CAHIER DE RECHERCHE ♯1003E
Département de science économique
Faculté des sciences sociales
Université d'Ottawa

WORKING PAPER ♯1003E
Department of Economics
Faculty of Social Sciences
University of Ottawa

Remanufacturing*

Sophie Bernard†

February 2010

* Acknowledgements: Research supported by the FQRSC (Fonds québécois de recherche sur la société et la culture). Special thanks to Louis Hotte, Stan Winer, Joan Canton, Stefan Ambec, seminar participants at Paris 1 Pantheon-Sorbonne, University of Ottawa and CREE 2009.
† Department of Economics, University of Ottawa, 55 Laurier E., Ottawa, Ontario, Canada, K1N 6N5; Email: sophiebernard_eco@yahoo.ca.

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.

This paper presents a theoretical model of remanufacturing where a duopoly of original manufacturers produce a component of a final good. The component needing to be replaced creates an aftermarket. An environmental regulation assessing a minimum level of remanufacturability is also introduced.

The main results indicate that a social planner could use collusion of the firms on the level of remanufacturability as a substitute for environmental regulation. However, if an environmental regulation is to be implemented, collusion should be repressed since competition supports the public intervention better. One of the results also coincides with the Porter Hypothesis.

Key words: *remanufacturing, competition, environmental regulation, Porter Hypothesis.*

JEL Classification: H23, L10, L51, Q53, Q58.

Résumé

Le remanufacturing est une forme de recyclage où des biens durables usagés sont remis à neuf. Tout en consommant moins d'énergie et de ressource, les biens remanufacturés sont produits à une fraction du coût original et émettent moins de pollution.

Ce papier présente un model théorique de remanufacturing où un duopole de manufacturiers originaux produisent un composant d'un bien final. Ce composant devant être changé, un marché secondaire est créé. Une réglementation environnementale déterminant un niveau minimal de remanufacturabilité est introduite au modèle.

Les principaux résultats indiquent qu'un planificateur social pourrait substituer la réglementation environnementale par la collusion des firmes sur le niveau de remanufacturabilité. Cependant, lorsqu'une réglementation environnementale est prévue, la collusion devrait être réprimée puisque la compétition s'accorde mieux avec une intervention publique. Un des résultats coïncide aussi avec l'hypothèse de Porter.

Mots clés: *remanufacturing, compétition, réglementation environnementale, hypothèse de Porter.*

Classification JEL: H23, L10, L51, Q53, Q58.

1 Introduction

Remanufacturing is a specific type of recycling in which used durable goods are repaired to a like-new condition. 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. Because the environmental benefits of such designs are not totally internalized, choices of production technology are suboptimal. Authors propose different public interventions for optimal recyclable technology. Take-back regulations, consumption and production taxes, subsidies to green designs as well as subsidies to the demand for recyclable material input create strong incentives for the development of recyclable goods [Fullerton and Wu 1998; Eichner and Pethig 2001; Eichner and Runkel 2005; Toffel *et al.* 2008]. 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 contents 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 requires products to have a reusable or recyclable content of 65 percent[1].

Although existing governmental regulations are not specifically directed towards remanufacturing, it seems that similarities between recycling and remanufacturing are such that their corresponding public interventions use comparable mechanics. Webster and Mitra

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

(2007) and Mitra and 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.

After a product's first life, recycled material can be redirected towards any industry. On the contrary, the material going through the remanufacturing process goes back to the same industry. Then, remanufacturing-oriented designs permit the *original manufacturers* (OMs) to access the aftermarket's benefits. Indeed, while remanufactured products are sold at 60 to 70 percent of the new products' price, their production accounts 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 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 60-100 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 are 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 *et al.* 2008]. Valeo and Bosch are two important alternator producers in Europe. They started remanufacturing activities in the early 90's, following the announcement of legislation prohibiting the production, sale and use of asbestos[3]: a technological constraint that has made alternator

[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 enacted in 1993 in Germany and in 1997 in France, the respective headquarters of

remanufacturing commercially viable.

A study by Debo *et al.* (2005) analyzes the technology selection for remanufacturable goods when a higher remanufacturability may invite entry by *independent remanufacturers* (IRs)[4]. Stronger competition on the remanufacturing market pulls down prices and OMs show lower interest in costly production technology. Therefore, governmental interventions promoting competition on the aftermarket negatively influence the level of remanufacturability. This corroborates the observation of Ferrer (2000) who says that remanufacturing is viable only if the remanufactured product is priced above its marginal cost.

Studies that observe 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 *et al.* (2005) and framed on the particularities that characterize the alternator industry. A duopoly of OMs compete on the primary market where they face the threat of an outsider; they also compete 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 from their production in order to launch profitable remanufacturing activities.

The main results show that in the absence of environmental regulation, collusion leads to

---

Bosch and Valeo, with the European Union following suit in 1999 [European Commission 1999].

[4]Since 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 *et al.* (2005) and Majumder and Groenevelt (2001). In a different context, Heese *et 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.

a higher level of remanufacturability as well as higher profits in the industry. However, the introduction of environmental regulations imposing a minimum level of remanufacturability can be beneficial to firms. In the absence of public intervention, the threat of entry on the primary market imposes support for all the costs of remanufacturing-oriented technologies on the OMs, while environmental benefits are shared by all. Consequently, OMs can gain additional profits when the regulation justifies a raise in the original product price that covers the cost of remanufacturability. This result is in line with the Porter Hypothesis stating that environmental regulations may increase profits in regulated industries.

The model is introduced in the next section, which sets technologies, demands and the industrial structure. Section 3 completes the assumption on technology and describes the optimization problem for two cases: non-cooperation and collusion. Section 4 observes the effect of an environmental regulation. Section 5 concludes.

2 The Model

A duopoly[6] of 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. Since the same car goes through two or three alternators [Kim *et al.* 2008], the lifetimes of the alternator and the vehicle are 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, at any moment, there are an equal number of cars and alternators on the market.

When they originally produce a remanufacturable component, OMs participate in the aftermarket by recovering and remanufacturing used products. On this market, however,

[6] A duopoly is assumed for simplicity.

they face competition from independent remanufacturers (IRs).

2.1 Technology and pollution

OMs control their level of remanufacturability q_i, $i \in \{1, 2\}$, a technology choice corresponding to the ease with which a used product can be remanufactured[7] and leading to decreasing unit remanufacturing costs $c_r(q_i)$ and $c_s(q_i)$, for OMs and IRs respectively. However, IRs hold only partial information on the original product conception and hence, for any given q, they meet larger remanufacturing costs than OMs. This *technological advantage* for OMs over the IRs is represented by the following properties:

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

To make the original product more remanufacturable, OMs bear additional production costs reflected by an increasing and non-concave initial manufacturing cost, $c_m(q_i)$.

The remanufacturing cost reduction associated with a larger level of remanufacturability is mostly due to a reduction in energy and raw material consumption; hence it is environmentally desirable. In particular, 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 (equation (1)) can denote better use of material and energy. Therefore a social planner showing environmental concerns may manifest a preference for products remanufactured by OMs.

2.2 Demand functions

[7] In most models [see for instance Debo *et al.* 2005; Majumder and Groenevelt 2001; Ferrer and Swaminathan 2006] the level of remanufacturability is the percentage of remanufacturable used products. While the share of un-remanufacturable cores can exceed 30% for certain products, it is less than 15% for alternators [Kim *et al.* 2008]. In the present model, this number is assumed to be negligible so that the alternator/vehicle ratio stays equal to 1.

The demand for the component is segmented into two types: the demands 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 reasonably large range of prices (or until a certain choke price). Except for great demand elasticities, this assumption does not affect the results, but lightens the model. For simplicity, m is normalized to 1.

The demand for remanufactured products comes from consumers who need to replace the defective part at each of the b replacement periods. Consumer types are uniformly distributed over $\theta \in [0, 1]$, where θ is the marginal willingness to pay for quality. 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 express lower willingness to pay for IRs' products. The parameter $\delta \in [0, 1]$ reflects this perceived depreciation in quality.

At each replacement period, individuals maximize their consumer surplus by purchasing a product coming from an OM, an IR or no product at all. This maximization problem is given by: $\max[\theta + \alpha - p_r, (1-\delta)\theta + \alpha - p_s, 0]$, where p_r and p_s are respectively the selling price of OMs and IRs' products. The positive constant α indicates that even individuals from the lower bound are willing to pay a positive amount. Because the component price represents a small fraction of the final good's value, $\alpha \geq p_s$ mimics the inelastic aftermarket and ensures that everyone consumes a replacement good; that is, $r + s = 1$, where variables r and s designate the demand for components remanufactured by the OMs and the IRs respectively. Figure 1 illustrates the willingness to pay for the two differentiated products.

The set of consumers buying remanufactured products from the OMs is defined by θ such that $\theta + \alpha - p_r \geq (1 - \delta)\theta + \alpha - p_s$, or equivalently: $\theta \geq (p_r - p_s)/\delta$. In Figure 1, given prices p_r and p_s, individual θ_q is indifferent between the two products. Types $\theta \in [\theta_q, 1]$ prefer OMs' services while the others, $\theta \in [0, \theta_q]$, purchase lower quality goods. The shaded area corresponds to the total consumer surplus at each replacement period.

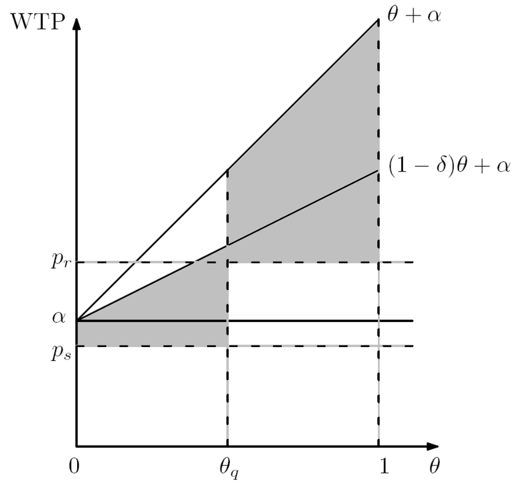

Figure 1: Willingness to pay and consumer surplus

Given a 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 of the parameter δ, this depicts the remanufactured alternator industry where the observed OMs' prices are from 25 to 200 percent higher than their competitors' [Kim *et al.* 2008]. This premium adds an incentive to the OMs that stays unexplored in the literature.

2.3 Industrial structure

Competition in the industry is described by the following four-stage game. In the first stage, two identical OMs produce the original component and control its level of remanufacturability q_i. Two different competitive environments will be considered in determining q_i: non-cooperation and collusion. These scenarios internalize, or not, the fact that firms can free-ride on each other's technology selection q_i.

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[8]. This threat forces price competition between OMs, reflecting the automotive industry: original components being perfectly substitutable, vehicle manufacturers can switch from one supplier to the other as soon as a lower price is offered.

The third and fourth stages occur on the aftermarket. Although this market is shared with IRs, OMs hold an oligopolistic power on high quality products. In the third stage, OMs compete by choosing quantities r_i. In the final stage, IRs compete perfectly and their remanufactured good's price is established.

Because of the inelastic aftermarket size, it is assumed that OMs and IRs cannot discriminate between products that have different levels of remanufacturability (everything has to be remanufactured).

OMs have perfect knowledge of each other. Their decisions in each stage are made and applied simultaneously. They also have perfect information about IRs' characteristics. Since OMs are identical, a symmetric subgame-perfect equilibrium in pure strategies in the four-stage game is computed.

[8] 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 entrants cannot benefit from a price premium 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 $0 < \beta_l < 1$ is the discount factor associated with the length of time l. The first term is the 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 weighed by their respective participation in the original market.

3.1 Prices and quantities

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

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

In the third stage, OM 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 as well as the levels of remanufacturability (q_i, q_j) as given. It also considers IRs' behavior through equation (3). The OMs maximization problem at this stage is:

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

and the first-order condition is:

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

The symmetric Nash equilibrium for the supply of remanufactured products is defined by:

$$r_i^*(m_i, m_j, q_i, q_j) = \frac{\delta + m_i(c_s(q_i)-c_r(q_i)) + m_j(c_s(q_j)-c_r(q_j))}{3\delta} \text{ for } i=1,2 \text{ and } j \neq i \quad (5)$$

and the second-order condition for an interior maximum is respected when evaluated at the symmetric equilibrium r_i^*.

Here, IRs play a passive role since 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 $s^* = 1 - 2r_i^*$. Note that the choice of $2r_i^*$ also corresponds to OMs' aftermarket share.

In the second stage, the two OMs compete on the primary market where free-entry of the outsider keeps the component price p_{mi} at the minimum production cost; that is,

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

By offering a common original price, OMs share this market equally with $m_i = 1/2$. If a higher price is set, the outsider, by proposing the lowest level of remanufacturability, can make a strictly positive profit and deter competitors. 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 ($p_{mi} - c_m(q_i) = c_m(0) - c_m(q_i) \leq 0$).

Two situations are considered for the determination of q_i and q_j in the first stage. The first case reflects the non-cooperative problem that occurs when an OM remanufactures used products from random origin and free-ride on the technology selection of the other. The second case considers the possibility 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 the technology selection

At this step, only the first stage equilibrium remains to be solved and everything thereafter 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 (equation (5)) is reduced to:

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

when the individual market share in equilibrium, $m_i = 1/2$, is taken into account.

A variation in q affects the profit through two channels: i) the original production cost $c_m(q_i)$; and ii) the total net revenue of remanufacturing activities $R_i(q_i, q_j)$. Since OMs are identical, the analysis will focus on symmetric equilibria $q_i = q_j = q$. OMs know that, for any given q, their profit depends substantially on their technological advantage: $c_s(q) - c_r(q)$.

The comparative static

$$\frac{\partial r_i^*}{\partial q} = \frac{c_s'(q) - c_r'(q)}{3\delta} \tag{9}$$

indicates that, with an increasing technological advantage, a higher level of remanufacturability leads to a larger aftermarket share and, consequently, higher remanufacturing revenues.

The following assumption completes the description of the technological advantage introduced in section 2.1. It is assumed that for small levels of remanufacturability, OMs 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 small enough q, OMs pick a technology for which their unit remanufacturing cost decreases more than their competitors'[9]; that is: $c_s'(q) - c_r'(q) > 0$. As the level of remanufacturability goes higher, the range of technology choices 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 that were originally costlier for IRs[10]. Formally, with $\widehat{q} < \widetilde{q}$, the technological advantage is described by equation (1) and:

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

Variation of the technological advantage with the level of remanufacturability is illustrated in Figure 2.

[9] 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].

[10] 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).

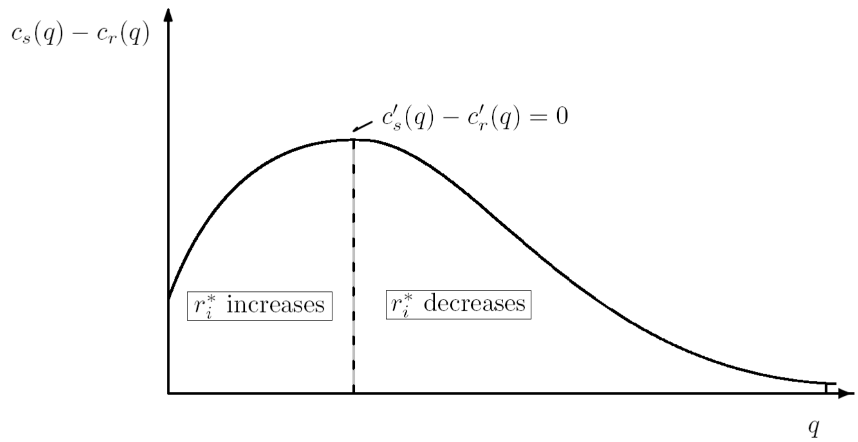

Figure 2: Technological advantage

3.3 The non-cooperative case

Each manufacturer i maximizes its profits by choosing the level of remanufacturability q_i, taking the technology choice of the other q_j 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 maximization problem is:

$$\max_{q_i \geq 0} \pi_i^* = (c_m(0) - c_m(q_i))\frac{1}{2} + \sum_{t=1}^{b} \beta_l^t \left[\delta r_i^*(q_i, q_j)^2\right] \text{ for } i = 1, 2 \text{ and } j \neq i$$

$$\text{s.t. } r_i^*(q_i, q_j) = \frac{\delta + c_s(q_i) - c_r(q_i)}{6\delta} + \frac{(\delta + c_s(q_j) - c_r(q_j))}{6\delta},$$

and the first-order condition is:

$$\begin{aligned} \frac{\partial \pi_i^*}{\partial q_i} &= 0 \Longleftrightarrow -\frac{c'_m(q_i)}{2} + \sum_{t=1}^{b} \beta_l^t \left[\frac{2\delta(c'_s(q_i) - c'_r(q_i))}{6\delta} r_i^*(q_i, q_j)\right] = 0 \\ & \text{for } i = 1, 2 \text{ and } j \neq i \end{aligned}$$

where the marginal cost of a higher level of remanufacturability is equal to the marginal revenue generated when the choice of the other is taken as fixed. The symmetric Nash equilibrium q^*_{nc} is defined by:

$$-c'_m(q^*_{nc}) + \underbrace{\sum_{t=1}^{b} \beta_l^t \left[\frac{2(c'_s(q^*_{nc}) - c'_r(q^*_{nc}))}{3} r^*_i(q^*_{nc})\right]}_{R'(q^*_{nc})} = 0 \qquad (11)$$

where the subscript nc stands for the non-cooperative case. It is assumed that the second-order condition for an interior maximum is respected when evaluated at the symmetric equilibrium q^*_{nc}[11]. In presence of a corner solution $q^*_{nc} = 0$, the component is not remanufacturable.

A positive q^*_{nc} denotes *voluntary* remanufacturing activities in the industry.

3.4 When collusion on q is tolerated

In this scenario, OMs agree on a unique level of remanufacturability $q_i = q_j = q_c$, where the subscript c refers to the collusive case. OMs internalize each other's free-riding behaviour by choosing the level of remanufacturability q^*_c that maximizes joint profit (however they still suffer from IRs' free-riding activities), which becomes:

$$\max_{q \geq 0} \pi^*_1 + \pi^*_2 = (c_m(0) - c_m(q_c)) + 2\sum_{t=1}^{b} \beta_l^t [\delta r^*_i(q_c)^2] \qquad (12)$$

$$\text{s.t. } r^*_i(q_c) = \frac{\delta + c_s(q_c) - c_r(q_c)}{3\delta}.$$

[11] The second-order condition is $-c''_m(q^*_{nc}) + R''(q^*_{nc})$. For any given q, $R''(q) = \sum_{t=1}^{b} \beta_l^t \left[\frac{2}{3}\left(\frac{(c''_s(q) - c''_r(q))}{3} r^*_i(q) + \frac{(c'_s(q) - c'_r(q))^2}{3\delta}\right)\right]$. From the specifications of equation (10), the condition is satisfied in a large neighbourhood of $q = \widehat{q}$. Note that if $c''_s(q) - c''_r(q)$ is monotonically increasing for $q < \widetilde{q}$, then when a maximum exists, it is included in the neighbourhood of $q = \widehat{q}$ and it is unique.

The first-order conditions is:

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

and it is assumed that the second-order condition for an interior maximum is respected when evaluated at q_c^*[12].

Proposition 1 *Collusion on the level of remanufacturability leads to a higher level of remanufacturability, larger OMs' remanufacturing activities and higher profits:*

$$q_{nc}^* < q_c^*,\ r_i^*(q_{nc}^*) < r_i^*(q_c^*) \text{ and } \pi_i^*(q_{nc}^*) < \pi_i^*(q_c^*).$$

Proof: The optimal choice of q_{nc}^* and q_c^* are determined by equations (11) and (13). From the second-order condition, $-c_m''(q)/2 + R''(q) \leq 0$. Therefore, $q_{nc}^* < q_c^*$. Both q_{nc}^* and q_c^* are in a neighbourhood where $R'(q) > 0 \Longleftrightarrow (c_s'(q) - c_r'(q)) > 0$. Hence, from equation (9), $r_i^*(q_{nc}^*) < r_i^*(q_c^*)$. Finally, $\pi_i^*(q_{nc}^*) < \pi_i^*(q_c^*)$ because the externality is internalized.

Figure 3 illustrates $\pi_i^*(q)$ (the lower curve) and shows $q_{nc}^* < q_c^*$ as well as $\pi_i^*(q_{nc}^*) < \pi_i^*(q_c^*)$. *Proposition 1* suggests that a government seeking environmental objectives without public intervention could tolerate industrial agreements on the level of remanufacturability as a partial substitute to environmental regulations; although this could be interpreted as a cartel strategy. These agreements could take place within manufacturers and remanufacturers associations like the international Automotive Parts Remanufacturers Association or the United States Council for Automotive Research[13].

In this scenario however, firms' private benefits still omit the environmental benefits. Therefore public intervention remains necessary for a socially optimal technology selection.

[12] The second-order condition is $-c_m''(q_c^*)/2 + R''(q_c^*)$. See footnote 11 for details.
[13] See http://apra.org/ and www.uscar.org.

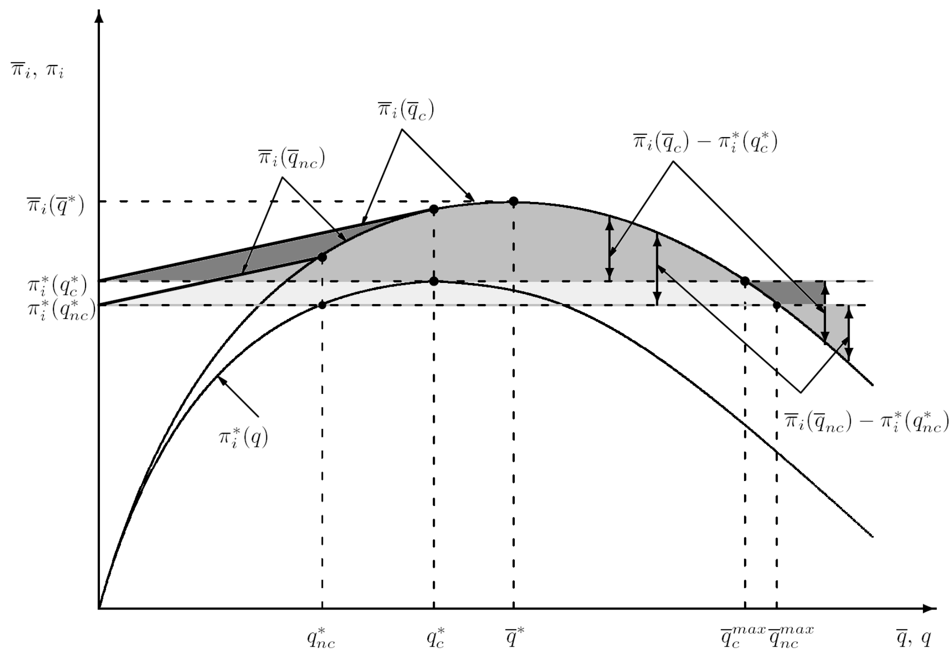

Figure 3: Profit with and without regulation

4 Environmental regulation

In this economy, the government may decide to introduce an environmental regulation which establishes a minimum level of remanufacturability, denoted by $\overline{q}$.

Here, the objective is not to solve for the social planner's problem, but to observe how the industry would react in case of an environmental regulation. In particular, the analysis shows under which conditions the OMs go along with the regulation or resist compliance with it.

4.1 Public intervention

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

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

Hence, the profit function becomes:

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

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

An environmental regulation will be *effective* if it is larger than voluntary remanufacturability, i.e. when $\overline{q} > q_k^*$. However, if a regulation applies to different industries with uneven remanufacturing initiatives, the regulation might be *non-effective* for some industries with $\overline{q} < q_k^*$. In this case, the regulation constraint is not biding and the selected level of remanufacturability stays unchanged. The applied level of remanufacturability and the difference in profits before and after regulation are:

$$\overline{q}_k = \begin{cases} q_k^* \text{ if } q_k^* \geq \overline{q} \\ \overline{q} \text{ if } q_k^* \leq \overline{q} \end{cases} \tag{15}$$

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

Figure (3) shows how profits vary with the imposition of a regulation. The difference between the curves $\overline{\pi}_i(\overline{q}_k)$ and the horizontal lines $\pi_i^*(q_k^*)$ describes the difference in profits due to all possible levels of regulation. The light and medium shade areas show the non-cooperative case while the medium and dark shade areas exhibit the collusive case.

When the regulation is non-effective (i.e. when $\overline{q}_k = q_k^* \geq \overline{q}$), the level of remanufacturability stays unchanged. However, the OMs' profit increases by $(c_m(\overline{q}) - c_m(0))/2$ due to the higher original product price, partially shifting the cost of remanufacturability towards final good producers and consumers. When a social utility function that equally weights producers' profits and consumers' surpluses is considered, this money transfer leaves the social welfare unchanged.

An effective regulation ($\overline{q}_k = \overline{q} > q_k^*$) influences OMs' profits through two effects. First, price and cost are now equal on the primary market and OMs' initial deficit vanishes. This shifts up profits by $(c_m(q_k^*) - c_m(0))/2$. Second, a higher level of remanufacturability influences OMs' technological advantage and, consequently, their ability to reach a larger aftermarket share (equations (9) and (10)). As long as the OMs gain technological advantage, $c_s'(\overline{q}) - c_r'(\overline{q}) \geq 0$, their profits increase. When $c_s'(\overline{q}) - c_r'(\overline{q}) \leq 0$, 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 $\overline{q} = \overline{q}_k^{\max}$, where the second effect overtakes the first one. Above this threshold, regulation results in net costs for the OMs.

Proposition 2 *Environmental regulations can be complementary to firms' benefits for both the non-cooperative and the collusive cases:*

$$\overline{\pi}_i(\overline{q}_k) - \pi_i^*(q_k^*) > 0 \Longleftrightarrow \overline{q} < \overline{q}_k^{\max}.$$

In particular, this remains true when the environmental regulation is effective:

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

This result coincides with the Porter Hypothesis, which says that profits may increase in the industry with the application of environmental regulations. The present model corroborates the argument of Ambec and Barla (2007) under which the Porter Hypothesis requires the presence of at least one market imperfection beside the environmental externality. The phenomenon here is the result of two market characteristics.

The first is the threat of the outsider on the primary market, which keeps the original price at the minimum production cost. Hence, OMs cannot pass on 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 ($p_m = c_m(\overline{q})$). This result shows how free-entry on the original alternator market has prevented OMs from engaging in remanufacturing initiatives and how the asbestos ban was welcomed by the industry.

The second characteristic occurs in the non-cooperative scenario. From *Proposition 1*, it is known that collusion leads to higher profits. Here, the regulation solves for this collective action problem. Although non-cooperation is not a necessary condition in confirming the Porter Hypothesis, it increases the extent to which regulations generate profits. This specific effect is graphically represented in Figure 3 by the area framed above and below by the horizontal lines $\pi_i^*(q_c^*)$ and $\pi_i^*(q_{nc}^*)$, and to the left by the curve $\pi_i^*(q)$. André *et al.* (2009) obtains similar results when a duopoly simultaneously choose between the production of a "standard" or a "green" product. A discrete choice of options can keep the standard quality as the Nash equilibrium, even if Pareto dominated by the green choice. Therefore, a regulation that forces cooperation between firms for the environmentally-friendly option can benefit firms, consumers and the environment. This additional role given to the regulation explains the difference between the non-cooperative and the collusive scenarios and leads to propositions 3 and 4.

In view of the positive variation in profits, any regulation below $\overline{q}_k^{\max}$ should be positively supported by the OMs. In contrast, regulations above $\overline{q}_k^{\max}$ are likely to meet resistance in their application. The difference in profits before and after the regulation (equation (16)) can therefore be interpreted as the *intensity* of compliance or resistance towards the regulation. Hence:

Proposition 3 *It is always easier to introduce an environmental regulation $\overline{q}$ under the non-cooperative case:*

$$\overline{\pi}_i(\overline{q}_{nc}) - \pi_i^*(q_{nc}^*) > \overline{\pi}_i(\overline{q}_c) - \pi_i^*(q_c^*)$$

Proposition 4 *The maximum level of regulation positively supported by the industry is larger under the non-cooperative case:*

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

In the absence of environmental regulation, the government can promote collusion as a substitute for regulation. However, when a regulation is scheduled, collusion should be repressed since non-cooperation better supports the regulation.

4.2 Intervention maximizing OMs' profit

Let $\overline{q}^*$ denotes the optimal regulation that would be chosen by the OMs. This scenario differs from the collusive case in the absence of regulation; for whichever level of remanufacturability chosen by the OMs, the outsider, constrained by the regulation, will not have the opportunity to produce at lower costs and, consequently, the threat vanishes. With $p_{m1} = p_{m2} = c_m(\overline{q})$, the maximization problem is:

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

The optimal condition is:

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

and the second-order condition is always satisfied. Note that $\overline{q}^*$ coincides with $\widehat{q}$, the level of remanufacturability that maximizes the OMs' technological advantage (see equation (10)). Figure 3 displays $\overline{q}^*$ and $\overline{\pi}_i(\overline{q}^*)$, the privately optimal regulation and the corresponding profit. Comparing the optimal conditions for the determination of $\overline{q}^*$, q_c^* and q_{nc}^* leads to the following propositions:

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

$$\overline{q}^* > q_c^* > q_{nc}^*$$

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

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

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

When the regulation is selected by the private sector, OMs take into account the fact that the entire production cost is covered by the selling price. They can therefore seize the maximum aftermarket share by costlessly choosing the level of remanufacturability leading to their largest technological advantage. When $\overline{q} = \overline{q}^*$, OMs's profits are maximized as well as their aftermarket size.

When OMs' remanufacturing activities pollute significantly less than IRs', the social planner may want to maximize the OMs' aftermarket share to the detriment of higher remanufacturability by choosing $\overline{q} = \overline{q}^*$.

4.3 Note on the consumer surplus

Through the original market, any regulation will have a negative impact on the consumer surplus since it shifts, totally or partially, the cost of remanufacturability $(c_m(\overline{q}) - c_m(0))$ towards consumers. However, on the aftermarket, a higher level of remanufacturability has a positive effect because it reduces replacement products' prices through lower remanufacturing costs (this can be found using equations (2), (3) and (8)). Consumer surplus will also vary with the share of high quality goods $2r_i^*$. It can be shown that the level of remanufacturability maximizing consumer surplus on the aftermarket is larger than the environmental regulation maximizing OMs' profit[14].

[14] Because consumers' willingness to pay on the aftermarket shows an explicit form, it is possible to find the level of remanufacturability maximizing the consumer surplus on this market, q_{cs}^*. Referring to Figure 1, total consumer surplus is formally defined by: $S = \sum_{t=1}^{b} \beta_l^t \left[\int_{\theta_q}^{1} (\theta + \alpha - p_r)\partial\theta + \int_0^{\theta_q} ((1-\delta)\theta + \alpha - p_s)\partial\theta \right]$. Markets clear in equilibrium, therefore $1 - \theta_q = 2r_i^*$. Using (2), (3) and (8), the total consumer surplus for a given q becomes: $S(q) = \sum_{t=1}^{b} \frac{\beta_l^t}{2} \left[(1-\delta) + \delta 2 r_i^*(q)^2 + 2(\alpha - c_s(q)) \right]$, and the first-order condition is: $\delta 2 r_i^*(q_{cs}^*) \partial r_i^*(q_{cs}^*)/\partial q - c_s'(q_{cs}^*)) = 0$. Using equations (9), (10) and (17), it is shown that q_{cs}^* occurs in a range where the technological advantage decreases and that $q_{cs}^* > \overline{q}^*$.

When combining the consumer surplus on both the original market and the aftermarket, the overall effect of an environmental regulation is ambiguous.

5 Conclusion

Original manufacturers produce a component as an input for the final good where the threat of an outsider keeps 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. Later, consumers of the final good have to replace the specific component. They consider products remanufactured by either independent remanufacturers or original manufacturers, and they are willing to pay a price premium for the latter. In this set-up, used products can be remanufactured by any firms, causing original manufacturers to suffer from free-riding on their technology selection and discourages investment in remanufacturing-oriented designs. When the original manufacturers collude on the level of remanufacturability, they only face the externality of independent remanufacturers and select a higher level of remanufacturability.

Remanufacturing benefits the population through less post-consumption waste, lower energy and raw material consumptions, and lower prices for replacement products. It also benefits the industry through the generation of positive profits. While the gains of remanufacturing are shared among the society, the costs of remanufacturing-oriented technology are born solely by the original manufacturers. Consequently, public regulation is necessary.

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 cost of complying with the regulation is redirected towards final good producers and consumers. Hence, original manufacturers can see their profits increase. This observation corroborates the Porter Hypothesis.

A social planner who wants to stimulate remanufacturing activities can consider allowing 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 be achieved through the application of an environmental regulation that reduces the threat of the outsider and solves for the collective action problem. 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.

References

Ambec, Stefan, and Philippe Barla (2007) 'Survol des fondements théoriques de l'hypothèse de porter.' *L'Actualité économique* 83, 3, 399–413

André, Francisco J., Paula González, and Nicolás Porteiro (2009) 'Strategic quality competition and the porter hypothesis.' *Journal of Environmental Economics and Management* 57, 182–194

Chung, Chun-Jen, and Hui-Ming Wee (2008) 'Green-component life-cycle value on design and reverse manufacturing in semi-closed supply chain.' *International Journal of Production Economics* 113, 528–545

Commission Directive 1999/77/EC (1999) *Official Journal of the European Communities* L207, p.18

Debo, Laurens G., L. Beril Toktay, and Luk N. Van Wassenhove (2005) 'Market segmentation and product technology selection for remanufacturable products.' *Management Science* 51, 1193–1205

Eichner, Thomas, and Marco Runkel (2005) 'Efficient policies for green design in a vintage durable good model.' *Environmental and Resource Economics (2005)* 30, 259–278

Eichner, Thomas, and Rudiger Pethig (2001) 'Product design and efficient management of recycling and waste treatment.' *Journal of Environmental Economics and Management* 41, 109–134

Ferrer, Geraldo (1997) 'The economics of personnal computer remanufacturing.' *Resources, Conservation and Recycling* 21, 79–108

—— (2000) 'Market segmentation and product line design in remanufacturing.' Technical Report, Working paper, The Kenan-Flagler Business School, University of North Carolina, Chapel Hill, NC.

Ferrer, Geraldo, and Jayashankar M. Swaminathan (2006) 'Managing new and remanufactured products.' *Management Science* 52, 15–26

Fullerton, Don (1998) 'Policies for green design.' *Journal of Environmental Economics and Management* 36, 131–148

Giuntini, Ron, and Kevin Gaudette (2003) 'Remanufacturing: The next great opportunity for boosting US productivity.' *Business Horizons* 46, 41–48

Heese, Hans S., Kyle Cattani, Geraldo Ferrer, Wendell Gilland, and Aleda V. Roth (2005) 'Competitive advantage through take-back of used products.' *European Journal of Operational Research* 164, 143–157

Kiesmuller, Gudrun P., and Erwin A. van der Laan (2001) 'An inventory model with dependent product demands and returns.' *International Journal of Production Economics* 72, 73–87

Kim, Hyung-Ju, Semih Severengiz, Steven J. Skerlos, and Gunther Seliger (2008) 'Economic and environmental assessment of remanufacturing in the automotive industry'

Lebreton, Baptiste, and Axel Tuma (2006) 'A quantitative approach to assessing the profitability of car and truck tire remanufacturing.' *International Journal of Production Economics* 104, 639–652

Majumder, Pranab, and Harry Groenevelt (2001) 'Competition in remanufacturing.' *Production and Operations Management* 10, 125–141

Mitra, Supriya, and Scott Webster (2008) 'Competition in remanufacturing and the effects of government subsidies.' *International Journal of Production Economics* 111, 287–298

Steinhilper, Rolf (1998) *Remanufacturing The Ultimate Form of Recycling* (Remanufacturing Industries Council International Automotive Parts Rebuilders Association (APRA))

Toffel, Michael W. (2004) 'Strategic management of product recovery.' *California Management Review* 46, 120–141

Toffel, Michael W., Antoinette Stein, and Katharine L. Lee (2008) 'Extending producer responsibility: An evaluation framework for product take-back policies.' Technical Report, Harvard Business School

Webster, Scott, and Supriya Mitra (2007) 'Competitive strategy in remanufacturing and the impact of take-back laws.' *Journal of Operations Management* 25, 1123–1140