Implementing a Circular Economy with Producer Responsibility Organisations

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<Preliminary Draft>

May 15, 2020

Recycling, reuse, and reduction of exhaustible resources has become a major goal in developed economies, which entails the active participation of producers. The implementation of Extended Producer Responsibility, whereby firms are financially responsible for their products' end-of-life costs, is commonly delegated to a Producer Responsibility Organisation (PRO). PROs are playing a crucial role in the development of a circular economy. PROs finance collection, sorting and recycling of waste by collecting fees from producers that are subject to EPR. These fees should reflect waste management costs and consequently influence producers on their product design and material use. Hence PRO pricing behaviour can influence the whole recycling program and production. We propose a theoretical model where downstream material flows and waste management are delegated to a PRO in order to study the efficiency of this dominant industry organisation. The analysis allows to address the key policy questions and provides guidance for the design of EPR programs.

Keywords: Industrial organisations, Environmental Policy, Circular Economy

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1 Introduction

Product design is key in the development of a circular economy. A study of the European Commission (2010) shows that among several waste prevention policy strategies, ecodesign of products has the highest potential for waste prevention. Material use in production will determine the potential development of downstream recycling industries, by determining its inputs. To foster recycling rates and ecodesign of products, the European Commission has long advocated the introduction of Extended Producer Responsibility (EPR).

Extended Producer Responsibility (EPR) is an approach in which producers become financially responsible for their products' end-of-life (OECD, 2016). EPR is associated with recycling objectives. Therefore, producers are expected to internalise waste management costs of their products and adapt their product design towards waste prevention and enhanced recyclability. In Europe, EPR has been implemented for several product streams. Notably, EPR was mandated by the European Commission for Electrical and Electronic Equipement (WEEE) in Dir. 2012/19/EU, batteries (Dir. 2006/66/EC) and for End-of-Life Vehicules (ELV) in Dir. 2000/53/EC. EPR is not mandatory for household packaging but is commonly used as means for achieving recycling objectives of 2018/852. Usually, each individual producer is allowed to organise its own recycling program (*individual EPR*), but in practice such individual systems imply prohibitive costs. Hence producers are usually organised collectively around Producer Responsibility Organisations (PRO; OECD, 2016).[1] In France, 15 EPR programs are in place, and all are organised around PROs.[2]

PROs are major actors of the European circular economy. PROs finance the

[1] Generating economics of scale.

[2] https://www.ecologique-solidaire.gouv.fr/cadre-general-des-filieres-responsabilite-elargie-des-producteurs

recycling program under EPR (collecting, sorting and recycling) by collecting fees from producers. The introduction of EPR is generally associated with a boost in recycling rates (OECD, 2016). Fees are set by the PRO and influence the producer's product design and material use. Design of products will in turn partly determine recycling activities (material flows, recyclability). If fees reflect the true recycling costs, recyclable materials and design will be privileged, i.e., cost internalisation is effective. However, what can guarantee that the PRO will effectively charge the true recycling costs?

EPR is a way of delegating waste policies to producers (Fleckinger and Glachant, 2010), but the government has several instruments to manage EPR recycling programs and PROs. First, the EPR program is associated with a recycling objective in line with the European Directive or the national legislation. Public authorities may also set requirements on fees' structure in order to favour the use of some materials or product design (e.g., fees differentiated by materials). In addition, PROs may be imposed a zero profit constraint and/or the presence of competitors.[3] Finally, the PRO can be under control or influenced by producers. All these parameters, and hence the design of EPR programs, will influence the PRO pricing behaviour, and in turn, the functioning of the recycling program.

In this paper we want to understand which policy design will lead to a true pricing of recycling costs by the PRO. Doing so, we can also answer the question: if producers and environmental organisations could lobby for their own interests, which configuration would they encourage and why? How does that differ with that of the social planner? Our analysis addresses the key policy questions and provides guidance for the design of EPR programs.

There is a small literature on EPR and its effects on welfare (Runkel, 2003;

[3] In practice, PROs activities are monitored by public authorities (accreditation, audits, etc; OECD, 2016).

Fleckinger and Glachant, 2010), recycling performances (Ozdemir-Akyildirim, 2015) and waste exports (Bernard, 2015). Runkel (2003) study how EPR influences product durability and welfare. The author shows that non-EPR measures implement the first-best optimum if households are fully rational and if they do not use moonlight dumping. Fleckinger and Glachant (2010) extend Runkel's model by endogeneising the design of EPR programs, i.e. where producers choose fees. Thus, they are able to study collusion issues. They centre their analysis to the case of imperfect competition with a duopoly model. They find that when waste management is provided competitively, individual EPR programs are more desirable than a perfect collusive PRO in terms of welfare. In the presence of market power in the waste management industry however, the perfect collusive PRO outperforms individual programs. Ozdemir-Akyildirim (2015) compares individual compliance scheme, modelled by deposit-refund system, with collective compliance scheme (similar to a PRO). The author finds that individual compliance leads to less costs but lower recycling rates than PROs. Bernard (2015) theoretically analyses how more stringent regulations in the North can impact product reusability of Northern firms, when considering a model with north-south trade in reusable goods. In her model, she considers that Nothern producers join a PRO and are either owners or stockholders, and hence, the PRO turns its decisions towards firms' profit maximisation. The PRO minismises the net disposal costs of firms producing an homogenous good, notably through waste exports to Southern countries.

We contribute to the literature by being the first to analyse in depth PROs pricing behaviour, and to look at competitive PRO markets. In order to deepen the analysis at the PRO level, we restrict to the case of perfect competition in the product market and take recycling costs as given.

We model an homogenous and atomized sector producing a given amount of material waste. We consider several status and market design: for-profit, not-for-profit, competition and producers' governance. We show that if the PRO charges the true recycling cost, material use is always too high as compared to optimal levels. This is because EPR programs usually do not incorporate environmental externalities of recycling and disposal in their design, hence firms are expected to only internalise economic costs of recycling. If policy-makers do not wish to integrate these externalities in EPR, complementary mechanisms may be proposed to reach a social optimum.

We show that a monopolistic PRO has always an incentive to distort fees from recycling costs, be it for increasing its profit or its size, as a non-profit. However, when the PRO is fully under producers' control, it equals fees at the exact recycling cost, for a null profit. Nevertheless, a full governance in a monopolistic PRO is rather unlikely in atomized and homogenous product markets. Opening competition between PROs further reduce the fees by cutting operational expenses and prevent decorrelation of material fees from the recycling costs. In this context, producers would always lobby for competitive PRO markets, to have the lowest fees and implicit control over the PRO. Environmental organisations lobby for an independent for-profit monopolistic PRO for the highest tariffs with the priority of reducing materials in production if no complementary waste prevention plan is in place.

The second section introduces more context on EPR implementation and justifies the model's hypotheses. Section 3 presents the model. Section 4 introduces results of the restricted model (independance of materials in production). Section 5 review our results when materials are interdependent. Section 6 concludes.

2 Context

The status of PROs and the question of having a PRO market in a competitive or monopolistic situation is a debate that has occupied research and public bodies for decades. The main juridical form of PROs is a non-profit institution, owned by adhering producers (European Commission, 2014). Another common form is a for-profit PRO owned by profit-looking investors (often, waste management operators; OECD, 2016). Finally, there are public (non-profit) PROs. Producers' control should influence PRO pricing behaviour.

The objective function of a non-profit PRO, beyond financing the recycling program with no profit, is not straightforward. In the economic literature, researchers distinguish between two main objectives for non-profit organisations (NPOs). Tullock (1966) proposed budget maximisation as objective function of managers running NPO, looking for higher salaries and prestige (Steinberg, 1986). In this setting, NPOs maximise their *size*, irrespective of the costs (gross revenues ; Brooks, 2005). Steinberg (1986) empirically shows that budget maximisation is the strategy of health firms in four U.S. metropolitan areas. Weinberg (1980) introduced service-maximisation which corresponds to the maximisation of the service provided (Steinberg, 1986; Brooks, 2005). This concept includes cost control, so as to increase the share of charitable service (Steinberg, 1986).

Because of their ability to set fees, PROs are not reliant on fundraising as in Brooks (2005) or Steinberg (1986) and can adjust compliance revenues to recycling costs. Hence, we assume that non-profit PROs set fees so as to increase their budget while equalling revenues to expenses.

On the other hand, PROs are under influenced or over control of producers, who will require low fees thus maximising the amount of waste and recycling services. In this case, the governance structure will tend to maximise PROs' services by minimising producers' production costs.

The competition issue in PRO markets has mainly been addressed by the OECD (OECD, 2016), which states that a monopoly situation may be beneficial to the creation of the recycling channel in order to address a context of uncertainty and the need for large investments. They argue that competition restrictions should be removed as soon as possible to improve cost efficiency (OECD, 2016). PROs' pricing behaviour needs to be better understood in order to clarify to what extent competition is beneficial to the recycling program. In Germany, competition between packaging PROs has arrived in 2003, with today around 10 PROs (European Commission, 2014). Since then, fees have dropped.

Competition increases producers' power of balance, since they choose their PRO. Nevertheless, this also increase the power of public authorities who can threat to not accredit a PRO. In the case of competition between non-profit PROs, objectives of the PRO and producers can be aligned. Indeed, PROs' size will be determined by their capacity to attract member producers, and thus, minimise producers' production costs. In practice, the existence of several PROs does not necessarily reflect the market structure. PROs may simply have different scope (e.g. product subcategories or geographical scope; European Commission, 2014).

In addition, public authorities may set requirements on the fee structure in order to favour the use of some materials or product design (*fee modulation*). As recycling consists in the recovery of a given material, recycling costs are by definition material-specific. Hence, the government may impose different fees per material. *Fee modulation* is implemented at the material level in EPR schemes for packaging in the EU. This means that different fees apply to glass, metals, plastics, etc. However the modulation is less often implemented at the material sub-type level (e.g. PET, PP, HDPE; European Commission (2014)). Table 1 shows fees set by the French monopolistic non-profit PRO for household packaging (Citeo) in 2019 .[4]

Table 1: Household packaging fees in France (2019)

Packaging material	Fee (2019 €/t)
Aluminium	110.4
Steel	45.6
Paper and cardboard	162.8
Bricks	249.7
Plastics	346.3
Glass	14.0

Source: Citeo, 2019

Notes: Citeo also charges unit-based fee (per packaging unit), not mentioned in this table.

Citeo set uniform fees for plastics, hence producers have incentives to reduce their plastic use all alike although plastics have different recycling costs.

For many product streams however, the fee is set at the product level, because of the product's complexity. For example, a smartphone contains up to 70 materials (ADEME, 2018), hence the need of simplifying the compliance procedure. Table 2 shows the main materials contained in a smartphone and the corresponding 2018 unit fee charged by Eco-systemes, the main PRO for WEEE in France. Unit fees do not provide incentives to eco-design of products. If fees are important in light of producers' margin, they can only reduce the production quantity.

[4]Other design aspects affect a product's recyclability (e.g. ease of disassembly, multi-layering, metal alloy, etc...) than the material-itself. This may lead to further fee modulation, that we do not consider in our analysis.

Table 2: An example of *unit fees*: Smartphone unit fee of the French PRO Ecosystèmes (2018)

Material	Average quantity in one smartphone (g)	Fee (2018 €/smartphone)
Aluminium	22.18	
Copper	15.12	
Plastics	9.53	
Magnesium	5.54	0.02-0.05 €
Tin	1.21	
Steel	0.88	
Tungsten	0.44	
Silver	0.31	
Neodymium	0.05	
Gold	0.03	
Other	99.34	

Source: Manhart et al. (2016); Eco-systèmes (2018)
Notes: "Other" includes glass and ceramics.

3 The model

A sector of homogenous firms produce an output q entailing m materials. This sector can be seen as one firm. Hence the firm's production is $q = (q_1 ... q_m)$.

When no EPR is implemented, the business as usual production is defined by:

$$q^0 = (q_1^0 ... q_m^0) \tag{1}$$

We suppose that firms have the possibility to reduce their material use and to use other materials and substances. Any change is costly. The quadratic abatement cost function of the firm is given by:

$$c(q^0, q) = (q^0 - q)^t \cdot C \cdot (q^0 - q) \tag{2}$$

where q denotes the production scenario when EPR is implemented.

$$q = (q_1...q_m) \tag{3}$$

Table 3: Notation used throughout the paper

State's decision variable	
r_i	Recycling objective mandated by the State for material i
Producers' decision variable	
q_i	Quantity of material i used in good q
PRO decision variable	
f_i	Material-specific compliance fee charged by the PRO
f	Uniform compliance fee charged by the PRO
Parameters	
q_i^0	Initial quantity of material i used in good q
c_i	Cost of abatement of material i
$c_{i,j}$	Cost of switching from material i to j and $c_{i,j} = c_{j,i}$
γ	Transportation/Information costs linked to collection
z_i	Recycling costs of material i (excluding the collection phase)
w_i	Recycling costs of material i (including the collection phase)
e_{R_i}	Externality of material i when it recycled
e_{D_i}	Externality of material i when it is not recycled
a	Administrative and operational costs of the PRO

Abatement and substitution costs are given by the square matrix C:

$$C = \begin{pmatrix} c_{1,1} & c_{1,2} & \cdot & \cdot & c_{1,m} \\ c_{2,1} & \cdot & & & \cdot \\ \cdot & & \cdot & & \cdot \\ \cdot & & & \cdot & \cdot \\ c_{m,1} & \cdot & \cdot & \cdot & c_{m,m} \end{pmatrix} \tag{4}$$

This means that to reduce q_1^0 to q_1, the firm bears an abatement cost $c_{1,1}$. In the case where q_1 represents an essential material for q, $c_{1,1}$ would approach infinity. $c_{1,2}$ represents the cost of switching from material 1 to material 2 for the firm .

For m materials, the abatement cost function is given by:

$$c(q^0, q) = \sum_{i=1}^{m} \left(\sum_{j=1}^{m} c_{i,j}(q_i^0 - q_i)(q_j^0 - q_j) \right) \tag{5}$$

All producers are enrolled in a collective EPR scheme and delegate their responsibility to a PRO. The PRO charges a material-specific compliance fee f_i. The producer minimises its total cost (TC) function:

$$\min_{q_i} \mathrm{TC} = \sum_{i=1}^{m} f_i q_i + \frac{1}{2} \sum_{i=1}^{m} \left(\sum_{j=1}^{m} c_{i,j}(q_i^0 - q_i)(q_j^0 - q_j) \right) \tag{6}$$

The PRO's profit function is given by its compliance revenues minus the recycling costs:

$$\pi_{PRO} = \sum_{i=1}^{m} f_i q_i - \sum_{i=1}^{m} r_i(w_i + a)q_i \tag{7}$$

where w_i denotes recycling cost of material i, r_i the recycling objective assigned by the State, and a administrative and functioning costs charged by the PRO.

We first consider a restricted form of the model in the following section.

4 Setting with independent materials

In this setting, materials are considered independent, i.e. $c_{i,j} = 0$ when $i \neq j$. Hence the matrix C is diagonal and defined by:

$$C = \begin{pmatrix} c_1 & & & \\ & \cdot & & 0 \\ & & \cdot & \\ 0 & & & \cdot \\ & & & c_m \end{pmatrix} \tag{8}$$

The abatement cost function of the firm becomes:

$$c(q, q^0) = \frac{1}{2} \sum_{i=1}^{m} c_i (q_i^0 - q_i)^2 \tag{9}$$

Without substitution possibilities, the cost of the abatement is simply the cost of reducing the use of material while maintaining the performance and strength of the product. This is more commonly called "material efficiency" (as in Worrell et al., 1995) and refers to applications such as: microcircuits, smaller batteries, thinner protection (e.g. stronger and thinner alloy), etc.

4.1 Social optimum

The recycling rate r_i is chosen by public authorities for each material and $r_i \in [0, 1]$. 100% recycling may be very hard to achieve, if not impossible. These difficulties should be mostly attributable to the collection phase, which embodies the difficulty to set a recycling program. We assume that collection costs increase more proportionally than the recycling target r_i due to transportation and information costs. In fact, some households may live in remote areas and some waste are dispersed in nature. A high recycling target, and therefore, a high collection target, will be more and more costly to achieve because this implies collecting waste, which is the most costly to collect (e.g. mountain chalet, picking up waste in dense forests). This could also be interpreted as information costs: informing and convincing the most reticent or uninterested households not sorting their waste or leaving litter in nature can be very costly. Hence collecting 100% of waste costs more as twice than collecting 50% of waste. Finally, 100% recycling may be technologically impossible to achieve, as recycling activities themselves lead to secondary waste and lost of materials during the recycling process.

We make the assumption that material waste i, and hence transportation/information costs γ, are linearly distributed over $[0, 1]$. Hence unit collection costs for a given r_i are:

$$\gamma \int_0^{r_i} x dx = \frac{1}{2}\gamma r_i^2 \tag{10}$$

Therefore collection costs are given by:

$$\frac{1}{2}\gamma r_i^2 q_i \tag{11}$$

Let denote z_i, material i's recycling costs (excluding the collection phase). The social cost function writes as:

$$SC = \frac{1}{2}\sum_{i=1}^{m} c_i(q_i^0 - q_i)^2 + \sum_{i=1}^{m} r_i(z_i + \gamma r_i + a)q_i + \sum_{i=1}^{m} e_{R_i} r_i q_i + \sum_{i=1}^{m}(1 - r_i)e_{D_i} q_i \tag{12}$$

where e_{R_i} denotes the environmental pollution generated by recycling activities and e_{D_i} the environmental cost of disposing waste. We assume that e_{D_i} is superior to e_{R_i}, meaning that it is always environmentally preferable to recycle rather than dispose of waste in nature, as recycling saves resources and extraction activities.

Lemma 1 (First-best r_i)**.** *A social optimum can be reached with the following parameters:*

$$r_i^{FB} = \min(\max(0, \frac{(e_{D_i} - e_{R_i}) - (z_i + a)}{2\gamma}), 1) \tag{13}$$

$$f_i^{FB} = r_i(z_i + \gamma r_i + a) + e_{R_i} r_i + (1 - r_i) e_{D_i} \tag{14}$$

$$q_i^{FB} = \max\{0, q_i^0 - \frac{f_i^{FB}}{c_i}\} \tag{15}$$

The optimal recycling rate increases with the environmental preferability of recycling over disposal, minus the operational costs of recycling. This rate is lowered by the practical difficulty of implementing a recycling program, reflected by collection costs and thus, the society's willingness to recycle and the distribution of households over the territory. The EPR compliance fee is differentiated by materials and is akin to a Pigouvian tax.

Proof. The proof is presented in appendix D. □

We can rewrite f_i^{FB} as:

$$f_i^{FB} = e_{D_i} - \gamma (r_i^*)^2 \tag{16}$$

Hence, $f_i \in [e_i - \gamma, e_i]$.

The socially optimal quantity of material i, q_i^{FB} decreases with economic costs of recycling $r_i(z_i + \gamma r_i + a)$ as well as environmental costs of waste $e_{R_i} r_i$ and $(1 - r_i) e_{D_i}$. It increases with abatement costs, e.g. in the case this material would represent an essential component of the good. In case both, externalities and economic costs, were too high as compared to c_i and q_i^0, it is optimal to have $q_i^{FB} = 0$. For example, plastics have strong economic and environmental costs at end-of-life. In some cases, one may be able to avoid them at reasonable abatement costs, e.g. for packaging and $q_i^{FB} = 0$. However it seems more difficult to avoid them as electrical insulators or medical infusion bags [5], which would imply a high c_i and $q_i^{FB} > 0$. Note that the initial material use q_i^0 matters as well. It represents a certain inertia that can exists when a material is very much use, e.g. habits of use, already existing infrastructures, knowledge, businesses and jobs associated to the material.

The first best (FB) optimum excludes all materials i such that $c_i q_i^0 < f_i^{FB}$.

This FB optimum can only be reached with a material-specific fee, as q_i^{FB} is differentiated according to economic and environmental costs for a given material i. However in practice, it may be difficult to implement a full modulation e.g. for goods with multiple components. We study the implication of using uniform fees in Section 4.3.

4.1.1 Design of EPR programs

We expect environmental organisations to always lobby for higher recycling objectives than the social planner. This is because the social planner accounts for the economic feasibility of such an objective whereas environmental organisations only focus on the environmental parameter $(e_{D_i} - e_{R_i})$. At the opposite, we expect producers to lobby for low recycling rates, since they will pay for the recycling program.

PROs' role is then usually to ensure compliance with the recycling target at the cost of producers. Externalities of recycling and disposal may go beyond their scope of responsibility, as their role is simply to finance the recycling program. Hence, by definition and depending on how EPR is designed, we cannot expect the PRO to set $f_i = f_i^{FB}$. This implies that material use, e.g. packaging quantities, will always be too high as compared to the social optimum, if complementary mechanisms to reduce materials are not in place (reduction objectives, complementary packaging/material

[5] Reference to the Secretary of State B. Poirson interviewed the 5th of June 2019 on the radio *France Inter*, which declared plastics have some essential applications such as medical infusion bags.

taxes).

But at least, we can expect the PRO to price the real economic costs of recycling, i.e. $f_i = r_i(z_i + \gamma r_i + a)$, i.e. the "true recycling costs".

Throughout the article, we analyse the PRO pricing behaviour. For the sake of simplicity we use the notation $w_i = \gamma r_i + z_i$. We assume that the PRO takes the recycling target and waste management costs as given.

4.2 The PRO program with modulation requirements

We assume in this section that fee differentiation by materials is mandated by the State. Uniform fees are studied in Section 4.3.

4.2.1 For-profit PRO

We first consider a for-profit PRO. If producers have shares in the PRO, they have a decision power of α. Hence $1 - \alpha$ can be seen as the independence degree of the PRO *vis-à-vis* producers. The governance structure of the PRO maximises the function H:

$$H = (1 - \alpha)\pi_{PRO} - \alpha TC \tag{17}$$

where TC is the producer's total cost function.

$$TC = \sum_{i=1}^{m} f_i q_i + \frac{1}{2} c_i (q_i^0 - q_i)^2 \tag{18}$$

Here, $\alpha \leq \frac{1}{2}$ otherwise the PRO looses profit. We obtain:

$$f_i^* = \frac{1 - 2\alpha}{2 - 3\alpha} c_i q_i^0 + \frac{1 - \alpha}{2 - 3\alpha} r_i (w_i + a) \tag{19}$$

$$\begin{cases} \text{when } \alpha \to 0,\ f_i^* = \frac{1}{2}(c_i q_i^0 + r_i(w_i + a)) \\ \text{when } \alpha \to \frac{1}{2},\ f_i^* = r_i(w_i + a) \end{cases} \tag{20}$$

Proposition 1 (For-profit PRO)**.** *An independent profit-maximiser PRO distort its tariffs from recycling costs. It inflates the fees with the firm's abatement costs and initial material use. As producers gain in governance, fees decrease until equalisation with recycling costs, for a null profit of the PRO.*

Proof. The proof is presented in Appendix C.3.1 □

With a high $c_i q i_i^0$, the independent PRO can tariff a higher fees without fearing to decrease output too much. In parallel, the fee should cover recycling costs of the material and hence, increases with $r_i(w_i + a)$.

No matter the governance structure, the PRO excludes all materials for which $c_i q_i^0 < r_i(w_i + a)$.

4.2.2 Non-profit PRO

We now consider a non-profit PRO, to which we assign a *size maximisation* program. We argue that while having an objective of zero profit, the PRO will tend to maximise $\sum_{i=1}^{m} f_i q_i$. Nevertheless, if producers are active in the governance, they can favour their own interest: production costs' minimisation, and thus we tend to a service maximisation objective by the PRO.

The Lagrangian associated to the problem write as:

$$\mathcal{L} = (1 - \alpha) \sum_{i=1}^{m} f_i q_i - \alpha(TC) - \lambda(\pi_{PRO}) \tag{21}$$

In the non-profit case, $\max \alpha = 1$. Producers can fully control the PRO ($\alpha = 1$) while respecting the zero profit constraint.

In the size maximisation problem, materials are linked in pairs by the relation:

$$f_i \left[(3\alpha - 2)\, r_j(w_j + a) - \alpha c_j q_j^0 \right] = f_j \left[(3\alpha - 2)\, r_i(w_i + a) - \alpha c_i q_i^0 \right] + (1 - 2\alpha) \left[c_j q_j^0 \cdot r_i(w_i + a) - c_i q_i^0 \cdot r_j(w_j + q) \right] \quad (22)$$

This leads to the following proposition:

Proposition 2 (Non-profit PRO)**.** *Considering a budget balanced with $m - 2$ materials, an independent size-maximiser non-profit PRO systematically implements cross-subsidies between two materials, except when condition 23 holds. As producers gain in governance ($\alpha \to 1$), cross-subsidies diminish and fees tend to their real recycling costs. The proposition is illustrated by Figure 1.*

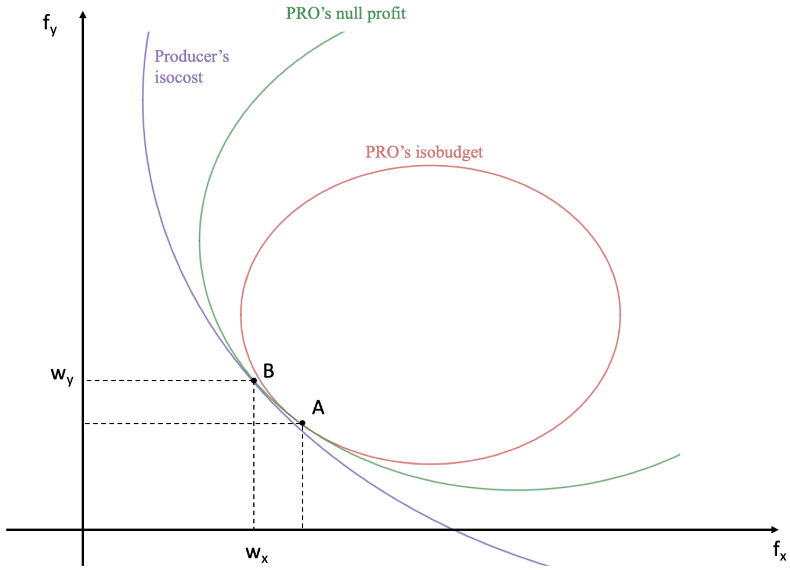
Proof. The proof is presented in Appendix B.3.2 □

Condition 23 writes as:

$$\frac{c_i q_i^0}{c_j q_j^0} = \frac{r_i(w_i + a)}{r_j(w_j + a)} \quad (23)$$

Quite intuitively, if there is a perfect proportionality the PRO cannot use cross-subsidy while respecting a zero profit.

Figure 1: Illustration of proposition 2 with two materials (x,y)



A: fees maximising the size of the PRO for a null profit
B: fees minimising producers' production costs for a null profit

When $\alpha = 0$ the non-profit PRO distort fees as shown by point A on Figure 1. As measure as $\alpha \to 1$, the equilibrium moves to B.

Example 1 (Two materials)**.** *We consider a good constituted of two materials. We set* $w_1 = \frac{1}{4}$, $w_2 = \frac{1}{2}$, $c_1 = 1$ *and* $c_2 = \frac{1}{2}$, *the size maximisation program leads to the following optimal schedule:*

$$f_1 = w_2 \tag{24}$$

$$f_2 = w_1 \tag{25}$$

Proof. The proof is presented in Appendix E.1.1. □

4.2.3 On monopolistic PRO markets with modulation requirements

We have shown that when producers have no bargaining power, a monopolistic for-profit and the not-for-profit PRO distort material fees from their recycling costs.

The for-profit PRO charges higher fees than the non-profit, assuming high c_i and q_i^0.

No matter the PRO's status, when producers control the PRO, material fees equal their recycling costs, for a null profit of the PRO.

This result is linked to fundamental assumptions of the model (homogeneous producers, no market power in the product market).

4.3 Uniform fees

We consider in this section that the PRO charges a material-homogeneous fee f. For instance, the French PRO Citeo charges an homogenous fee for all kind of plastics (see Section 2).

Let us analyse graphically what this implies for exclusion in Figure 2. With material-modulated fees, all materials which have a f_i above $c_i q_i^0$ are excluded (i.e. all points located in the blue area). In the constrained optimum with uniform fees and for given r_i, materials in the red area are excluded such that $f > c_i q_i^0$. Hence we observe that the two systems do not exclude the same materials.[6]

For example, let us consider the point B, representing a material i_B having a very high w_{i_B} such that $q_{i_B} = 0$. In the constrained optimum, as it also has a high c_{i_B} and/or $q_{i_B}^0$, i_B would remain on the market. The point A illustrates a reverse case, for a material with low recycling and environmental costs but cheap to abate as compared to f^u.

[6]This is because we have allowed recycling costs to be not aligned with material use and abatement costs. Shall these two be aligned, results of both mechanisms would look more similar.

Figure 2: Comparing exclusion of materials with differentiated and uniform fees

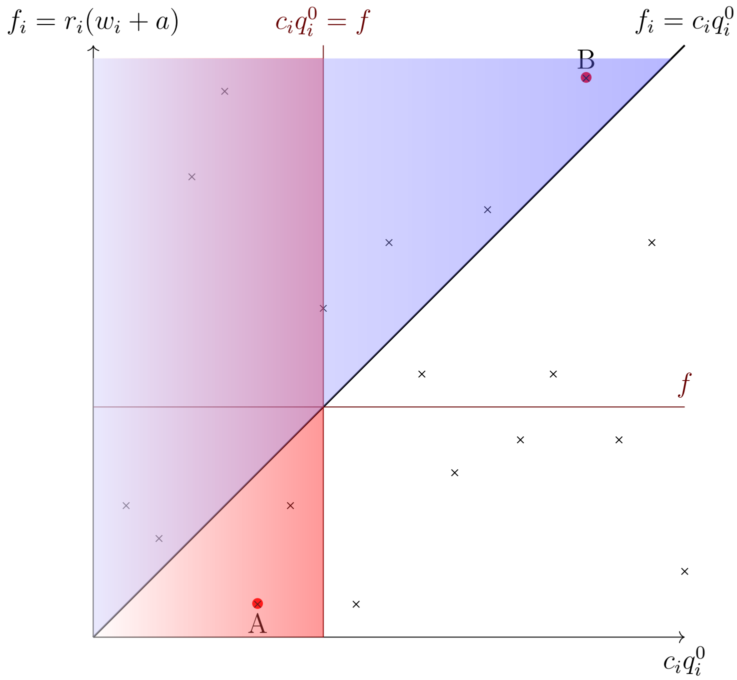
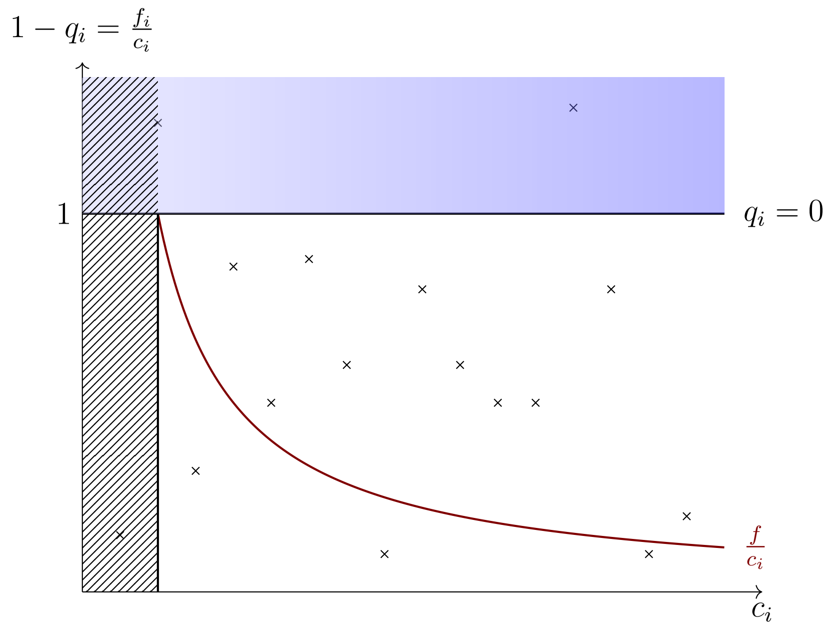


Figure 3 allows showing exclusion and reduction of materials with the use of modulated vs. uniform fees. For simplifying the graphical representation we set $q_i^0 = 1$ for all i. In the blue area are materials which would be excluded with modulated fees. In the shaded area, are materials exlcluded with a uniform fee. The reduction of material use in the case of uniform fees is given by the red line. While the reduction with modulated fees is material specific and is given by each cross.

Figure 3: Comparing reduction of materials with differentiated and uniform fees for $q_i^0 = 1$



The PRO profit is now given by:

$$\pi_{PRO} = f \sum_{i=1}^{m} q_i - \sum_{i=1}^{m} r_i(w_i + a)q_i \tag{26}$$

The producer aims at minimising its total costs function TC.

Remark 1. *In a setting for a given uniform fee f and without substitution, producers lower use of materials which have lowest unit cost of abatement and initial use. Considering that the i materials are ordered according to $c_i q_i^0$, the firm will completely renounce to materials i in $[1, i_0]$ for which $c_i q_i^0 < f$. For $i \in [i_0 + 1, m]$, the reduction of material use by the firm is given by:*

$$q_i(f) = q_i^0 - \frac{f}{c_i} \tag{27}$$

When $i_0 = 0$ all materials remained on the market.

Depending on the mix of materials in circulation and their associated costs (c_i, w_i, e_i), there exists a uniform fee, f^u, allowing reaching a second-best constrained optimum, i.e. that leads to an exclusion and a decrease of material use that is more socially desirable as any other f for a given r_i.

Lemma 2. *There exists a uniform pricing leading to a second best-optimum, considering an exogenous recycling objective r_i. This schedule is defined as the harmonic mean of abatement costs weighted by economic and environmental costs of end-of-life products.*

$$f^u = \frac{\sum_{j=i_0+1}^{m} \frac{f_j^{FB}}{c_j}}{\sum_{j=i_0+1}^{m} \frac{1}{c_j}} \tag{28}$$

$$q_i^u = \max\{0, q_i^0 - \frac{f^u}{c_i}\} \tag{29}$$

f^u increases with economic and environmental costs of all materials, which will give firms homogeneous incentives to reduce materials. f^u increases with a given c_i when material i has relatively low recycling and environmental costs. Firms reduce use of material i that is cheapest to do so.

Comparatively to the first best optimum, f^u may exclude more or less materials, but most importantly, not the same materials as in the first best. Figure 2 illustrates this point.

In the extreme case where $e_i \to \infty$ and $w_i \to \infty$ for one given i, the constrained optimum leads to $q_i = 0$ for all i and r_i.

4.4 For-profit PRO

Quite intuitively, if a for-profit PRO has the choice, it will never use fee averaging as it prevents price discrimination. But in practice, such a tariff can be implemented to reduce administrative costs.

Proposition 3. *The for-profit PRO if using uniform fees, charges f^{max}, which averages abatement costs, material initial use and recycling costs of non-excluded materials ($i > i_0$).*

$$f^{max} = \frac{1}{2}\frac{(1-2\alpha)\sum_{i=1}^{m} q_i^0 + (1-\alpha)\sum_{i=1}^{m}\frac{r_i(w_i+a)}{c_i}}{(1-\frac{3}{2}\alpha)\sum_{i=1}^{m}\frac{1}{c_i}} \tag{30}$$

$$\tag{31}$$

Proof. The proof is present in Appendix C.3.1. □

- $\alpha \to 0 \Rightarrow f^{max} = \frac{1}{2}\frac{\sum_{i=1}^{m}\left(q_i^0 + \frac{r_i(w_i+a)}{c_i}\right)}{\sum_{i=1}^{m}\frac{1}{c_i}}$
- $\alpha \to \frac{1}{2} \Rightarrow f^{max} = \frac{\sum_{i=1}^{m}\left(\frac{r_i(w_i+a)}{c_i}\right)}{\sum_{i=1}^{m}\frac{1}{c_i}}$

As α increases the PRO profit decreases, but does not necessarily equal zero.

A profit-maximising PRO increases f with initial material use and recycling costs. It increases f^{max} following the increase of abatement costs of a given material except if it has already high recycling costs. Indeed, when abatement costs of an expensive-to-recycle material increase (e.g. Polypropylene (PP)), there is more PP to recycle. Hence by decreasing its fee (f^{max}), the PRO increases the quantity of all materials (on average less costly to recycle than PP), which decreases the average cost of recycling.

4.5 Non-profit PRO

Lemma 3. *We consider the set $E = \{1, m\}$ containing all materials. The i materials are ordered according to $c_i q_i^0$ such that $c_{i-1}q_{i-1}^0 < c_i q_i^0$ for all i. Considering k subsets*

E_k of materials belonging to E that allows balancing the budget and $k \in [0, m]$. The PRO chooses $f^{BB} < \min(c_i q_i^0)|i \in E_j|j \in [0, k]$. The fee satisfies two conditions:

$$(i): \; f^{BB}_{i \in E_j} \sum_{i \in E_j} q_i \geq f^{BB}_{i \in E_h} \sum_{i \in E_{h \neq j}} q_i \tag{32}$$

$$(ii): \; f^{BB}_{i \in E_j} = f^{max}_{i \in E_j} - A \qquad \text{if } E_j \text{ contains at least two materials, else } f^{BB} = w_m \tag{33}$$

with A an expression contained between 0 and f^{max}.

Proof. The proof is presented in Appendix C.3.2 . □

If the PRO is allowed to exclude materials, the non-profit PRO charges the f^{BB} that allows balancing its budget and maximising its size. First, one needs to identify a subset of materials allowing a balanced budget. For example, let us consider a total set of two materials, ceramics, having a low $c_i q_i^0$ but a high $r_i(w_i + a)$; and cardboard, with a high $c_i q_i^0$ and low $r_i(w_i + a)$. First, it may be impossible to treat both materials and respect the null profit constraint. Indeed, in order to treat both materials, the fee should be lower than the lowest $c_i q_i^0$ (ceramics) and finances at the same time high recycling costs of ceramics and large quantity of cardboard. Then, treating only cardboard may also be impossible if its $r_i(w_i + a)$ is lower than the lowest $c_i q_i^0$. Once this set are identified, the PRO chooses the one that maximises its revenues (condition *(i)*).

As the profit function is strictly concave, there exists two f^{BB} that allows equalling revenues and expenses without discouraging production in a given set. We show in Appendix C.3.2 that charging a lower f allows a larger size (i.e. increase treated quantities).

Now assuming that recycling costs are small in front of abatement costs and materials' initial use, the PRO fails to exclude materials, and can only equal its profit to zero.

In this case, producers' control does not change fees.

4.5.1 Strategic use of uniform fees

Can the PRO choose voluntarily uniform fees? If the PRO is controled by producers, it anticipates that fee modulation will lead to a true pricing of recycling costs. Hence fee averaging can consist in a hidden size maximisation strategy.

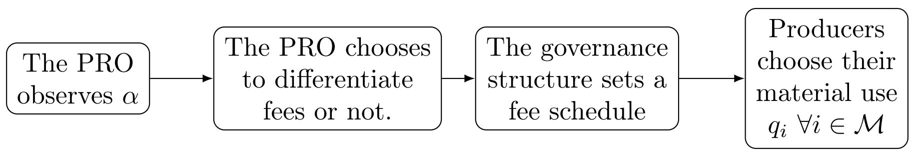


Figure 4: Game

4.6 Competition

4.6.1 Exclusive Competition

We consider a set $\mathcal{N} = \{1, ..., n\}$ of n producers, a set $\mathcal{P} = \{1, ..., p\}$ of p PROs and a set $\mathcal{M} = \{1, ..., m\}$ of m materials. Considering that each individual producer uses material $i \in \mathcal{M}$ in quantity x_i, the total production of the sector is defined by:

$$\sum_{i=1}^{m} q_i = \sum_{i=1}^{m} \sum_{j=1}^{n} x_{i,j} \tag{34}$$

At $t = 1$, each PRO k in P defines a fee schedule for the m materials and a level of a. At this stage, PROs do not know the number of memberships that they will receive.

$$\forall k \in \mathcal{P}, \quad F_k = \{f_1^k, ..., f_m^k, a^k\} \tag{35}$$

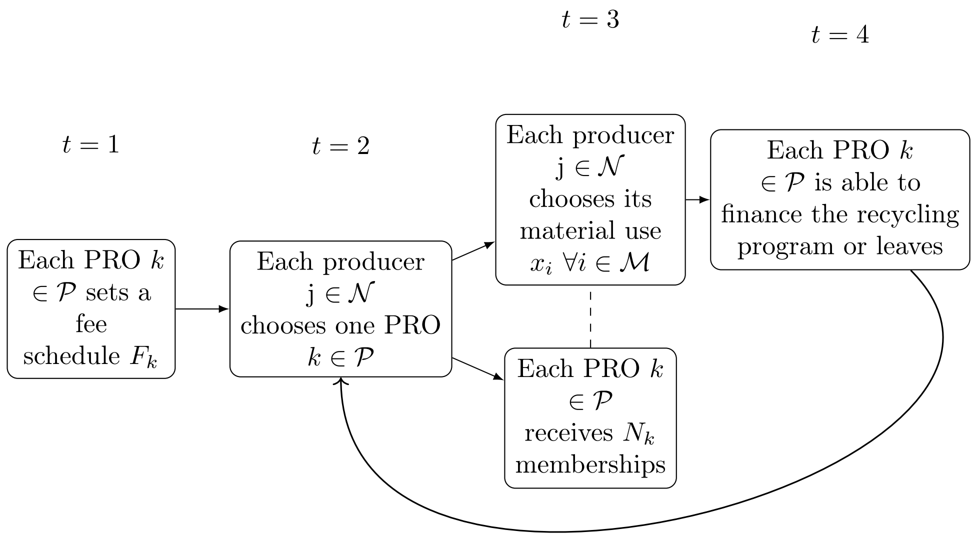


Figure 5: Exclusive competition

At $t = 2$, each producer plays a strategy S_j. It chooses one PRO $k \in \mathcal{P}$ to which it delegates all its material waste for a given fee schedule F_k.

$$\forall j \in \mathcal{N}, \quad S_j = \{k \in \mathcal{P}\} \tag{36}$$

At $t = 3$, each PRO $k \in \mathcal{P}$ knows its members N_k, a subset of $\mathcal{N}$. At the same time, each producer $j \in \mathcal{N}$ chooses its material use x_i $\forall i \in \mathcal{N}$ by minimising its production costs TC_j, according to the fee schedule F_k of the chosen PRO.

At $t = 4$, each PRO is able to finance the recycling program of its members or leaves the market.

4.6.2 Payoffs

Each agent plays with the intention of maximising its payoff. For each producer $j \in \mathcal{N}$ this is the minimisation of its production costs TC_j

$$TC_j = \sum_{i}^{m} f_i^k x_{i,j} + \frac{1}{2} c_i (x_{i,j}^0 - x_{i,j})^2 \tag{37}$$

A for-profit PRO aims at maximising its profit

$$\pi_{PRO,k} = \sum_{i}^{m} \sum_{j \in N_k} f_i^k x_{i,j} - r_i(w_i + a) x_{i,j} \tag{38}$$

A non-profit PRO aims at maximising its budget $\sum_i^m \sum_{j \in N_k} f_i^k x_{i,j}$, under a null profit.

4.6.3 Result

We solve this game using backward induction.

Producers choose the PRO with the fee schedule minimising their production costs. We showed in the last section that this is

$$F^* = \{r_1(w_1 + a), ..., r_n(w_n + a)\} \tag{39}$$

At the same time, PROs choose a fee schedule, that enables to satisfy the budget constraint at the producer level, as N_k is unknown. F^* allows financing the recycling program.

PROs may further compete for larger N_k by lowering a, i.e., competition *à la* Bertrand.

One reason of introducing competition is to incentivise PROs to look for cost efficiency in its own structure or downstream efficiency (e.g. tender process). In this model we take w_i as given but PROs can optimise administrative and operational costs by lowering $a \to 0$. We assume that there is no cost in decreasing a. The low-cost effect could in practice also have negative effects on collection quality (e.g. less budget for sorting campaigns).

In the case of exclusive competition, i.e. no decomposition of material flows, a Nash equilibrium is defined by $\mathcal{E} = \{\forall i \in \mathcal{M}, \forall k \in \mathcal{P}, f_i = r_i w_i\}$. No PRO has an interest in deviating from $\forall i \in \mathcal{M}, f_i = r_i w_i$.

- if some PROs set $f_i > r_i w_i$, they loose their market share and for each of them N_k is empty. Thus they have an incentive to set $f_i = r_i w_i$.
- if all PROs set $f_i > r_i w_i$, each $k \in \mathcal{P}$ has an incentive to deviate and set $f_i = r_i w_i$ to gain all market shares.
- if all or some PROs set $f_i < r_i w_i$, they leave the market. Thus they have an incentive to set $f_i = r_i w_i$ in order to stay in the market.

Hence opening competition between PROS, make all PROs converge to $\mathcal{E}$, be they for or non-profit, influenced or not, subject to modulation requirements or not. This leads us to Proposition 4.

Proposition 4. *Under competition, the pricing behaviour of all PROs converge to $\mathcal{E}$, an equilibrium without fee distortion and negligible a, without need for further regulation or producers' control.*

Proof. ... □

4.6.4 Non-exclusive Competition

We now consider that producers can decompose their material waste flows and eventually choose one PRO for each material.

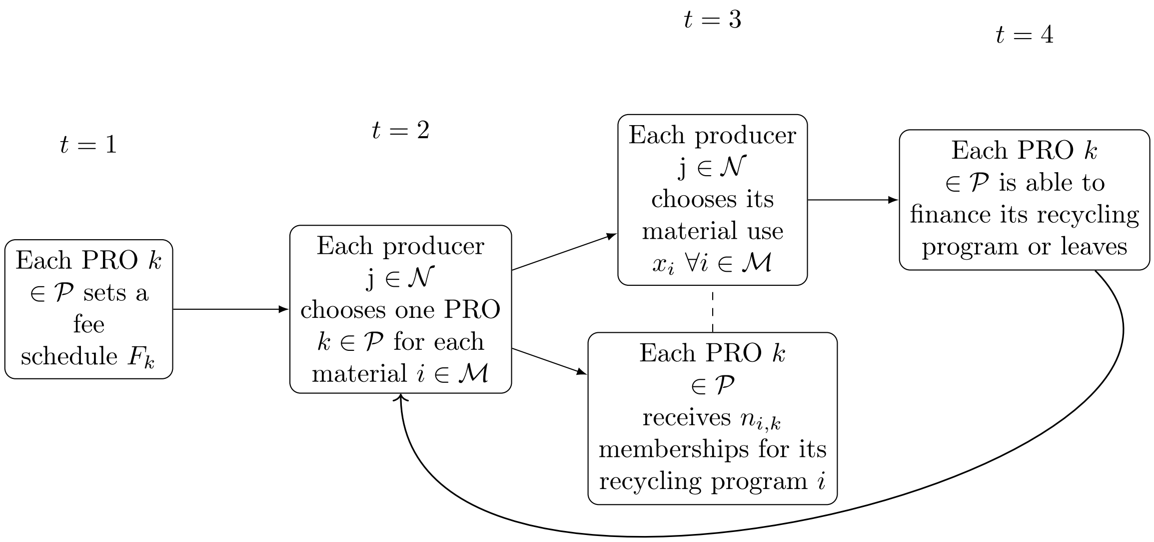


Figure 6: Non-exclusive competition

In this case we can expect a Bertrand competition on each material flow.

5 Interdependent use of materials

In this section we review our results when materials can be substituted or have complementary relations.

We consider two materials 1 and 2 who can be substitutes or complementary in a product. For instance, glass and plastic can substitutes to package water, but aluminium and carton are complementary in a milk brick.

We assume *symmetry of substitution costs*: $c_{1,2} = c_{2,1}$.

The producer minimises the total cost function (TC):

$$\text{TC}(q_1, q_2) = f_1 q_1 + f_2 q_2 + \frac{1}{2} c_1 (q_1^0 - q_1)^2 + \frac{1}{2} c_2 (q_2^0 - q_2)^2 + c_{1,2} (q_1^0 - q_1)(q_2^0 - q_2) \quad (40)$$

There exists a minimum if substitution costs are sufficiently low as compared to abatement costs (convex cost function):

$$c_1 c_2 > (c_{1,2})^2 \tag{41}$$

We obtain

$$q_i(q_j) = q_i^0 - \frac{f_i}{c_i} + \frac{c_{i,j}}{c_i}(q_j^0 - q_j) \tag{42}$$

If $c_{i,j} > 0$ materials are substitutable, else complementary.

We pose $\delta_{ij} = \frac{c_i c_j}{(c_{i,j})^2} > 1$

From the previous equation, we obtain the material use equation:

$$q_i* = q_i^0 - \frac{\delta_{ij}}{(\delta_{ij} - 1)} \left(\frac{f_i}{c_i} - \frac{c_{i,j}}{c_i c_j} f_j \right) \tag{43}$$

Equation 43 shows that the fee of a material j has an effect on the use of material i (increasing f_j increases q_i when $c_{i,j} > 0$).

5.1 Social Optimum

The social cost function (SC) writes as:

$$SC = \frac{1}{2}c_1(q_1^0 - q_1)^2 + \frac{1}{2}c_2(q_2^0 - q_2)^2 + c_{1,2}(q_1^0 - q_1)(q_2^0 - q_2) +$$
$$r_1(z_1 + \gamma r_1 + a)q_1 + r_2(z_2 + \gamma r_2 + a)q_2 + e_{R_1} r_1 q_1 + e_{r_2} r_2 q_2 + (1 - r_1)e_{D_1} q_1 + (1 - r_2)e_{D_2} q_2 \tag{44}$$

For $i = 1, 2$, we have

$$r_i^* = \frac{(e_{D_i} - e_{R_i}) - (z_i + a)}{2\gamma} \tag{45}$$

Like in the previous results, the optimal recycling rate increases with the environmental superiority of recycling over disposal and decreases with recycling and collection costs. The recycling rate is material-specific.

We obtain the following optimal quantities for material $i \neq j$:

$$q_i^* = q_i^0 - \frac{\delta_{ij}}{\delta_{ij} - 1} \left(\frac{A_i}{c_i} - \frac{c_{ij}}{c_i c_j} A_j \right) \tag{46}$$

And $A_i = r_i(z_i + \gamma r_i + a) + e_{R_i} r_i + (1 - r_i) e_{D_i}$. Using the optimal recycling rate expression, we can rewrite A_i it as f_i*

$$f_i* = e_{D_i} - \gamma(r_i*)^2 \tag{47}$$

Proposition 5 (optimal tarification)**.** *The optimal tarification requires to charge a material only with its own economic and environmental costs.*

5.2 PRO programme

The profit-maximising PRO maximises its profit taking into account the producer's behaviour (equation 43).

Proposition 6 (For-profit PRO)**.** *A profit-maximiser PRO sets its tariff in accordance with the firm's abatement costs and recycling costs of the material.*

$$f_i^* = \frac{1 - 2\alpha}{2 - 3\alpha}(c_i q_i^0 + c_{i,j} q_j^0) + \frac{1 - \alpha}{2 - 3\alpha} r_i (w_i + a) \tag{48}$$

$$\tag{49}$$

As before, the PRO increases f_i with $c_i q_i^0$ and recycling costs. It also increases f_i if substitution possibilities are expensive (high positive c_{ij}) and material j is abundantly used. If both materials are complementaries, the PRO decreases f_i because it anticipates that this will has reduction effect on other materials.

Taking r_i^* as given, the optimal fee is higher when taking substitution possibilities into account. The independent for-profit PRO inflates its fee knowing that substitution is costly.

The non profit PRO programme is when $\alpha = 0$:

$$f_i = \frac{A_i}{A_j} f_j + \frac{1}{2}(c_{i,j}q_j^0 + c_i q_i^0 - \frac{A_i}{A_j}(c_j q_j^0 + c_{i,j} qi^0)) \tag{50}$$

Again, the PRO systematically uses cross-subsidies to increase its size unless

$$\frac{A_i}{A_j} = \frac{c_i q_i^0 + c_{i,j} c_j^0}{c_j q_j^0 + c_{i,j q_i^0}} \tag{51}$$

Table 4: Results comparison

	$c_{i,i} = 0$ for all i, j	$c_{i,j} \neq 0$ for a unique $\{i, j\}$, $m = 2$
Optimal fee f_i^*	$r_i(w_i + a) + r_i e_{R_i} + (1 - r_i) e_{D_i}$	$r_i(w_i + a) + r_i e_{R_i} + (1 - r_i) e_{D_i}$
For-profit PRO ($\alpha = 0$) f_i	$\frac{1}{2}(c_i q_i^0 + r_i(w_i + a))$	$\frac{1}{2}(c_i q_i^0 + c_{i,j} q_j^0 + r_i(w_i + a))$
Producer-led PRO ($\alpha = \max(\alpha)$) f_i	$r_i(w_i + a)$	$r_i(w_i + a)$
f	$\frac{1}{2}\frac{\sum_{i=i_0+1}^{m}(q_i^0 + \frac{r_i(w_i+a)}{c_i})}{\sum_{i=i_0+1}^{m}\frac{1}{c_i}}$	$\frac{1}{2}\frac{\sum_{i=i_0+1}^{m}(q_i^0 + r_i(w_i+a)\frac{c_j - c_{i,j}}{c_i c_j - c_{i,j}^2})}{\sum_{i=i_0+1}^{m}\frac{c_j - c_{i,j}}{c_i c_j - c_{i,j}^2}}$

6 Conclusion

We have modelled the effects of EPR policy parameters on PROs' pricing behaviour.

We have shown that a monopolistic PRO has always an incentive to distort fees from recycling costs, be it for increasing its profit or its budget, as a non-profit. However, when the PRO is fully under producers' control, it equals fees at the exact recycling cost, for a null profit. These results are based on our model's hypotheses: homogenous and atomized product market, and a size maximisation objective for non-profit PRO.

Competitive PROs always charge the true recycling costs for a null profit, because this minimises the production costs of producers having no divergence of interest in their product design. Hence, producers always lobby for competitive PRO markets, to have the lowest fees and implicit control over the PRO. Environmental organisations lobby for 100% recycling and an independent for-profit monopolistic PRO for the highest tariffs for the priority of reducing material use. This strategy differs from the social planner which accounts for the feasibility of implementing a 100% recycling target. Both, the social planner and environmental organisations, require lower levels of materials in production when EPR only aim at economic internalisation.

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