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Extended producer responsibility: regulation design and responsibility sharing policies for a supply chain

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Abstract: In this paper, we study the problem of responsibility sharing for product recovery, and its relation to the design of Extended Producer Responsibility (EPR) regulations. By defining several scenarios for responsibility sharing policies, we show that designing an EPR regulation and allocating the responsibilities within the supply chain must be done simultaneously. Furthermore, we prove that sharing the penalties and rewards of collection and remanufacturing with the retailer has no financial or environmental impact if the manufacturer is collecting. However, making the retailer solely responsible to collect results in a higher collection rate, and in more new and fewer remanufactured products. Finally, a numerical analysis is performed for three electronic products to illustrate the use of our model. This research provides a set of guidelines for regulators seeking to improve environmental standards by designing and implementing EPR regulations.

Keywords: Extended producer responsibility, responsibility sharing, closed-loop supply chain, stackelberg game

Résumé : Dans cet article, nous étudions le problème du partage de responsabilités dans la récupération de produits usés et son lien avec la conception d'une réglementation relative à la *responsabilité élargie des producteurs* (REP). Nous considérons plusieurs scénarios de politiques de partage de responsabilités, et montrons que la conception d'une réglementation de REP et la répartition des responsabilités au sein d'une chaîne d'approvisionnement, formée d'un manufacturier et d'un détaillant, doivent être effectuées simultanément. De plus, nous montrons que le partage avec le détaillant des taxes et des subsides résultant de la collecte de produits usés et de la refabrication n'a pas d'impact financier ou environnemental si le manufacturier est l'agent désigné pour collecter les produits usés. Cependant, rendre le détaillant seul responsable de la collecte des produits usés entraîne un taux de collecte plus élevé, davantage de fabrication de produits nouveaux et moins de produits reconditionnés. Enfin, nous illustrons l'utilisation de notre modèle à travers trois exemples de produits électroniques. Cette recherche fournit un ensemble de lignes directrices aux régulateurs cherchant à améliorer les performances environnementales en concevant et en appliquant des réglementations en matière de REP.

Mots clés : Responsabilité élargie du producteur, partage des responsabilités, chaîne d'approvisionnement en boucle fermée, jeu de Stackelberg

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1 Introduction

Extended Producer Responsibility (EPR) is a regulatory approach whose aim is to shift the responsibility for managing end-of-use products from municipalities to producers. When defining an EPR, the social planner (SP) must (i) design the structure of the regulation and (ii) allocate the responsibilities and financial incentives, if any, to the different parties. This paper incorporates into a single framework both regulation design and responsibility allocation, with the aim of providing regulatory agencies with a tool to guide their policies.

The design part concerns the structure of the regulation itself, which, generally speaking, can take the form of a reward-penalty mechanism (Wang et al., 2015, 2017; Pazoki and Zaccour, 2018; Cheng et al., 2017), or a constraint on minimum product recovery process(es) (Jacobs and Subramanian, 2012). This area of research has attracted a great deal of attention from scholars and practitioners. However, the literature's main focus has been on how to design a regulation, while assuming that a single (centralized) entity will carry out the obligations resulting from that regulation. In other words, the literature does not specifically address how the rewards and penalties should be distributed among the supply chain members when designing the regulation. This distribution is a main concern of this paper.

Allocation of responsibilities is the other focus of EPR. One key aspect of defining an EPR regulation is the definition of *producer(s)*, a point on which the seemingly similar EPR regulations differ and where dispute may emerge. For instance, in 2008 the mayor of New York City, rejected a regulation requiring the manufacturers to collect and recycle 65% (volume-based) of the products they have previously produced. The mayor, Mr. Bloomberg, argued that manufacturers do not have the infrastructure to implement this regulation, and that wholesalers and consumers must also be held accountable. In Canada, EPR is in a similar situation, in that the definition of producer varies across provinces. For instance, in Manitoba and Quebec, only the first importers or brand owners of oil, filters and containers are targeted by EPR, but Alberta holds all producers and users responsible.[1] The EPR regulations for batteries in the US and Sweden are other examples of policies in which only the manufacturer is responsible for collecting the products (Tojo et al., 2003). Therefore, although it has been several years since EPR regulations began appearing, identifying the producer(s) in the value chain remains an administrative challenge (OECD, 2014). Defining who the producers are involves clarifying the responsibilities allocated to supply chain members.

The allocation of responsibilities among supply chain members is referred to as the Responsibility Sharing Policy (RSP). Typically, responsibilities are categorized as physical or financial, with specific definitions being given to each. *Physical responsibility sharing* refers to the distribution of recovery activities such as collection, recycling, and reuse among supply chain members (also referred to as operational responsibility). *Financial responsibility sharing*, then, implies the allocation of collection, recycling, and reuse costs among supply chain members. Jacobs and Subramanian (2012) study the problem of sharing financial responsibilities between a supplier and a manufacturer, where there are mandates for minimum collection and recycling levels. Cheng et al. (2017) decide on which member should collect the products, while both members can be financially involved in collection and remanufacturing efforts, and where the degree to share financial responsibility is a decision variable of the more powerful member. While the literature on RSP generally focuses on the firm's point of view, the social planner has a different perspective. Its aim is to know who is responsible for what action, and how incentives are to be distributed between the parties. In this paper, we deviate from previous definitions in order to meet the SP's need and to cope with the potential disputes mentioned above. Throughout this paper, the member who is physically responsible for a certain process will also pay the cost of the process (Chen and Chen, 2017).[2] Furthermore, as in Wang et al. (2015), the allocation of penalties or subsidies defined through regulation will be called financial responsibility sharing. One question that has not been fully addressed in the literature is whether distributing financial responsibilities is the best social option, and whether sharing physical responsibilities is likely to improve or worsen the environmental outcome. In this paper, we want to also address this question.

[1] *Extended Producer Responsibility: current status, challenges and perspectives*, Quebec's Ministry of Sustainable Development, the Environment and the Fight Against Climate Change, source: http://www.assnat.qc.ca/en/deputes/melancon-isabelle-16779/coordonnees.html, March 2008.

[2] If a certain supply chain member, who collects or remanufactures the products, is not financially responsible for doing so, the distribution of physical responsibilities merely involves delegating them.

Our work contributes to the literature by integrating the two focuses of EPR, namely, regulation design and responsibility allocation. Firstly, we study the simultaneous allocation of physical and financial responsibilities in a generic supply chain to figure out which policy serves which of the social planner's goals. At the same time, this should clarify whether whether physical and financial responsibility allocations are interrelated. Secondly, we determine how the distribution of responsibilities affects regulation design decisions. In other words, this research reveals if the way in which responsibilities are distributed affects how the regulation performs toward achieving its goal. If we find that there is a relation between RSP and the choice of parameters in EPR regulations, this would be the first research to provide regulators with a complete set of tools for designing regulations and for distributing responsibilities among the supply chain members.

In this paper, we consider a supply chain consisting of a manufacturer and a retailer who sells new and remanufactured products to the same market. A performance-based regulation is employed to explore regulation design strategies. To understand and investigate the responsibility sharing policies, we study the regulated supply chain under different scenarios, in which product recovery responsibilities are either centralized or shared between the supply chain members. First, we show that allocation of physical responsibilities and financial incentives should be done in an integrated manner. Subsequently, the underlying relation between the responsibility sharing policy and regulation design is uncovered. Second, we show that transferring all responsibility for collection to the retailer yields higher collection rates and also a lower remanufacturing quantity, which makes it a good strategy to boost material recycling but a bad strategy to promote remanufacturing.

The remainder of this paper is organized as follows. In Section 2, the assumptions, RSP scenarios, and their mathematical models are presented. The proposed models are solved and analyzed in Section 3. Section 4 is devoted to comparing the proposed scenarios in order to address the research questions and obtain valuable insights about EPR design and the RSP problem. While Section 4 analyzes the scenarios from an environmental performance perspective, Section 5 comments on the financial implications of RSP scenarios and regulatory approaches. Finally, we conclude in Section 6.

2 Model

In order to address financial and physical responsibility sharing policies, we characterize and contrast the results of four different scenarios. First we introduce the assumptions that are common to all scenarios, and next we define them.

2.1 Assumptions

The supply chain is formed of one manufacturer and one retailer. The manufacturer produces a good that comes in two varieties, namely, a new product (N) that is manufactured with new material, and a remanufactured product (R). The manufacturer decides the wholesale price w_i of product i, and the retailer chooses the quantity to order $q_i; i = N, R$. We assume that the game is played à la Stackelberg, with the manufacturer acting as leader (first announcing its wholesale prices) and the retailer as follower. Next, we introduce our main assumptions related to time horizon, prices and quantities, collection rate, EPR regulation, and performance measures. Table 1 gives the notation used throughout the paper.

Time horizon: We consider a mature market operating at its steady-state value, that is, a situation where the decisions and parameter values do not vary over time. A single-period model has often been used in the literature (see, e.g., Jacobs and Subramanian, 2012; and Bulmuş et al., 2014). Although the motivation behind this approach is tractability, we believe that with a simple model we will still be able to shed a light on our research questions.

Prices and quantities: The new and remanufactured products are imperfect substitutes, with the customers discounting on their willingness to pay for the remanufactured products. The inverse demand functions are assumed to be linear and given by $p_N = 1 - q_N - \delta q_R$ and $p_R = \delta(1 - q_N - q_R)$. These demand functions (i) capture vertical differentiation between the two products and also consider the outside good option (Debo et al., 2005; Bulmuş et al., 2014; Abbey et al., 2017); (ii) are micro-founded, that is, they are derived from consumer maximization of a quadratic utility; and (iii) are empirically robust (see Abbey et al., 2017).

Table 1: Model notation

Variables	
q_N	Quantity of brand new products
q_R	Quantity of remanufactured products
w_N	Wholesale price of brand new products
w_R	Wholesale price of remanufactured products
τ	Collection rate
Parameters	
c_τ	Collection cost coefficient
c_R	Remanufacturing cost per unit of product
c_N	Manufacturing cost per unit of product
π_A	Collection target rate
π_R	Remanufacturing target rate
θ_A	Deviation incentive for collection target
θ_R	Deviation incentive for remanufacturing target
δ	Remanufactured products discount factor
α	Price of selling a collected product to a recycler
ϕ	Manufacturer's share of financial responsibility

Collection rate: The chain member who is responsible for collection decides upon the collection rate τ, which is defined as the ratio of collected products to brand new products. τ is realized by implementing product return programs, which include, but not limited to, all activities that mentally and financially encourage the customers to bring back used products instead of discarding them. These activities (which are also known as green activities in the literature) include communicating the merits of product recovery, offering monetary incentive for returning the used products, installing collection points, and advertising the possible ways of returning the products. For a more detailed description of green activities and product recovery programs, see De Giovanni et al. (2016) and De Giovanni and Zaccour (2014). To account for marginal decreasing returns, the cost of these activities is assumed to be convex increasing and given by $C(\tau) = c_\tau \tau^2$, with $c_\tau > 0$. The parameter c_τ is interpreted as collection efficiency and will increase for more expanded collection infrastructures. This assumption is common in the literature on closed-loop supply chains, both for single-period and dynamic models; see, e.g., De Giovanni (2011), De Giovanni et al. (2016), De Giovanni and Zaccour (2014), and Jøorgensen and Zaccour (2003).

EPR regulation: To a large extent, EPR regulation is about collecting (acquiring) and remanufacturing used products. We suppose that regulation takes the following reward/penalty form in the manufacturer's optimization problem:

$$f(q_N, q_R, \tau) = \theta_A q_N(\pi_A - \tau) + \theta_R(\tau \pi_R q_N - q_R). \tag{1}$$

The regulation embedded in Equation (1), which is proposed in Pazoki and Zaccour (2018), merits three comments. First, collection normally applies to past sold products, and consequently we should expect a lagged sales term in the above function. Given our assumption that the market is at its steady-state value, we are capturing collection by a contemporary term, τq_N. Second, our EPR function mimics a number of established regulations with specific values for target rates and deviation incentives (e.g., take-back, tax incentive, and carbon emission tax). Third, our formulation is very flexible as it allows the regulator to implement high/low targets (i.e., π_A and π_R) combined with high/low incentives (i.e., θ_A and θ_R), leading to a large range of regulatory policies.

Remark 1 *There can be four regulatory approaches for collection and remanufacturing: (i) strictly penalizing (high target rate and high deviation incentive); (ii) strictly rewarding (low target rate and high deviation incentive); (iii) weakly penalizing (high target rate and low deviation incentive); and (iv) weakly rewarding (low target rate and low deviation incentive). The latter can be seen as no regulation since there is a tendency to put both values to zero and subsequently deregulate the market. The terms "weakly rewarding" and "no regulation" are used interchangeably in this paper.*

Performance measures: The role of the social planner is to design an EPR regulation. We do not assign the regulator a specific objective to optimize, but suppose that the SP has various objectives in mind. In this sense, we wish to provide the SP with a decision support model that makes it possible to simulate at will the impact of the four parameters under its control, i.e., π_A, π_R, θ_A, θ_R, and of course the RSP. We retain the following performance criteria:

Product landfill. Reducing the volume of used products ending up in landfill is a self-defining objective that is of particular interest when the production process involves toxic materials (Atasu et al., 2009).[3] This objective is quantified by $q_D = (1 - \tau)q_N$.

Collection rate. This rate is an indicator of the ratio of the materials being reclaimed and saved to the new materials (De Giovanni and Zaccour, 2014). Although τ appears in q_D, distinguishing between the two objectives is of interest in itself, but especially when τ and q_N are not under the control of the same player.

Total energy consumption. This indicator has been proposed in, e.g., Gutowski et al. (2011) and Raz et al. (2017). The assumption is that the environmental impact is measured by energy consumption throughout the product's entire life cycle, which consists of manufacturing (m), remanufacturing (rm), landfill (d), recycling (rc), and usage (u) stages. Denote by e_i the per-unit energy consumption at each stage. Then, the total environmental impact of manufacturing and remanufacturing are $E_m = e_m q_N$, and $E_{rm} = e_{rm} q_R$, respectively. The quantity of recycled products is $\tau q_N - q_R$. Therefore, the environmental impacts of recycling is $E_{rc} = e_{rc}(\tau q_N - q_R)$. Assuming that the product is remanufacturable only once (a pessimistic point of view), the environmental impact of landfilling would be $E_d = e_d((1-\tau)q_N + q_R)$. Finally, at the usage stage, we have $E_u = e_u(q_N + q_R)$. The total environmental impact is then given by $E = E_m + E_{rm} + E_{rc} + E_d + E_u$, that is,

$$E = (e_m + e_d + (e_{rc} - e_d)\,\tau + e_u)\, q_N + (e_{rm} - e_{rc} + e_d + e_u)\, q_R.$$

2.2 Scenarios

We introduce and investigate four scenarios defined in terms of how the financial and physical responsibilities are shared between the manufacturer and the retailer. For physical responsibilities, we consider two options. The first, more traditional, option is to also hold the manufacturer responsible for collection.[4] In the second one, the retailer is required to collect (and recycle), while the manufacturer is responsible for remanufacturing (Chen et al., 2018).[5] Ultimately, the decision about who should be in charge of collection depends on the regulator's goal as well as on the product type, existing infrastructures, and other preexisting conditions. Financial responsibilities could be designed such that each supply chain member is financially responsible only for its own task, or to have both members being financially responsible for both their actions. This latter case is retained for two reasons: (i) it acts as a benchmark for investigating the impact of financial responsibility sharing policy, and (ii) it allows the regulator to still influence the retailer when collecting is the manufacturer's duty; otherwise, the retailer would not be affected directly by the EPR regulation. A similar approach is adopted in Wang et al. (2015), where one player is responsible for collection while both players pay the penalty or receive the reward.

As in all considered scenarios, we assume, not unrealistically, that remanufacturing can only be done by the manufacturer, we do not need to highlight it in the labeling of the different scenarios.

Remark 2 *The equilibrium results of each scenario (not in its statement to avoid unduly complicating the notation) will be superscripted with two letters, the first referring to the player in charge of collection, that is, m or r, and the second referring to the financial responsibility, which can either be own responsibility (O) or shared proportionally between the two players (P). The four scenarios, which are depicted in Figure 1, are now formally defined.*

[3] Article 5 of Directive 2012/19/EU of the European Parliament and of the Council on Waste Electrical and Electronic Equipment (WEEE), July 2012, mentions: "Member states shall adopt appropriate measures to minimise the disposal of WEEE...."

[4] Depends on the definition of producer in that specific region.

[5] In Article 5 of Directive 2012/19/EU of the European Parliament and of the Council on Waste Electrical and Electronic Equipment (WEEE), July 2012, it is stated that:"...distributors provide for collection....free of charge for the end-users..."

Financial Responsibility \ Physical Responsibility	Centralized	Shared
Centralized	mO	rO
Shared	mP	rP

Figure 1: Scenarios defined based on the sharing of financial and physical responsibilities

Scenario mO**.** The manufacturer is responsible for collection and bears the financial responsibility. The optimization problems of the manufacturer and the retailer are as follows:

$$\begin{aligned} \max_{w_N, w_R, \tau} \Pi^m &= (w_N - c_N)q_N + (w_R - c_R)q_R - c_\tau \tau^2 - (\pi_A - \tau)q_N\theta_A \\ &\quad -(\tau\pi_R q_N - q_R)\theta_R + \alpha(\tau q_N - q_R), \\ \max_{q_R, q_N} \Pi^r &= (1 - q_N - \delta q_R - w_N)q_N + (\delta(1 - q_N - q_R) - w_R)q_R. \end{aligned}$$

Scenario mP**.** The manufacturer is in charge of collecting used products, while the financial responsibility is shared between the two members of the supply chain. The optimization problems of the manufacturer and the retailer are as follows:

$$\begin{aligned} \max_{w_N, w_R, \tau} \Pi^m &= (w_N - c_N)q_N + (w_R - c_R)q_R - \phi((\pi_A - \tau)q_N\theta_A \\ &\quad +(\tau\pi_R q_N - q_R)\theta_R) + \alpha(\tau q_N - q_R) - c_\tau \tau^2, \\ \max_{q_R, q_N} \Pi^r &= (1 - q_N - \delta q_R - w_N)q_N + (\delta(1 - q_N - q_R) - w_R)q_R \\ &\quad -(1-\phi)((\pi_A - \tau)q_N\theta_A + (\tau\pi_R q_N - q_R)\theta_R), \end{aligned}$$

where $1 - \phi$ is the share of the retailer in the financial incentive. The parameter ϕ $(0 < \phi < 1)$ is under the regulator's control.

Scenario rO**.** The retailer is responsible for collection and bears the financial responsibility. The optimization problems of the manufacturer and the retailer are as follows:

$$\begin{aligned} \max_{w_N, w_R} \Pi^m &= (w_N - c_N)q_N + (w_R - c_R)q_R - (\tau\pi_R q_N - q_R)\theta_R, \\ \max_{q_R, q_N, \tau} \Pi^r &= (1 - q_N - \delta q_R - w_N)q_N + (\delta(1 - q_N - q_R) - w_R)q_R \\ &\quad -(\pi_A - \tau)q_N\theta_A + \alpha(\tau q_N - q_R) - c_\tau \tau^2. \end{aligned}$$

Scenario rP**.** The retailer collects used products, while the financial responsibility is shared between the two members of the supply chain. The optimization problems of the manufacturer and the retailer are as follows:

$$\begin{aligned} \max_{w_N, w_R} \Pi^m &= (w_N - c_N)q_N + (w_R - c_R)q_R - \phi((\pi_A - \tau)q_N\theta_A \\ &\quad +(\tau\pi_R q_N - q_R)\theta_R), \\ \max_{q_R, q_N, \tau} \Pi^r &= (1 - q_N - \delta q_R - w_N)q_N + (\delta(1 - q_N - q_R) - w_R)q_R - c_\tau \tau^2 \\ &\quad -(1-\phi)((\pi_A - \tau)q_N\theta_A + (\tau\pi_R q_N - q_R)\theta_R) + \alpha(\tau q_N - q_R). \end{aligned}$$

For all the models presented above, the following constraints must be satisfied:

$$\begin{aligned}
\text{Nonnegativitity contraints} &: \quad q_N, \tau, q_R \geq 0, \\
\text{Upper bound on collection rate} &: \quad \tau \leq 1, \\
\text{Upper bound on manufacturing} &: \quad q_N \leq 1, \\
\text{Upper bound on remanufacturing} &: \quad q_R \leq \tau q_N.
\end{aligned}$$

These scenarios merit the following comments: (i) Scenario mO corresponds to many real-life cases. An illustrative example is the Rethink Tires program in Ontario, Canada, where used tires must be recycled, reused, or disposed of in an environmentally safe way; and the program is wholly funded by the brand owners or first importers.[6] (ii) Scenarios with proportional financial responsibility (mP and rP) have been considered by Wang et al. (2015), whose study was motivated by the China's need to design an incentive policy for electronic products. Finally, (iii) contrasting two scenarios that differ in only one feature will allow us to isolate and assess the impact of that feature. For instance, contrasting the results of scenarios mP and mO gives the regulator a measure of the impact of varying financial responsibility on performance criteria.

3 Results

We shall (essentially) do the following for each of our scenarios: First, we provide the follower's (retailer's) reaction functions and comment on the strategic relationship between the manufacturer's and the retailer's decisions. Second, we give the equilibrium values, assuming an interior solution. Third, we state the conditions under which the solution is indeed interior. Finally, we comment on (some) corner solutions.

Before proceeding to the solutions, we introduce the following notation to simplify the presentation and discussion of the results:

$$\begin{aligned}
\text{Recycling profit} &: \quad A = \alpha + \theta_A - \pi_R \theta_R \\
\text{Retailer's recycling profit} &: \quad A_{rP} = \alpha + (1-\phi)(\theta_A - \pi_R \theta_R) \\
\text{Retailer's recycling profit} &: \quad A_{rO} = \alpha + \theta_A \\
\text{Potential remanufacturing profit} &: \quad L = \delta - 1 + c_N - c_R + \theta_R + \pi_A \theta_A - \alpha.
\end{aligned}$$

Recycling profit (A): If a product is collected but not remanufactured, the supply chain is rewarded[7] by $\theta_A - \pi_R \theta_R$. The collected products must then be recycled, and the recycling profit (or cost) is α. Therefore, $A = \alpha + \theta_A - \pi_R \theta_R$ is the recycling cost/profit for the whole supply chain.

Retailer's recycling profit A_{rP}: This parameter is specific to scenario rP where the retailer collects but the rewards and penalties are distributed between the retailer and the manufacturer by the factor of ϕ. In this sense, while the retailer earns α from recycling the collected product, its share of the regulation reward is $(1-\phi)(\theta_A - \pi_R \theta_R)$. Therefore, $A_{rP} = \alpha + (1-\phi)(\theta_A - \pi_R \theta_R)$. We assume that the regulation on collection is more strict than the regulation on remanufacturing, resulting in $\theta_A > \pi_R \theta_R$. Because the regulation of remanufacturing is not widely defined, and where it is defined, the collection regulation is more strictly enforced, we claim that the addressed assumption is the case in most (if not all) real life cases. Consequently, $A > A_{rP}$ holds, and we assume that it is the case throughout this paper, unless otherwise stated.

Retailer's recycling profit A_{rO}: This parameter shows up in scenario rO, where the retailer is the sole responsible for collection. In this sense, it sells the product for α and pays θ_A less in penalties. Therefore, its gain for recycling the product is $A_{rO} = \alpha + \theta_A$.

[6] See http://rethinktires.ca/program-participants

[7] Reward is equivalent to not paying the penalty.

Potential remanufacturing profit L**:** If a collected product is remanufactured, the supply chain saves $\theta_R + \pi_A\theta_A$ in penalties (considering that one more unit of remanufactured product means one less unit of new product, and assuming that the collected quantity is not changed). The maximum possible prices for the new and remanufactured products are 1 and δ, while they cost c_N and c_R, respectively. Therefore, the potential gain on a remanufactured product is $\delta - c_R$ and the potential loss of not selling a new product is $1 - c_N$. Furthermore, the profit from recycling is α, which will be lost if a collected product is remanufactured instead of being recycled. Therefore, the potential remanufacturing profit, which consists of the potential gain from remanufacturing, the potential loss caused by cannibalization, and the loss from not recycling the product, would be $L = \delta - 1 + c_N - c_R + \theta_R + \pi_A\theta_A - \alpha$.[8]

Furthermore, let $S = 8c_\tau(1-\delta)$, which represents the attractiveness of the remanufactured product and the collection cost-efficiency. Defining the above parameters brings us to the following conditions: if (i) the consumer discount factor for remanufactured products is low, (ii) collection is not being done cost-efficiently, and (iii) the recycling profit is not large enough, then $A^2 - S < 0$, $2A_{rP}A - S < 0$ and $2A_{rO}A - S < 0$. Given these new secondary parameters, we now characterize the equilibrium in the different scenarios.

Scenario mO**.** Assuming an interior solution, the reaction functions of the retailer are given by

$$q_N(w_R, w_N, \tau) = \frac{1 - \delta + w_R - w_N}{2(1-\delta)}, \tag{2}$$

$$q_R(w_R, w_N, \tau) = \frac{\delta w_N - w_R}{2\delta(1-\delta)}. \tag{3}$$

The retailer's order for each product is (i) decreasing in the wholesale price of that product, that is, we have strategic substitution; (ii) increasing in the wholesale price of the other product (strategic complementarity); and (iii) independent of the collection rate τ (strategic independence).

The manufacturer, as the leader, takes into account the above reaction functions in its optimization problem. Proposition 1 presents the unique equilibrium values for scenario mO.

Proposition 1 *Assuming an interior solution, the unique Stackelberg equilibrium is given by*

$$\begin{aligned}
w_N^{mO} &= \frac{1 + c_N + \pi_A\theta_A}{2} - \frac{A^2|L|}{2(S - A^2)},\\
w_R^{mO} &= \frac{\delta - \theta_R + c_R + \alpha}{2},\\
\tau^{mO} &= \frac{A|L|}{S - A^2},\\
q_N^{mO} &= \frac{2c_\tau|L|}{S - A^2},\\
q_R^{mO} &= \frac{(\delta + \theta_R - \alpha - c_R)}{4\delta} - \frac{2c_\tau|L|}{S - A^2}.
\end{aligned}$$

Proof. First, we substitute the retailer's reaction functions in the manufacturer's optimization problem. Second, assuming an interior solution, differentiating the profit function with respect to w_R, w_N, and τ, and equating to zero, yields the results. The required condition for the manufacturer's objective function concavity is $S - A^2 > 0$, which requires costly remanufacturing ($L < 0$) □

[8] In the definitions of A, A_{rP}, A_{rO}, and L, it is assumed that the product is already collected. This way, the collection cost is not included in the recycling profit. Since the collection cost function is not linear, the marginal collection cost changes with the amount of production. Therefore, one can interpret the introduced parameters as we have or as the fixed part of the marginal profit or costs, or as potential cost or profit indicators.

The results in the above proposition merit the following comments:

1. A stricter remanufacturing regulation means a lower remanufacturing cost $|L|$ and a higher penalty for not remanufacturing for the manufacturer. Therefore, on the one hand, it reduces w_R^{mO} to encourage the retailer to order more remanufactured products, and on the other hand, it reduces the collection rate and increases w_N^{mO} to shift the demand from new to remanufactured products.
2. A larger collection target rate results in a higher recycling profit (A), and consequently, the manufacturer increases the collection rate to gain more profit from recycling.
3. If the recycling unit profit (α) increases, the recycling profit (A) and the remanufacturing cost ($|L|$) increase. Under this condition, the manufacturer increases the collection rate and the remanufactured products' wholesale price while reducing the new products' wholesale price at the same time, in order to force the retailer to order more new and fewer remanufactured products, and consequently, having more products to recycle.

Proposition 1 assumes an interior solution. In the next proposition, we provide the conditions under which this assumption holds true.

Proposition 2 *Let $J = S - A^2$, and $\Delta = 1 + A(\delta + \theta_R - c_R - \alpha)/2\delta c_\tau$. The required conditions for an interior solution are*[9]

$$\pi_A \leq \frac{1}{\theta_A}\left(\frac{-J(\sqrt{\Delta}-1)}{2A} + 1 - \delta + c_R - c_N + \alpha - \theta_R\right),$$

$$\pi_A \geq \frac{1}{\theta_A}\left(\frac{-J}{A} + 1 - \delta + c_R - c_N + \alpha - \theta_R\right),$$

$$\pi_A \geq \frac{1}{\theta_A}\left(\frac{-J(\delta + \theta_R - \alpha - c_R)}{8c_\tau \delta} + 1 - \delta + c_R - c_N + \alpha - \theta_R\right),$$

Proof. See Appendix 7.1. □

The interior solution conditions are translated into two lower bounds and one upper bound for the collection target rate. On the lower bounds or below, the manufacturer either stops remanufacturing or it collects all the products (see Appendix 7.1). On the upper bound or above, no collected product would be recycled.

To illustrate, we provide a numerical example. Since there are 6 constraints, generally, the feasible region can be divided into a maximum number of 2^6 areas. However, in our case, the maximum number of possible regions is 6 for the following reasons: (i) under a certain set of inputs, none of the curves intersect another one; (ii) the nonnegativity constraint on remanufacturing guarantees an upper bound for the manufacturing constraint; (iii) the upper bound on the remanufacturing constraint guarantees the nonnegativity of the collection rate constraint; (iv) the non-negativity constraints for the manufacturing and the collection rate coincide; and (v) either the non-negativity constraint on remanufacturing guarantees the upper bound on the collection constraint, or vice versa. Therefore, the region for an interior solution is built by 2 constraints, and the total number of possible regions is 4. Figure 2 depicts the discussed regions. (The numerical values are given in Appendix 7.2.)

[9] These conditions can be rewritten more compactly as

$$\frac{1+\alpha-\delta-\theta_R+c_R-c_N}{\theta_A} - \frac{1}{\theta_A}\max\left\{\frac{J}{A}, \frac{J(\delta+\theta_R-\alpha-c_R)}{8\delta c_\tau}\right\} \leq \pi_A$$

$$\leq \frac{1+\alpha-\delta-\theta_R+c_R-c_N}{\theta_A} - \frac{J}{2A\theta_A}\left(\sqrt{1+\frac{A(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}} - 1\right).$$

However, for interpretation purposes, it is easier to proceed as done in the proposition.

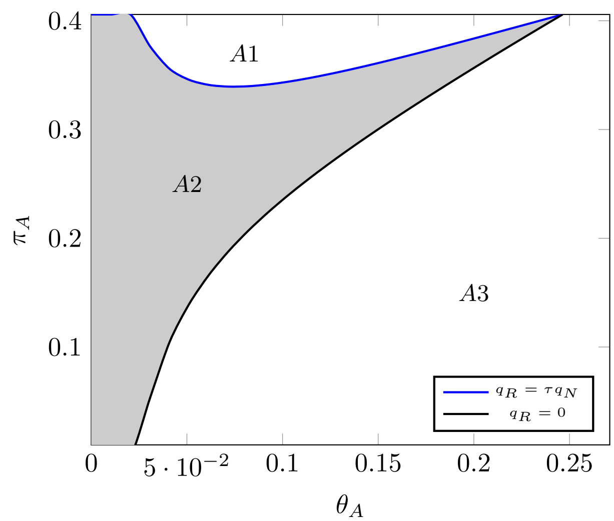

Figure 2: Feasible area for π_A and θ_A in mO scenario

Region *A1* denotes the no-recycling region. In other words, all collected products are remanufactured. In region *A2*, the solution is interior, meaning that a proportion of the products is collected and a proportion of the collected products is remanufactured. In region *A3*, however, the manufacturer stops remanufacturing. The area where collection is stopped is positioned beyond the domain, which is determined by the nonnegativity and upper-bound conditions.

Scenario mP: In this scenario, the retailer maximizes

$$\begin{aligned}\Pi^r_{mP} \;=\;& (1 - q_N^{mP} - \delta q_R^{mP} - w_N^{mP})q_N^{mP} + (\delta(1 - q_N^{mP} - q_R^{mP}) - w_R^{mP})q_R^{mP} \\ & -(1-\phi)((\pi_A - \tau^{mP})q_N^{mP}\theta_A + (\tau^{mP}\pi_R q_N^{mP} - q_R^{mP})\theta_R),\end{aligned}$$

where $1-\phi$ is the proportion of the financial incentive shifted to the retailer. The reaction functions of the retailer are

$$q_N^{mP} = \frac{(1-\phi)(\theta_A(\tau^{mP} - \pi_A) - \theta_R - \pi_R\theta_R\tau^{mP}) - w_N^{mP} + w_R^{mP} - \delta + 1}{2(1-\delta)}, \tag{4}$$

$$q_R^{mP} = \frac{(1-\phi)(\delta\theta_A(\pi_A - \tau^{mP}) + \theta_R + \delta\pi_R\theta_R\tau^{mP}) - w_R^{mP} + \delta w_N^{mP}}{2\delta(1-\delta)}. \tag{5}$$

Like in scenario mO, the retailer's orders are increasing in the other product's wholesale price and decreasing in the same product's wholesale price. However, the collection rate is now involved in the retailer's reaction functions; the orders of new and remanufactured products decrease and increase in the collection rate, respectively. Furthermore, comparing (4) and (5) with (2) and (3) reveals that by sharing the financial incentives, the SP has direct control (in addition to indirect control through the manufacturer) over the retailer's reaction functions by the terms $(1-\phi)(\theta_A(\tau^{mP} - \pi_A) - \theta_R - \pi_R\theta_R\tau^{mP})$ and $(1-\phi)(\delta\theta_A(\pi_A - \tau^{mP}) + \theta_R + \delta\pi_R\theta_R\tau^{mP})$, for q_N and q_R, respectively. Furthermore, the collection rate has entered the retailer's reaction functions, giving the manufacturer more control over the retailer.

Taking into account the retailer's reaction functions, the manufacturer's total profit is

$$\begin{aligned}\Pi^m_{mP} \;=\;& (w_N^{mP} - c_N)q_N^{mP} + (w_R^{mP} - c_R)q_R^{mP} - \phi((\pi_A - \tau^{mP})q_N^{mP}\theta_A + (\tau^{mP}\pi_R q_N^{mP} - q_R^{mP})\theta_R) \\ & +\alpha(\tau^{mP}q_N^{mP} - q_R^{mP}) - c_\tau(\tau^{mP})^2,\end{aligned}$$

where ϕ is the manufacturer's share of the financial responsibilities.

Proposition 3 *Assuming an interior solution, the unique Stackelberg equilibrium is given by*

$$\begin{aligned} w_N^{mP} &= \frac{(1-2\phi)(\theta_A(\tau^{mP}-\pi_A)-\pi_R\theta_R\tau^{mP})+1+c_N-\alpha\tau^{mP}}{2}, \\ w_R^{mP} &= \frac{(1-2\phi)\theta_R+\delta+\alpha+c_R}{2}, \\ \tau^{mP} &= \frac{A|L|}{S-A^2}, \\ q_N^{mP} &= \frac{2c_\tau|L|}{S-A^2}, \\ q_R^{mP} &= \frac{(\delta+\theta_R-\alpha-c_R)}{4\delta}-\frac{2c_\tau|L|}{S-A^2}. \end{aligned}$$

Proof. See the proof for Proposition 1. The necessary and sufficient condition for the manufacturer's objective function concavity is $A^2 - S < 0$. □

To keep it compact, the equilibrium value for w_N^{mP} is written in terms of τ^{mP}. The equilibrium collection rate in this scenario is the same as in scenario mO where the manufacturer is the only one financially responsible for product recovery. Therefore, although the SP can directly affect the retailer's reaction functions, the transactions between the retailer and the supplier nullify the SP's control. Thus, the environmental outcome is not changed by sharing the financial incentives if the physical responsibilities are centralized to the manufacturer. The only impact of implementing this scenario is the redistribution of the total profit between the supply chain members.

Since the market outcomes (production, collection, and discarded quantities) are the same for mO and mP, the same conclusions reached from the corner solutions and sensitivity analysis of mO can also be reached for mP.

Scenario rP: In this scenario, the retailer maximizes

$$\begin{aligned} \Pi_{rP}^r &= (1-q_N^{rP}-\delta q_R^{rP}-w_N^{rP})q_N^{rP}+(\delta(1-q_N^{rP}-q_R^{rP})-w_R^{rP})q_R^{rP}-c_\tau(\tau^{rP})^2 \\ &\quad -(1-\phi)((\pi_A-\tau^{rP})q_N^{rP}\theta_A+(\tau^{rP}\pi_R q_N^{rP}-q_R^{rP})\theta_R)+\alpha(\tau^{rP}q_N^{rP}-q_R^{rP}), \end{aligned}$$

and, assuming an interior solution, the best responses of the retailer are

$$q_N^{rP} = \frac{2c_\tau(1-\delta-w_N^{rP}+w_R^{rP}-(1-\phi)(\theta_R+\pi_A\theta_A))}{S/2-A_{rP}^2}, \tag{6}$$

$$q_R^{rP} = \frac{\delta-w_R^{rP}+(1-\phi)\theta_R-\alpha}{2\delta}-\frac{2c_\tau(1-\delta-w_N^{rP}+w_R^{rP}-(1-\phi)(\theta_R+\pi_A\theta_A))}{S/2-A_{rP}^2}, \tag{7}$$

$$\tau^{rP} = \frac{q_N^{rP}A_{rP}}{2c_\tau}. \tag{8}$$

Note that since $A_{rO} > A > A_{rP}$ and $S - 2A_{rO}A > 0$, we conclude that $S - 2A_{rP}^2 > 0$, and consequently, the nonnegativity of q_N^{rP} requires $1 - \delta - w_N^{rP} + w_R^{rP} - (1-\phi)(\theta_R + \pi_A\theta_A) > 0$. This term can be interpreted as the potential remanufacturing loss for the retailer. Similarly to the retailer's best response in scenarios mO and mP, the quantity of new products is increasing in the remanufactured products' wholesale price and is decreasing in its own wholesale price. The exact opposite observations are made for the quantity of remanufactured products. Finally, as expected, a larger retailer's profit for recycling, a more cost-efficient collection, and a higher collection rate are equivalent to more brand new production.

Taking into account the retailer's reaction functions, the manufacturer maximizes

$$\Pi_{rP}^m = (w_N^{rP}-c_N)q_N^{rP}+(w_R^{rP}-c_R)q_R^{rP}-\phi((\pi_A-\tau^{rP})q_N^{rP}\theta_A+(\tau^{rP}\pi_R q_N^{rP}-q_R^{rP})\theta_R).$$

Proposition 4 *Assuming an interior solution, the unique Stackelberg equilibrium is given by*

$$\begin{aligned}
w_N^{rP} &= \frac{(1-2\phi)\theta_R + 2 + \alpha + \delta + c_R - 2(1-\phi)(\theta_R + \pi_A\theta_A)}{2} - \frac{|L|(S-2A_{rP}^2)}{S-2A_{rP}A}\\
w_R^{rP} &= \frac{(1-2\phi)\theta_R + \delta - \alpha + c_R}{2},\\
\tau^{rP} &= \frac{A_{rP}|L|}{S-2A_{rP}A},\\
q_N^{rP} &= \frac{2c_\tau|L|}{S-2A_{rP}A},\\
q_R^{rP} &= \frac{\delta - \alpha - c_R + \theta_R}{4\delta} - \frac{2c_\tau|L|}{S-2A_{rP}A}.
\end{aligned}$$

Proof. See the proof for Proposition 1. In order to guarantee concavity of the manufacturer's problem, condition $S - 2A_{rP}A > 0$ must hold. □

The closed form of w_N^{rP} is too long and complex to be amenable to a qualitative analysis. For $\phi > 1/2$, increasing the remanufacturing deviation incentive θ_R yields a lower w_R^{rP}. However, the impact of the collection target rate does not depend on the value of ϕ; a higher collection target rate means a higher new product wholesale price, and consequently, less brand new production.

The structural forms of q_N^{rP} and τ^{rP} are the same as those in scenarios mO and mP. However, the term A in q_N^{mO} and τ^{mO} is partially replaced by A_{rP} in q_N^{rP} and τ^{rP}, and that is where the financial responsibility distribution (ϕ) comes in. The impacts of remanufacturing and collection profitability on the collection rate and the quantity of new products are the same as in scenario mO. The only factor that has entered the analysis is ϕ, which is an important lever for the SP. On the one hand, assuming $\theta_A > \pi_R\theta_R$, A_{rP} decreases in ϕ. On the other hand, while the collection rate and the quantity of new product are increasing in A_{rP}, the quantity of remanufactured product is a decreasing function of the retailer's collection profit. Therefore, putting a larger burden of the regulation's financial responsibility on the shoulders of the manufacturer (i.e., increasing ϕ) yields a lower collection rate, fewer new products, and more remanufactured products. Therefore, one way to shift the demand from new to remanufactured products when the retailer is collecting is to give greater financial responsibility to the manufacturer, who is not in charge of collection at all. Otherwise, if $\theta_A < \pi_R\theta_R$, increasing ϕ means more recycling profit for the retailer and less recycling cost for the manufacturer, resulting in more production of the new product, more collection, and less remanufacturing.

The presence of ϕ modifies the conditions for interior solutions, as shown in Proposition 5.

Proposition 5 *Let $J = S - 2A_{rP}A$. In scenario rP, the conditions for interior solutions are*[10]

$$\pi_A \le \frac{1}{\theta_A}\left(-\frac{J}{2A_{rP}}\left(\sqrt{1+\frac{A_{rP}(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}}-1\right)+\alpha-c_N+c_R-\theta_R+\delta-1\right), \tag{9}$$

$$\pi_A \ge \frac{1}{\theta_A}\left(-\frac{J}{A_{rP}}+\alpha-c_N+c_R-\theta_R+\delta-1\right), \tag{10}$$

$$\pi_A \ge \frac{1}{\theta_A}\left(-\frac{J(\delta+\theta_R-\alpha-c_R)}{8\delta c_\tau}+\alpha-c_N+c_R-\theta_R+\delta-1\right). \tag{11}$$

[10]A more compact way of writing the three conditions is

$$\frac{\alpha-c_N+c_R-\theta_R+\delta-1}{\theta_A} - \frac{1}{\theta_A}\max\left\{\frac{J}{A_{rP}}, \frac{J(\delta+\theta_R-\alpha-c_R)}{8\delta c_\tau}\right\} \le \pi_A$$
$$\le \frac{\alpha-c_N+c_R-\theta_R+\delta-1}{\theta_A} - \frac{J}{2\theta_A A_{rP}}\left(\sqrt{1+\frac{A_{rP}(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}}-1\right).$$

However, for interpretation purposes, it is easier to proceed as done in the proposition.

Proof. See Appendix 7.1. □

Similarly to scenario mO, there are two lower bounds and one upper bound. If the upper bound is violated, all of the collected products are remanufactured. Otherwise, if the lower bounds do not hold, either no remanufacturing is done (inequality (11)) or no products are collected (inequality (10)). Therefore, we conclude that, while increasing the collection target rate may mean less recycling and/or more remanufacturing, decreasing it means less collection and remanufacturing.

The domain of Figure 3 is determined for positive new product quantity (and, consequently, positive collection rate). The curve that points to the region where all products are collected is not placed within this domain. Region *A1* denotes the area where there is no remanufacturing. In region *A2*, which is the region of an interior solution, a proportion of the products is collected and remanufactured. Finally, all the collected products will be remanufactured in region *A3*. From Figure 3, one can observe that a lower deviation incentive and/or a higher collection target rate pushes for more remanufacturing, while a higher deviation incentive and/or a lower collection target rate deter remanufacturing.

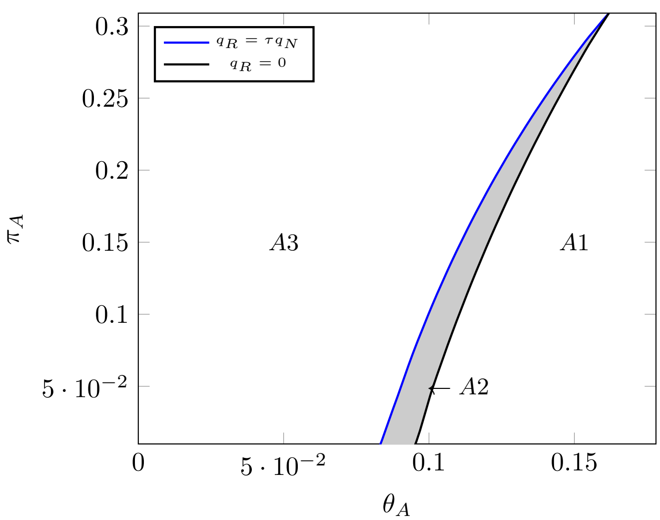

Figure 3: Feasible area for π_A and θ_A in scenario rP

Scenario rO: Here, the retailer collects and the manufacturer remanufactures, and each of them is responsible for its own actions. The retailer maximizes

$$\Pi^r_{rO} = (1 - q^{rO}_N - \delta q^{rO}_R - w^{rO}_N)q^{rO}_N + (\delta(1 - q^{rO}_N - q^{rO}_R) - w^{rO}_R)q^{rO}_R - c_\tau(\tau^{rO})^2 \quad (12)$$

$$-(\pi_A - \tau^{rO})q^{rO}_N\theta_A + \alpha(\tau^{rO}q^{rO}_N - q^{rO}_R). \quad (13)$$

Assuming an interior solution, the reaction functions of the retailer are given by

$$q^{rO}_N = \frac{2c_\tau(\delta - 1 + w^{rO}_N - w^{rO}_R + \pi_A\theta_A)}{A^2_{rO} - S/2},$$

$$q^{rO}_R = \frac{A^2_{rO}(\delta - \alpha - w^{rO}_R) - 4c_\tau(\delta w^{rO}_N + \delta\pi_A\theta_A - \alpha - w^{rO}_R)}{2\delta A^2_{rO} - S},$$

$$\tau^{rO} = \frac{A_{rO}(\delta - 1 + w^{rO}_N - w^{rO}_R + \pi_A\theta_A)}{A^2_{rO} - S/2}.$$

Taking into account the above reaction functions, the manufacturer maximizes

$$\Pi^m_{rO} = (w^{rO}_N - c_N)q^{rO}_N + (w^{rO}_R - c_R)q^{rO}_R - (\tau^{rO}\pi_R q^{rO}_N - q^{rO}_R)\theta_R.$$

Proposition 6 characterizes the unique Stackelberg equilibrium.

Proposition 6 *Assuming an interior solution, the unique Stackelberg equilibrium is given by*

$$\begin{aligned} w_N^{rO} &= \frac{\pi_R \theta_R A_{rO}|L|}{S - 2A_{rO}A} + \frac{1 + c_N - \pi_A \theta_A}{2}, \\ w_R^{rO} &= \frac{\delta + c_R - \alpha - \theta_R}{2}, \\ \tau^{rO} &= \frac{A_{rO}|L|}{S - 2A_{rO}A}, \\ q_N^{rO} &= \frac{2c_\tau |L|}{S - 2A_{rO}A}, \\ q_R^{rO} &= \frac{\delta + \theta_R - c_R - \alpha}{4\delta} - \frac{2c_\tau |L|}{S - 2A_{rO}A}. \end{aligned}$$

Proof. See the proof for Proposition 1. $S - 2A_{rO}A > 0$ is the necessary and sufficient condition for the concavity of the manufacturer's objective function. □

We make the following observations:

1. If collection is costly and recycling has a low value, ($S - 2A_{rO}A > 0$) this results in less brand new production and collection when the retailer faces a higher collection target rate. A lower quantity of new products on the one hand, and a decreased remanufacturing cost on the other hand, means that a lower quantity of new products will be compensated for by a higher quantity of the remanufactured product.
2. Unlike in scenarios mO, mP, and rP, a higher collection target rate results in a lower wholesale price for new products. Scenario rO is the only scenario where the manufacturer is completely disengaged from collection. When the collection target rate increases, the potential remanufacturing cost decreases. Therefore, the retailer orders fewer new products to deal with the collection regulation, and also reduces the collection rate to avoid increasing the collection cost (because the collection cost is a convex increasing function in the collection rate). However, since the total loss for the manufacturer is lower that what it was in the other scenarios where it was involved with collection, it reduces the new product wholesale price to balance the reduced amount of new products ordered.

Since all equilibrium values in Proposition 6 have the same structure as their counterparts in Propositions 1, 3, and 4 (except w_N^{rO}), we do not comment further on these values.

To obtain the equilibrium values in Proposition 6, we assumed an interior solution. The conditions for having such a solution are presented in Proposition 7.

Proposition 7 *Let $J = S - 2A_{rO}A$. The conditions for having an interior solution are*[11]

$$\begin{aligned} \pi_A &\leq \frac{1}{\theta_A}\left(\frac{-J\left(\sqrt{1 + \frac{A_{rO}(\delta + \theta_R - \alpha - c_R)}{2c_\tau \delta}} - 1\right)}{2A_{rO}} + 1 + \alpha - \delta - \theta_R + c_R - c_N\right), \\ \pi_A &\geq \frac{1}{\theta_A}\left(\frac{-J}{A_{rO}} + 1 + \alpha - \delta - \theta_R + c_R - c_N\right), \\ \pi_A &\geq \frac{1}{\theta_A}\left(\frac{-J(\delta + \theta_R - \alpha - c_R)}{8c_\tau \delta} + 1 + \alpha - \delta - \theta_R + c_R - c_N\right). \end{aligned}$$

[11] These conditions can be rewritten more compactly as

$$\begin{aligned} &\frac{1 + \alpha - \delta - \theta_R + c_R - c_N}{\theta_A} - \frac{1}{\theta_A}\max\left\{\frac{J}{A_{rO}}, \frac{J(\delta + \theta_R - \alpha - c_R)}{8\delta c_\tau}\right\} \leq \pi_A \\ &\leq \frac{1 + \alpha - \delta - \theta_R + c_R - c_N}{\theta_A} - \frac{J}{2\theta_A A_{rO}}\left(\sqrt{1 + \frac{A_{rO}(\delta + \theta_R - \alpha - c_R)}{2c_\tau \delta}} - 1\right). \end{aligned}$$

However, for interpretation purposes, it is easier to proceed as done in the proposition.

Proof. See Appendix 7.1. □

If we replace A_{rP} by A_{rO}, then the conditions in Proposition 7 would be the same as those in Proposition 5. This change does not alter the conclusions then made about the impact of the cost of remanufacturing and the value of recycling on production quantities and collection rates. Therefore, we conclude that the responsibility sharing policy does not affect the impact of collection target rate on the overall response of the supply chain.

Figure 4 is presented to show how modifying the collection target and incentive changes the production and collection policy of the supply chain. The data used to create this graph are given in Appendix 7.2.

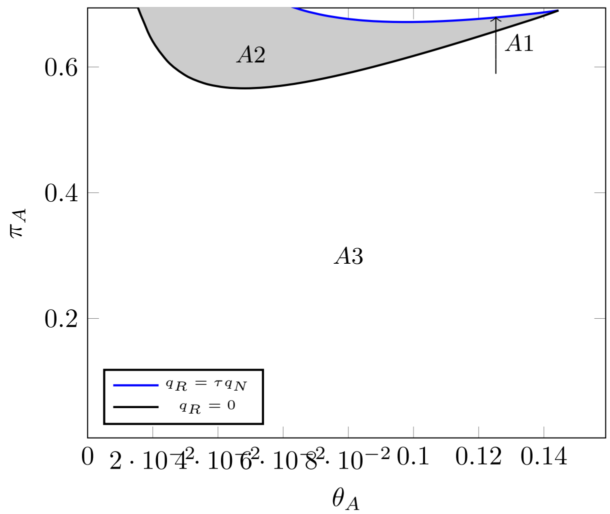

Figure 4: Feasible area for π_A and θ_A in scenario rO

The interior solution conditions are $\theta_A \in [0, 0.144]$ and $\pi_A \in [0, 0.694]$. As in Figure 3, not all the possible regions are shown as they were positioned beyond the domain of this graph. Region *A1* denotes the area with full remanufacturing. In region *A2*, a proportion of the products is collected and remanufactured (interior solution region). Finally, remanufacturing stops in region *A3*. According to this illustration, decreasing the collection target results in less remanufacturing. Therefore, as was the case for the other scenarios, remanufacturing is controlled without directly targeting remanufacturing.

Table 2 summarizes the meaning of each region in Figure 4.

Table 2: Meaning of regions in Figure 4

Regions	Collection	Remanufacturing
A1	partial	all
A2	partial	partial
A3	partial	none

Having presented the equilibria in all scenarios and their regulatory implications, we now compare them in order to propose guidelines to regulators depending on their specific environmental goal.

4 Environmental performance analysis

In this section, we look at the environmental performance of each of the considered scenarios. Our objective is to derive insights for EPR regulation design and responsibility sharing policies.

Proposition 8 confirms that decision regarding financial responsibility sharing cannot be made independently from those about physical responsibility sharing. This proposition is based on the conclusions in Section 3.

Proposition 8 *If all physical responsibilities are centralized to the manufacturer, sharing financial responsibility does not affect the collection rate or the quantity landfilled. However, this is not the case if the physical responsibilities are distributed.*

Proof. Solutions were already presented in Section 3. For the first part of the proposition, all that is needed is to show that the closed-form solutions of q_R, τ, and q_N for the mO and mP scenarios are the same. From Propositions 1 and 3, we have

$$\begin{aligned}
\tau^{mO} &= \tau^{mP} = \frac{A|L|}{S - A^2}, \\
q_N^{mO} &= q_N^{mP} = \frac{2c_\tau|L|}{S - A^2}, \\
q_R^{mO} &= q_R^{mP} = \frac{(\delta + \theta_R - \alpha - c_R)}{4\delta} - \frac{2c_\tau|L|}{S - A^2}.
\end{aligned}$$

Therefore, the production and collection policies are the same under both scenarios. However, as for the second part, from Propositions 4 and 6 we have

$$\begin{aligned}
&A_{rO} \neq A_{rP} \longleftrightarrow \frac{A_{rO}|L|}{S - 2A_{rO}A} \neq \frac{A_{rP}|L|}{S - 2A_{rP}A} \longleftrightarrow \tau^{rO} \neq \tau^{rP}, \\
&A_{rO} \neq A_{rP} \longleftrightarrow \frac{2c_\tau|L|}{S - 2A_{rO}A} \neq \frac{2c_\tau|L|}{S - 2A_{rP}A} \longleftrightarrow q_N^{rO} \neq q_N^{rP}, \\
&A_{rO} \neq A_{rP} \longleftrightarrow \frac{\delta + \theta_R - c_R - \alpha}{4\delta} - \frac{2c_\tau|L|}{S - 2A_{rO}A} \neq \frac{\delta + \theta_R - c_R - \alpha}{4\delta} - \frac{2c_\tau|L|}{S - 2A_{rP}A} \longleftrightarrow q_R^{rO} \neq q_R^{rP}.
\end{aligned}$$

Therefore, the production and collection policies for scenarios rP and rO are the same. □

The next step is to determine the conditions under which a responsibility sharing policy is the best one. Proposition 9 deals with the scenario with the best collection rate.

Proposition 9 *For a low collection cost-efficiency and a low consumer discount factor for remanufactured products, or for a low recycling profit for the member who collects, scenario rO leads to the highest collection rate.*

Proof. See Appendix 7.1. □

Therefore, if the SP aims to maximize the proportion of products collected, the best RSP strategy is to have the retailer collect and to hold it financially responsible to pay the related penalties, if it could not meet the collection rate target. Furthermore, scenario rO has the largest new product and the lowest remanufactured product quantities, making it an undesirable RSP policy if the SP seeks to promote remanufacturing.

Alternatively, if the product contains toxic materials, the quantity landfilled is an important indicator of environmental performance. There could be cases where the collection rate is increased while the quantity landfilled is not reduced. A significant increase in the quantity of the new products is one possible reason for this outcome. Aside from the collection rate and quantity discarded, a SP may want to reduce the overall energy consumption. However, since there are numerous conditions that put one scenario ahead of the others in terms of the discarded quantity and the total energy consumed, and consequently, it is almost impossible to extract insightful conclusions, we leave this criteria to be discussed through a numerical analysis.

We investigate the case of electronic products because they (i) are generally remanufacturable, (ii) are generally remanufacturable only once, (iii) mostly fall under environmental regulations, and (iv) usually contain toxic materials and are dangerous to landfill. The data for three types of electronic products are available from Esenduran et al. (2016). To consider low, medium, and high energy consumption during the production process, they have selected cell phones, LCD monitors, and refrigerators, respectively. For further details about the data, interested readers may refer to Appendix B of Esenduran et al. (2016). Since the assumptions on the demand function in Esenduran et al. (2016) are slightly different from ours, some adjustments are made to fit the data to our model.

Table 3: Data for numerical analysis

Parameters	Cell Phones	Refrigerators	LCD Monitors
α	$\begin{pmatrix} 1/60 & 1/100 & 1/140 \\ 1/30 & 1/50 & 1/70 \\ 1/20 & 3/100 & 3/140 \end{pmatrix}$	$\begin{pmatrix} 1/60 & 1/120 & 1/180 \\ 1/25 & 1/50 & 1/75 \\ 19/300 & 19/600 & 19/900 \end{pmatrix}$	$\begin{pmatrix} 1/40 & 1/80 & 1/120 \\ 9/200 & 9/400 & 3/200 \\ 13/200 & 13/400 & 13/600 \end{pmatrix}$
c_N	$\begin{pmatrix} 1/4 & 3/20 & 3/28 \\ 5/12 & 1/4 & 5/28 \\ 7/12 & 7/20 & 1/4 \end{pmatrix}$	$\begin{pmatrix} 1/4 & 1/8 & 1/12 \\ 1/2 & 1/4 & 1/6 \\ 3/4 & 3/8 & 1/4 \end{pmatrix}$	$\begin{pmatrix} 1/4 & 1/8 & 1/12 \\ 1/2 & 1/4 & 1/6 \\ 3/4 & 3/8 & 1/4 \end{pmatrix}$
c_R/c_N	0.05, 0.50	0.05, 0.50	0.05, 0.50
θ_R/α	1.1, 1.3, 1.5	1.1, 1.3, 1.5	1.1, 1.3, 1.5
θ_A/θ_R	1.1, 1.3, 1.5	1.1, 1.3, 1.5	1.1, 1.3, 1.5
δ	0.5,..,0.9	0.5,..,0.9	0.5,..,0.9
ϕ	0.2, 0.5, 0.8	0.2, 0.5, 0.8	0.2, 0.5, 0.8
c_τ	0.0089	0.0089	0.0089

The reason to define α and c_N in matrices is that not all 9 values are to be considered for each set of other parameters (i.e., instead of 3 values, we have defined 3 sets of values to adjust the data to our model). For instance, if the values for α are 1/60, 1/100 and 1/140, the corresponding values for high, medium, and low manufacturing costs are 1/4, 3/20 and 3/28, respectively. The reason to consider α and c_N this way was to adjust for variations in prices of each type of electronic products. The value of θ_R/α is selected in such a way that it accounts for low, medium, and high values of remanufacturing penalty relative to the value of collected but not remanufactured products. The higher this ratio is, the higher is the incentive to remanufacture rather than to sell away the collected products. The ratio θ_A/θ_R represents the proportional emphasis on collection over remanufacturing from the SP's point of view. We selected 1.1, 1.3, and 1.5 to target high, medium, and low values of remanufacturing, respectively.

Table 4: Energy consumption parameters (Esenduran et al., 2016)

Parameter	Cell Phones	Refrigerators	LCD Monitors
e_{rm}/e_m	0.2,0.4	0.2,0.4	0.2,0.4
e_{rc}/e_m	-0.037	-0.01	0.026
e_d/e_m	0.00003	0.00125	0.00011
e_u/e_m	0.575	10.468	0.411
e_m	200	6909	2073

The numerical analysis procedure is as follows. To investigate the impact of the collection target level and for each of set of parameters, the performance indicators are calculated for π_A values ranging from 0.024 to 0.96 with a step of 0.024. The remanufacturing target rate belongs to the set $\{0.2, 0.4, 0.6\}$. To study the impact of the remanufacturing target, the values are reversed. For each set of the input data, the problem is solved and the value of the performance indicator(s) is obtained. We count the total number of times where the performance indicator is increased. At the end, the proportion of the times when increasing the target rate yields a higher value of performance indicator is calculated. In other words, this ratio represents the percentage of the time when increasing the target rate leads to an increase in the respective performance indicator.

The impacts of target rates on uncollected quantities are reported in Tables 5 and 6. According to Proposition 8, the quantity of brand new and remanufactured products, and the collection rate are the same for the mO and mP scenarios. The first two rows in Tables 5 to 8 numerically confirm this proposition.

Table 5: Impact of collection target rate on uncollected quantity

Scenarios	Cell Phones	Refrigerators	LCD Monitors
mO	%3.41	%7.30	%10.69
mP	%3.41	%7.30	%10.69
rO	%38.53	%35.45	%48.56
rP	%9.97	%6.75	%19.74

Table 6: Impact of remanufacturing target rate on uncollected quantity

Scenarios	Cell Phones	Refrigerators	LCD Monitors
mO	%86.95	%83.82	%78.85
mP	%86.95	%83.82	%78.85
rO	%38.18	%34.99	%47.28
rP	%96.95	%92.05	%92.49

For all three products, the variation of the values within each column is considerable. Thus, it is safe to make the following claims:

Claim 1 *For the three products and in terms of the uncollected quantity, the responsibility sharing policy impacts the way collection and remanufacturing target rates affect the environmental performance indicators.*

In other words, before increasing or decreasing the value of target rates, the imposed responsibility sharing policy should be taken into account. Furthermore, by observing all the values in Table 5, it could be concluded that increasing the collection target rate will most likely reduce the quantity of uncollected products. The same conclusion is not true for the remanufacturing target rate.

Tables 7 and 8 report the proportions of time when increasing the target rates results in an increase in the total energy consumption.

Table 7: Impact of collection target rate on total energy consumption

Scenarios	Cell Phones	Refrigerators	LCD Monitors
mO	%0.00	%0.06	%0.05
mP	%0.00	%0.06	%0.05
rO	%3.37	%6.75	%10.70
rP	%0.04	%1.60	%2.73

Table 8: Impact of remanufacturing target rate on total energy consumption

Scenarios	Cell Phones	Refrigerators	LCD Monitors
mO	%6.72	%0.06	%13.33
mP	%6.72	%0.06	%13.33
rO	%2.81	%5.85	%8.71
rP	%10.18	%3.47	%21.05

According to Tables 7 and 8, the following claims can be made for the total energy consumption:

Claim 2 *For the three products and in terms of the total energy consumption, the responsibility sharing policy has a significant impact on the effect of collection and remanufacturing target rates.*

Claim 3 *Increasing collection and remanufacturing target rates most likely yields a lower total energy consumption for all responsibility sharing policies.*

Claims 1 to 3 tend to show that the impact of the regulatory parameters on environmental performance depends on the selected responsibility sharing policy, and apparently, the product. Considering these observations, together with Propositions 8 and 9, we confirm the interrelation between physical and financial

RSPs on the one hand, and the interrelation between selecting the best RSP and EPR regulation design on the other hand. Thus, we have achieved the main research goals.

Any discussions of regulations from the environmental point of view is not complete unless the supply chain profitability and consumer surplus implications of the regulations are also considered.

5 Profitability and consumer surplus implications

Throughout this paper, EPR regulation design and RSP are discussed with the aim of improving environmental performance. However, supply chain profitability and consumer surplus are two other important considerations when designing an environmental regulation or allocating responsibilities among the supply chain members. For this purpose, we present numerical examples under different regulating scenarios. In Sections 5.1 and 5.2, the impacts of collection and remanufacturing regulations on consumer surplus and profitability are discussed for different responsibility sharing policies.

5.1 Collection regulation

To isolate the impact of the collection regulation, assume that there is no regulation on remanufacturing. To study different levels of regulation, we retain the following four scenarios: (i) strictly rewarding regulation, i.e., high deviation incentive and low target rate ($\theta_A = 0.7$ and $\pi_A = 0.3$); (ii) strictly penalizing regulation, i.e., high deviation incentive and target rate ($\theta_A = 0.7$ and $\pi_A = 0.7$); (iii) weakly rewarding regulation, i.e., low deviation incentive and target rate ($\theta_A = 0.3$ and $\pi_A = 0.3$); and (iv) weakly penalizing regulation, i.e., low deviation incentive and high target rate ($\theta_A = 0.3$ and $\pi_A = 0.7$). For each scenario, the manufacturer's profit, the retailer's profit, and the consumer surplus are calculated under the addressed RSP scenarios. The data used for the examples are presented in Table 9.

Table 9: Input data for profitability and consumer surplus implications under a collection regulation

Parameter	c_τ	ϕ	δ	c_R	c_N	α
Value	0.5	0.7	0.85	0.1	0.25	0.05

Table 10 reports the values of profit and consumer surplus for all collection regulation and RSP scenarios.

Table 10: Profitability and consumer surplus implications of collection regulations ($\times 10^{-5}$)

Collection Regulation	RSP Scenarios	Manufacturer Profit	Retailer Profit	Consumer Surplus
Strictly rewarding $\pi_A = 0.3$, $\theta_A = 0.7$	mO	4524	2686	1343
	mP	4524	2686	1343
	rO	5211	2666	1729
	rP	4144	2262	1186
Weakly rewarding $\pi_A = 0.3$, $\theta_A = 0.3$	mO	5743	3009	1504
	mP	5743	3009	1504
	rO	5900	2995	1585
	rP	5629	2879	1453
Strictly penalizing $\pi_A = 0.7$, $\theta_A = 0.7$	mO	1240	853	426
	mP	1240	853	426
	rO	1423	856	556
	rP	999	586	293
Weakly penalizing $\pi_A = 0.7$, $\theta_A = 0.3$	mO	3945	2114	1057
	mP	3945	2114	1057
	rO	4027	2081	1102
	rP	3796	1956	987

The following observations can be made from these tables:

1. The profit and surplus values are the same in the mO and mP scenarios. The difference between the wholesale price values for these scenarios shows that the manufacturer has to adjust the wholesale prices to compensate for the costs incurred to the retailer as the result of sharing the financial responsibilities.
2. The best RSP for the manufacturer and consumers is scenario rO. This result sheds light on the discussion between the manufacturers and the regulators on involving the retailers in the after-sale environmental services.
3. A weakly rewarding collection regulation (which can also be seen as no regulation) is the best scenario for the supply chain. It will benefit the supply chain more than a regulation that most probably rewards collection.
4. The best case for the remanufacturer occurs when the retailer is physically and financially in charge of collection, and the collection regulation is a weakly rewarding one. Retailers get the most from a weakly rewarding regulation where the manufacturer is in charge of collection. Finally, the highest consumer surplus is obtained when the retailer is totally responsible for collection and the the SP has stipulated a strictly rewarding collection regulation.

In the next section, the same analysis is done for a remanufacturing regulation, assuming that a collection regulation is also in place.

5.2 Remanufacturing regulation

In this section, we assume that remanufacturing and collection are both regulated. Using the same procedure, we study the impact of regulating remanufacturing and RSP scenarios on supply chain profitability and on consumer surplus. The same input data as used in Section 5.1 is also used here, with the only difference being that the previously varied parameters π_A and θ_A are now assigned a value of 0.5. To study different levels of remanufacturing regulation, four scenarios are defined: (i) a strictly rewarding regulation, i.e., high deviation incentive and low target rate ($\theta_R = 0.6$ and $\pi_R = 0.2$), (ii) a strictly penalizing regulation, i.e., high deviation incentive and target rate ($\theta_R = 0.6$ and $\pi_R = 0.6$), (iii) a weakly rewarding regulation, i.e., low deviation incentive and target rate ($\theta_R = 0.2$ and $\pi_R = 0.2$), and (iv) a weakly penalizing regulation, i.e., low deviation incentive and high target rate ($\theta_R = 0.2$ and $\pi_R = 0.6$). The results are reported in Table 11.

Table 11: Profitability and consumer surplus implications of remanufacturing regulations ($\times 10^{-5}$)

Remanufacturing Regulation	RSP Scenarios	Manufacturer Profit	Retailer Profit	Consumer Surplus
Strictly rewarding $\pi_R = 0.2$, $\theta_R = 0.6$	mO	4555	3005	1502
	mP	4555	3005	1502
	rO	4518	2690	1541
	rP	3483	1908	966
Weakly rewarding $\pi_R = 0.2$, $\theta_R = 0.2$	mO	3882	2312	1156
	mP	3882	2312	1156
	rO	4087	2234	1287
	rP	3429	1841	936
Strictly penalizing $\pi_R = 0.6$, $\theta_R = 0.6$	mO	4024	2456	1228
	mP	4024	2456	1228
	rO	4188	2336	1345
	rP	3282	1715	861
Weakly penalizing $\pi_R = 0.6$, $\theta_R = 0.2$	mO	3755	2184	1092
	mP	3775	2184	1092
	rO	3990	2138	1232
	rP	3365	1783	903

The observations made from Table 11 have similarities to and differences with those made from Table 10. Firstly, the best regulating policy for the consumers and the supply chain is a strictly rewarding remanufacturing regulation. This result is different from what was observed for the collection regulation, where a weakly rewarding regulation on collection best served the supply chain. Consequently, there are different best outcomes for supply chain members and for consumers. Given the input data, the best case for the manufacturer and the retailer is a strictly rewarding regulation where the manufacturer is collecting. The consumers, however, are better off if the retailer is collecting and paying the penalties or receiving the rewards. The main similarity between these results is that the financial outcomes of all stakeholders are equal, even if the financial responsibilities are shared. Furthermore, from the numbers reported in these two tables, it is apparent that the best responsibility sharing policy varies by regulatory approach (the four retained scenarios), and the best regulatory approach also varies according to which responsibility sharing policy is selected. Confirming and analyzing this interrelation was one of the main goals of our research.

In the final section, our research contribution, the main assumptions, and the main takeaways of this research are reviewed.

6 Conclusion

In this paper, the responsibility sharing problem is studied for a supply chain that is obliged to collect and remanufacture previously sold products. This paper contributes to the literature by highlighting the underlying relationship between responsibility sharing policy and EPR regulation design. A supply chain consisting of a manufacturer and a retailer is considered, where the manufacturer acts as the leader of the chain and interacts with the retailer through the wholesale price and the physical transfer of new, remanufactured, and returned products. The social planner stipulates a reward-penalty regulation to achieve a specified environmental goal. The reward-penalty regulation is based on target rates and deviation incentives for collection and remanufacturing.

Four scenarios are defined on the basis of physical and financial responsibility sharing policies. On the one hand, we showed that not only is there an interdependence between the selected financial and physical responsibility sharing policies, but also, the choice of the best policy – depending on the performance measure – may be affected by the selected target rates and deviation incentives (i.e., the regulation design). On the other hand, we obtained that the impacts of the target rates and deviation incentives depend on the chosen responsibility sharing policy. Thus, it is concluded that the EPR regulation design and the responsibility sharing policy must be considered simultaneously. Hence, any claim about the impact of any specific EPR regulation is incomplete unless it clarifies which member is responsible for what recovery action and how the incentives are to be distributed among the supply chain members.

Using a numerical example, we showed that, while a regulation that rewards remanufacturing is the best option for the supply chain members, expectedly, they prefer a weak collection regulation. Furthermore, the best RSP for the manufacturer is to have the retailer collect while the manufacturer has nothing to do with its financial consequences. However, the retailer prefers the scenario where the remanufacturer collects, except for the case of a regulation that strictly penalizes collection.

There are several possible ways to extend this paper. This study is built on a set of assumptions, which clearly have an impact on the results, and it would be worthwhile to relax some of them in future investigations. Firstly, we analyzed the scenarios under the conditions that collecting is costly and remanufacturing is not profitable, in order to concentrate on the critical cases where regulating the market is needed. Profitable remanufacturing may change the conclusions entirely. Secondly, we assumed that the market is in its steady state. However, if the remanufacturing market is not at its steady state, the amount of past production may affect the regulation design choices (Pazoki and Zaccour, 2018). Moreover, collection could be done by more than one member of the supply chain.

7 Appendices

7.1 Proof of propositions

Proposition 2. The constraints to be satisfied are $0 \leq q_R \leq \tau q_N$, $0 \leq \tau \leq 1$, and $0 \leq q_N \leq 1$. $0 \leq p_N \leq \delta$ and $0 \leq p_R \leq \delta$ will be automatically satisfied. Let $A = \theta_A + \alpha - \pi_R\theta_R$, $L = \delta - 1 + \theta_R + \pi_A\theta_A - c_R + c_N - \alpha$,

$S = 8c_\tau(1-\delta)$ and $\Delta = 1 + A(\delta + \theta_R - c_R - \alpha)/2\delta c_\tau$. Assuming $J = S - A^2 > 0$, the following conditions are obtained

$$
\begin{aligned}
\tau \geq 0 \rightarrow \quad & \pi_R\theta_R \leq \alpha + \theta_A \\
& \pi_A \leq (1 + \alpha - \delta - \theta_R + c_R - c_N)/\theta_A \\
\tau \leq 1 \rightarrow \quad & \text{conditions for } \tau \geq 0 \text{ and } J \geq A|L| \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{A} + 1 + \alpha - \delta - \theta_R + c_R - c_N\right)/\theta_A
\end{aligned}
$$

$$
\begin{aligned}
q_N \geq 0 \rightarrow \quad & \text{The same conditions as for } \tau \geq 0 \\
q_N \leq 1 \rightarrow \quad & \tau \leq 1 \text{ and } J \geq 2c_\tau|L| \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{2c_\tau} + 1 + \alpha - \delta - \theta_R + c_R - c_N\right)/\theta_A
\end{aligned}
$$

$$
\begin{aligned}
q_R \geq 0 \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \geq q_N = \frac{2c_\tau|L|}{J} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{8c_\tau\delta}(\delta + \theta_R - \alpha - c_R) + 1 + \alpha - \delta - \theta_R + c_R - c_N\right)/\theta_A \\
q_R \leq \tau q_N \rightarrow \quad & \\
& \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \leq \frac{2c_\tau|L|(A|L| + J)}{J^2} \\
& \pi_A \leq \left(\frac{-J(\sqrt{\Delta} - 1)}{2A} + 1 - \delta + c_R - c_N + \alpha - \theta_R\right)/\theta_A
\end{aligned}
$$

There are initially 2 upper bounds and 3 lower bounds for π_A. The upper bound found for $q_R \leq \tau q_N$ is smaller than that of $\tau \geq 0$, allowing us to conclude that there is only one upper bound resulting from $q_R \leq \tau q_N$. The lower bound obtained for $q_N \leq 1$ is smaller than that of $q_R \geq 0$. Therefore, the maximum of those found for $q_R \geq 0$ and $\tau \leq 1$ is the lower bound for π_A. Therefore, we end up with one upper bound and two lower bounds. □

Proposition 5. Let $A = \alpha + \theta_A - \pi_R\theta_R$, $L = \delta - 1 + \theta_R + \pi_A\theta_A - c_R + c_N - \alpha$, and $A_{rP} = \alpha + (1-\phi)(\theta_A - \pi_R\theta_R)$, and assume $J = S - 2A_{rP}A > 0$. We need to satisfy

$$
\begin{aligned}
\tau \geq 0 \rightarrow \quad & (1-\phi)\pi_R\theta_R \leq \alpha + (1-\phi)\theta_A \\
& \pi_A \leq (1 - \delta + \alpha + c_R - c_N - \theta_R)/\theta_A \\
\tau \leq 1 \rightarrow \quad & \text{conditions for } \tau \geq 0 \text{ and } J \leq |L|A_{rP} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{A_{rP}} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A
\end{aligned}
$$

$$
\begin{aligned}
q_N \geq 0 \rightarrow \quad & \text{same conditions as for } \tau \geq 0 \\
q_N \leq 1 \rightarrow \quad & \text{condition for } \tau \geq 0 \text{ and} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{2c_\tau} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A.
\end{aligned}
$$

$$
\begin{aligned}
q_R \geq 0 \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \geq q_N = \frac{2c_\tau|L|}{J} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J(\delta + \theta_R - \alpha - c_R)}{8c_\tau\delta} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A \\
q_R \leq \tau q_N \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \leq \frac{2c_\tau|L|(A_{rP}|L| + J)}{J^2} \\
& \pi_A \leq \left(-J\frac{\sqrt{1 + \frac{A_{rP}(\delta + \theta_R - \alpha - c_R)}{2c_\tau\delta}} - 1}{2A_{rP}} + \alpha - c_N + c_R - \theta_R + \delta - 1\right)\theta_A,
\end{aligned}
$$

There are initially 2 upper bounds and 3 lower bounds for π_A. The upper bound found for $q_R \leq \tau q_N$ is smaller than that of $\tau \geq 0$, allowing us to conclude that there is only one upper bound resulting from $q_R \leq \tau q_N$. The lower bound obtained for $q_N \leq 1$ is smaller than that of $q_R \geq 0$. Therefore, the maximum of those found for $q_R \geq 0$ and $\tau \leq 1$ is the lower bound for π_A. Therefore, we end up with one upper bound and two lower bounds, as presented in Proposition 5. □

Proposition 7. Let $A = \alpha + \theta_A - \pi_R\theta_R$, $A_{rO} = \alpha + \theta_A$ and $L = \delta - 1 + \theta_R + \pi_A\theta_A - c_R + c_N - \alpha$, and assume $J = S - 2A_{rO}A > 0$. We need to satisfy

$$\begin{aligned}
\tau \geq 0 \rightarrow \quad & (1-\phi)\pi_R\theta_R \leq \alpha + (1-\phi)\theta_A \\
& \pi_A \leq (1 - \delta + \alpha + c_R - c_N - \theta_R)/\theta_A \\
\tau \leq 1 \rightarrow \quad & \text{conditions for } \tau \geq 0 \text{ and } J \leq |L|A_{rO} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{A_{rO}} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A
\end{aligned}$$

$$\begin{aligned}
q_N \geq 0 \rightarrow \quad & \text{same conditions as for } \tau \geq 0 \\
q_N \leq 1 \rightarrow \quad & \text{condition for } \tau \geq 0 \text{ and} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{2c_\tau} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A.
\end{aligned}$$

$$\begin{aligned}
q_R \geq 0 \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \geq q_N = \frac{2c_\tau|L|}{J} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J(\delta + \theta_R - \alpha - c_R)}{8c_\tau\delta} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A \\
q_R \leq \tau q_N \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \leq \frac{2c_\tau|L|(A_{rO}|L| + J)}{J^2} \\
& \pi_A \leq \left(-J\frac{\sqrt{1 + \frac{A_{rO}(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}} - 1}{2A_{rO}} + \alpha - c_N + c_R - \theta_R + \delta - 1\right)\theta_A,
\end{aligned}$$

There are initially 2 upper bounds and 3 lower bounds for π_A. The upper bound found for $q_R \leq \tau q_N$ is smaller than that of $\tau \geq 0$, allowing us to conclude that there is only one upper bound resulting from $q_R \leq \tau q_N$. The lower bound obtained for $q_N \leq 1$ is smaller than that of $q_R \geq 0$. Therefore, the maximum of those found for $q_R \geq 0$ and $\tau \leq 1$ is the lower bound for π_A. Therefore, we end up with one upper bound and two lower bounds. □

Proposition 9. For the three scenarios (mP is the same as mO), the collection rates are $\tau^{mO} = A|L|/(S-A^2)$, $\tau^{rP} = A_{rP}|L|/(S - 2A_{rP}A)$ and $\tau^{rO} = A_{rO}|L|/(S - 2A_{rO}A)$. Furthermore, we know that $A_{rO} > A_{rP}$ and $A_{rO} > A$, and we assumed in the article that $\theta_A > \pi_R\theta_R$, which means that the collection regulation is more emphasized than the remanufacturing regulation. Therefore, $A_{rO} > A > A_{rP}$. We have

$$\tau^{rO} > \tau^{rP} \iff \frac{A_{rO}|L|}{S - 2A_{rO}A} > \frac{A_{rP}|L|}{S - 2A_{rP}A} \iff A_{rO}|L|S > A_{rP}|L|S \iff A_{rO} > A_{rP},$$

and

$$\tau^{rO} > \tau^{mO} \iff \frac{A_{rO}|L|}{S - 2A_{rO}A} > \frac{A|L|}{S - A^2} \iff A_{rO}A^2 > S(A - A_{rO}),$$

and thus conclude that scenario rO yields the highest collection rate. In a similar way, it is simple to show that q_N^{rO} and q_R^{rO} are the highest and the lowest among the addressed scenarios, respectively. □

7.2 Sensitivity analysis data

Table 12: Input data for Figures 2, 3, and 4

Parameter	δ	c_R	c_N	c_τ	α	ϕ	π_R	θ_R
Value	0.85	0.1	0.25	0.1	0.1	0.2	0	0

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