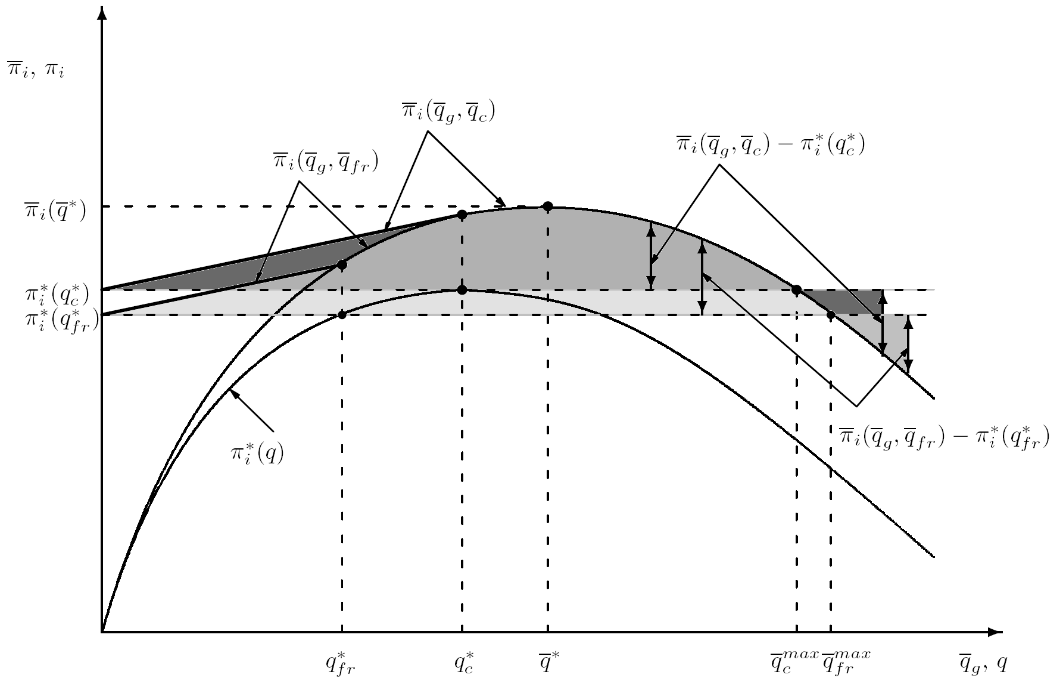

Figure 2: Profit with and without regulation

remanufacturability q_{fr}^* is suboptimal with $q_{fr}^* \leq q_c^*$. Both q_{fr}^* and q_c^* are in a neighborhood where $R'(q) > 0 \iff (c_s'(q) - c_r'(q)) > 0$. Hence, from equation (9), $r_i^*(q_{fr}^*) \leq r_i^*(q_c^*)$. Finally, $\pi_i^*(q_{fr}^*) \leq \pi_i^*(q_c^*)$ because the externality is internalized.

Figure 2 illustrates $\pi_i^*(q)$ (the lower curve) and shows $q_{fr}^* \leq q_c^*$ as well as $\pi_i^*(q_{fr}^*) \leq \pi_i^*(q_c^*)$. *Result 1* suggests that tolerating industrial "environmental" agreements could be substitute to the application of environmental regulations when a higher level of remanufacturability is socially desirable. However, all the costs associated with remanufacturability are supported by the firms while social benefits are not considered in the decision process. Therefore, public interventions stay necessary for a technology selection socially optimal.

4 Environmental regulation

In this economy, the government may decide to introduce an environmental regulation which establishes a minimum level of remanufacturability, denoted by $\overline{q}_g$. Alternatively, $\overline{q}_g$ can also be reached indirectly through the imposition of other environmental regulations. Asbestos ban in the alternator industry is an example.

4.1 Public intervention

With the public intervention, the four stages stay the same but face a more stringent technological constraint: $q \geq \overline{q}_g$. Because this regulation applies also on the eventual competitor, the minimum production cost increases at $c_m(\overline{q}_g)$ and the second stage equilibrium leads to an increased original component's price:

$$p_{m1} = p_{m2} = c_m(\overline{q}_g).$$

Hence, the profit function becomes:

$$\overline{\pi}_i(\overline{q}_g, \overline{q}_k) = (c_m(\overline{q}_g) - c_m(\overline{q}_k))\frac{1}{2} + \sum_{t=1}^{b} \beta_l^t \left[\delta r_i^*(\overline{q}_k)^2\right] \tag{14}$$

where $\overline{\pi}$ and $\overline{q}_k$ designate the profit and the optimal level of remanufacturability under environmental regulations. With $k \in (fr, c)$, equation (14) stands for either the free-riding or the collusive case and respects the equilibrium condition which stays equation (11) or (13).

Considering that the regulation can be laxer than voluntary remanufacturing activities, the applied level of remanufacturability and the difference in profits before and after regulation are:

$$\overline{q}_k = \begin{cases} q_k^* \text{ if } q_k^* \geq \overline{q}_g \\ \overline{q}_g \text{ if } q_k^* \leq \overline{q}_g \end{cases} \quad (15)$$

$$\overline{\pi}_i(\overline{q}_g, \overline{q}_k) - \pi_i^*(q_k^*) = \begin{cases} \frac{(c_m(\overline{q}_g) - c_m(0))}{2} \text{ if } q_k^* \geq \overline{q}_g \\ \frac{(c_m(q_k^*) - c_m(0))}{2} + \sum_{t=1}^{b} \beta_l^t [\delta(r_i^*(\overline{q}_g)^2 - r_i^*(q_k^*)^2)] \text{ if } q_k^* \leq \overline{q}_g \end{cases} \quad (16)$$

Figure (2) shows how profits vary with the imposition of a regulation. The difference between the curves $\overline{\pi}_i(\overline{q}_g, q_k^*)$ and the horizontal lines $\pi_i^*(q_k^*)$ describes the difference in profits due to different levels of regulation. The light and medium shade area shows the free-riding case while the medium and dark shade area exhibits the consensus case. When the public intervention is laxer than industrial initiatives ($\overline{q}_k = q_k^* \geq \overline{q}_g$), the applied level of remanufacturability stays unchanged, but the firm's profit increases by $(c_m(\overline{q}_g) - c_m(0))/2$ due to the higher original product price. In the case where the level of remanufacturability is constrained by the regulation ($\overline{q}_k = \overline{q}_g > q_k^*$), OMs make no deficit anymore on the primary market where price and cost are now equal. This shifts up profits by $(c_m(q_k^*) - c_m(0))/2$. Also, a higher level of remanufacturability affects OMs' aftermarket share and consequently the total remanufacturing revenue (equations (9) and (10)). As long as the OMs gain technological advantage, $c_s'(q) - c_r'(q) \geq 0$, their profits increase. When $c_s'(q) - c_r'(q) \leq 0$, the technological gap lessens and OMs see their aftermarket share reduced. Thereafter, the profit under regulation decreases until it reaches the initial firm's profit $\pi_i^*(q_k^*)$ at $\overline{q}_g = \overline{q}_k^{\max}$. Above this threshold, regulation engenders net costs for the OMs.

Result 2 *Environmental regulations can be complementary to industrial performances for both the free-riding and the consensus cases:*

$$\overline{\pi}_i(\overline{q}_g, \overline{q}_k) - \pi_i^*(q_k^*) \geq 0 \Longleftrightarrow \overline{q}_g \leq \overline{q}_k^{\max}.$$

In particular, this remains true when the environmental regulation constrains a minimum level of remanufacturability:

$$\overline{\pi}_i(\overline{q}_g, \overline{q}_k) - \pi_i^*(q_k^*) \geq 0 \Longleftrightarrow q_k^* \leq \overline{q}_g \leq \overline{q}_k^{\max}$$

This result coincides with the Porter Hypothesis which says that profits may increase in the industry with the application of environmental regulations. Here, this phenomenon is driven by the fact that regulation shifts the cost of remanufacturability towards final good producers and consumers through an increase in the original component price. Externality on the technology selection is not a necessary condition in confirming the Porter Hypothesis which is rather the result of competition on the original market. The present model corroborates the argument of Ambec and Barla (2007) saying that the Porter Hypothesis requires the presence of at least one market imperfection beside the environmental externality.

Furthermore, this result explains how the threat of entry on the original alternator market had prevented OMs to engage remanufacturing initiatives and how regulation on asbestos was welcome by the industry.

Considering that firms can adopt cooperative or adverse behaviors regarding a new regulation, the difference in profits before and after (equation (16)) can be interpreted as the intensity of cooperation to the regulation by the industry. This leads to the following results:

Result 3 *It is always easier to introduce an environmental regulation $\overline{q}_g$ when the technology is initially subject to free-riding:*

$$\overline{\pi}_i(\overline{q}_g, q_{fr}^*) - \pi_i^*(q_{fr}^*) \geq \overline{\pi}_i(\overline{q}_g, q_c^*) - \pi_i^*(q_c^*)$$

Result 4 *The maximal level of regulation positively supported by the industry is larger when* *the technology is initially subject to free-riding:*

$$\overline{q}_c^{\max} < \overline{q}_{fr}^{\max}.$$

4.2 Intervention privately optimal

Let introduce $\overline{q}^*$, the optimal regulation that would be chosen by the OMs. With $p_{m1} = p_{m2} = c_m(\overline{q}_g)$, the maximization problem is:

$$\max_{\overline{q}_g \geq 0} \overline{\pi}_i = \sum_{t=1}^{b} \beta_l^t [\delta r_i^*(\overline{q}_k)^2]$$
$$\text{s.t. } r_i^*(\overline{q}_k) = \frac{\delta + c_s(\overline{q}_k) - c_r(\overline{q}_k)}{3\delta} \text{ and (15).}$$

The optimal condition is:

$$\frac{\partial \overline{\pi}_i}{\partial q} = 0 \Longleftrightarrow c_s'(\overline{q}^*) - c_r'(\overline{q}^*) = 0. \tag{17}$$

Figure 2 displays $\overline{q}^*$ and $\overline{\pi}_i(\overline{q}^*)$, the regulation privately optimal and the corresponding profit. Comparing the optimal conditions for the determination of $\overline{q}^*$, q_c^* and q_{fr}^* leads to the following results:

Result 5 *The regulation preferred by the private sector leads to a level of remanufacturability above the one chosen in absence of regulation:*

$$\overline{q}^* \geq q_c^* \geq q_{fr}^*$$

Proof: From Result 1, it is already known that $q_c^* \geq q_{fr}^*$. The optimal conditions (11) and (13) for the choice of q in absence of environmental regulation imply a positive value of $(c_s'(q) - c_r'(q))$. Because $c_s''(q) - c_r''(q) < 0$ in this neighborhood (equation (10)), it is straightforward to see that the condition leading to the private optimal choice of regulation (17) results in $\overline{q}^* \geq q_c^* \geq q_{fr}^*$.

Result 6 *The size of remanufacturing activities (for the OMs) are maximized if and only if the public sector fixes the regulation at the level preferred by the OMs:*

$$\frac{\partial r_i^*}{\partial q} = \frac{(c_s'(q) - c_r'(q))}{3\delta} = 0 \Longleftrightarrow \overline{q}_g = \overline{q}^*$$

When OMs' remanufacturing activities pollutes significantly less than IRs', the social planer may want to maximize the OMs' aftermarket share to the detriment of higher remanufacturability.

One of the main characteristics of the market free of regulation is that OMs, subject to Bertrand competition on the primary market, cannot pass the information through prices that a product is remanufacturable. The competitive final good producers do not benefit from remanufacturability and see no incentive in raising production costs. Therefore, the selling price stays $p_m = c_m(0)$. When the regulation takes place, the selling price p_m carries the information up to the point justified by the public intervention ($p_m = c_m(\overline{q}_g)$). When the regulation is selected by the private sector, OMs take into account that the entire production cost is covered by the selling price. Therefore, they can seize the maximal aftermarket share by costlessly choosing the level of remanufacturability leading to their largest technological advantage. When $\overline{q}_g = \overline{q}^*$, OMs's profits are maximized as well as their aftermarket size.

5 Discussion

This paper exposes a theoretical model of an industry composed of original manufacturers, a final good producer and independent remanufacturers. In the first period, original manufacturers produce a component as an input for the final good where competition *à la* Bertrand

and the threat of an outsider keep the input's price at the minimum production cost. At the same time, they select the technology determining the level of remanufacturability of their products. In the following periods, consumers of the final good have to replace the specific component and consider remanufactured products. Independent remanufacturers enter the market, but because of asymmetric informations, original manufacturers offer higher quality good and benefit from a price premium. In this set-up, used products can be remanufactured by any firms and original manufacturers suffer from free-riding on their technology selection, what discourages investment in remanufacturability. Alternatively, the externality can be eliminated if original manufacturers collude on the level of remanufacturability.

Remanufacturing socially benefits to the population through less post-consumption waste, lower energy and raw material consumptions, and lower general prices for replacement products. It also benefits to the industry through the generation of positive profits. While the gains of a higher level of remanufacturability are shared among the society, the costs of remanufacturing-oriented technology of production are bore solely by the original manufacturers. Consequently, the selected level of remanufacturability remains too low in absence of public regulations.

The introduction of an environmental regulation, which imposes a minimal level of remanufacturability, justifies a price increase on the primary market. As a consequence, the costs of complying with the regulation are redirected towards final good producers and consumers. Hence, original manufacturers can see their profits increase. This observation corroborate the Porter Hypothesis.

A social planner who wants to stimulate remanufacturing activities can consider private collusion as an alternative to environmental regulation since it leads to a higher level of remanufacturability and, indirectly, to a larger supply of high quality remanufactured products. However, the social optimum can only be achieved through the application of an environmental regulation. If the social planner opts for this option, it should repress private collusions. When the variation in profits following the public intervention is interpreted as the industrial degree of cooperation with the regulation, original manufacturers will always offer stronger support, or lower opposition, when the technology choice is initially subject to free-riding.

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