

IMPROVING RECYCLING: HOW FAR SHOULD WE GO?

Paul Belleflamme, Huan Ha

REPRINT | 3290

CORE

Voie du Roman Pays 34, L1.03.01

B-1348 Louvain-la-Neuve

Tel (32 10) 47 43 04

Email: lidam-library@uclouvain.be

<https://uclouvain.be/en/research-institutes/lidam/core/core-reprints.html>



Improving Recycling: How Far Should We Go?

Paul Belleflamme^{1,2} · Huan Ha³

Accepted: 30 April 2024
© The Author(s) 2024

Abstract

We analyze, in a game-theoretic model, the strategic interaction between competing firms that source their inputs from either primary or recycled material. Because the manufacturers' primary production today serves as input for the recyclers' production tomorrow, manufacturers can limit the recyclers' scale of operation by reducing their output. Improving the recycling process generates then two opposite effects: it reduces primary production tomorrow by exposing manufacturers to stronger competition from recyclers, but it also lowers the manufacturers' incentives to reduce their primary production today. If primary production exerts a negative externality on the environment, then making the recycling process too efficient might be counterproductive. This intuition equally applies to remanufacturing.

Keywords Recycling · Remanufacturing · Circular economy · Strategic entry accommodation

JEL Classification L13 · L72 · O13 · Q58

1 Introduction

Research question. Authorities worldwide have committed to scaling up the collection of scraps for recycling. The expectation is that, by increasing the inputs for the recycling sector, they can reduce the volume of primary production and hence, lower the economy's

✉ Paul Belleflamme
Paul.Belleflamme@uclouvain.be
Huan Ha
huanht@neu.edu.vn

¹ CORE/LIDAM, Université catholique de Louvain, 34 Voie du Roman Pays, 1348 Louvain-la-Neuve, Belgium

² CESifo, Munich, Germany

³ National Economics University, 207 Giai Phong, Ha Noi, Vietnam

impacts on the environment.¹ The European Commission, for instance, announced in November 2022 proposals to reduce packaging waste by introducing new targets for reuse and recycling.

While recycling can reduce the negative impact of the economy on the environment, one may ask to *which extent an improvement in the collection of scraps for recycling can reduce the volume of primary production*. To answer this question properly, we need to analyse the strategic interaction between competing firms that source their inputs from either primary or recycled material. What makes this competition peculiar is that the firms producing from primary material (which we call the ‘*manufacturers*’) also supply inputs for the firms producing from recycled material (which we call the ‘*recyclers*’). Consequently, the manufacturers can control the scale at which the recyclers can operate; in particular, they may want to reduce their current production to limit the competition that recyclers will exert in the future. It is thus crucial to take this possibility into account when evaluating the impacts of improving the recycling process.²

Main result. Our analysis establishes that *an intensification of the recycling process may be counter-productive from an environmental—and even societal—point of view*. The intuition behind this result is the following. Improving the recycling process generates two opposite effects. On the one hand, it reduces primary production (and the negative externality associated with the use of primary resources) once recyclers enter the market; this is so because the competition they exert on manufacturers gets stronger as recycling is improved. On the other hand, the better the recycling process, the lower the incentives for manufacturers to reduce their primary production *before* recyclers enter. The benefit for manufacturers of limiting the recyclers’ future entry must indeed be assessed against the cost of forgoing current profits. An improvement of the recycling process worsens the benefit/cost ratio of this strategy because it forces manufacturers to accept a larger decrease in their current primary production to reach a given reduction in the recyclers’ scale of entry.

To establish this result, we consider a game-theoretic model with two periods. In period 1, manufacturers extract primary material and use it to produce some final products. In period 2, recyclers enter the market; they produce the final product using recycled material while manufacturers continue to produce from primary material. Periods are linked as follows: the available recycled material in period 2 is a fraction of what manufacturers

¹ Recycling of aluminium products, for example, requires as little as 5% of the energy and emits as little as 5% of greenhouse gas compared to the production of primary aluminium (International Aluminium Institute 2009). Recycling can also reduce the negative impact of waste on the environment (arguably better than landfills and incineration).

² The same intuition applies to remanufacturing, which is “a specific type of recycling in which used durable goods are repaired to a like-new condition” (Bernard 2011, p. 337). The difference is that, after a product’s first life, recycled material can be redirected towards any industry; on the contrary, the remanufactured products go back to the same industry. Nevertheless, both remanufacturing and recycling firms rely on the used products from the primary producers as input for their business. Hence, remanufacturers compete with manufacturers of primary products in the same way as recyclers do, meaning that the basic mechanisms of our analysis are also present in the case of remanufacturing. As an illustration, Örsdemir et al. (2014) explain that manufacturers have the incentive to reduce the competitive threat exerted by remanufacturers “through limiting quantity, specifically by creating a scarcity of cores available for remanufacturing.” They give the example of Lexmark, which made cores ineligible for remanufacturing (see <https://archive.grrn.org/lexmark/background.html>, last accessed April 4, 2024).

produced in period 1. To isolate the effects of strategic interaction, we assume in our baseline model that the manufacturer does not internalize the scarcity of the primary material.³

Related literature. Motivated by the notorious Alcoa case (Walter 1951),⁴ the early literature on recycling focuses on the price path and the respect of Hotelling rule in the extraction of exhaustible resources with the existence of a recycling sector.⁵ For this objective, the natural approach taken by most papers in this strand of literature is to relate steady-state outcomes (prices, market shares, etc.) to fundamentals (demand, recycling rate, production costs, etc.). In contrast, our approach borrows from industrial organization and focuses on two periods only (no steady-state is contemplated). Therefore, we do not consider the “recycling problem” as such, because there is no third period to anticipate. Instead, we analyze more sharply the impact of the fundamentals on the strategic interaction between primary and secondary producers.

Also motivated by the structure of the aluminium market and the nature of extracting and recycling industries, the literature is largely dominated by the twin assumptions that (i) the recyclers are perfectly competitive and (ii) resources are exhaustible. The assumption of a competitive recycling industry imposes that, by setting the price for the current period, the primary producer determines in advance the output of the recyclers since it knows that the recyclers will equate their marginal cost to the given price. By eliminating the possibility of a strategic reaction from the recyclers, this assumption allows the previously mentioned studies to focus on the price path of the resource and the primary producer’s market power. To the contrary, we differ by allowing the recyclers to exercise market power. This assumption lets us analyze how dynamic incentives interact with future changes in market structure.

We are not the first to explore the dynamic effects of recycling in an oligopoly competition. However, to the best of our knowledge, such studies either focus on the primary firm’s foreclosure incentive (Hollander and Lasserre 1988; Ba et al. 2020; Ba 2022) or assume that firms can commit to supply paths (Gaudet and Van Long 2003; de Beir et al. 2023). We extend this literature by considering how strategic behaviour interacts with environmental policy in a dynamic setting. This extension is necessary to discuss the interaction between strategic incentives and policies designed with environmental-friendly objectives.

Concerning the relationship between the exhaustibility of resources and the strategic reaction of firms, previous studies show that imposing this assumption leads to specific channels of reaction. For instance, Ba and Mahenc (2019) demonstrate that, by producing less in the first period, the primary producer signals that it will flood the market with primary products in the second period, hence, deterring the entry of the recyclers. In other studies, de Beir et al. (2023) and Ba (2022) assume a cost function of primary production that is convex with respect to the resource left unextracted. In such a setting, firms want to reduce primary production initially to save on future costs and, thereby, compete more aggressively against recyclers. In contrast, we abstract from exhaustibility in our baseline

³ In Sect. 4.3, we show that our results continue to hold when the manufacturer internalizes the scarcity of the primary material in its profit-maximization program. We also propose a scenario in which it might be plausible that the manufacturer ignores resource scarcity.

⁴ In 1945, Alcoa, the producer of primary aluminium, was found in a monopolistic position by virtue of its control over 90% of primary aluminium output, limiting the competitiveness of the recycling industry, which captured roughly 20% of the total aluminium market. Judge Learned Hand concluded that Alcoa constituted an illegal monopoly, in violation of the Sherman Antitrust Act: Alcoa was found to control strategically the recycling sector’s supply by manipulating the primary aluminium production.

⁵ See, for example, Gaskins (1974), Swan (1977), Hoel (1984), Suslow (1986), Hollander and Lasserre (1988), Grant (1999), Eichner (2005), and Honma and Chang (2010).

model and focus on the primary producer's control of the recycling input to constrain the recycler's scale of entry. Nevertheless, in Sect. 4.3, we extend our baseline model to account for resource exhaustibility. We show that the two motivations for reducing first-period production (future cost saving and entry limitation) reinforce one another.

Another assumption typically used in the literature is the existence of a technology threshold for the recycler to enter the market. Under this assumption, Ba and Mahenc (2019) and de Beir et al. (2023) establish a setting in which the primary producer can deter or accommodate the recycler by reducing its production before the recycler's entry. In our setting, we assume that the technology/availability of scraps is good enough so that the recycler can always enter the market. As a result, only two strategies are possible for the primary producer: limit the recycler's competition or let it exist. In both cases, the manufacturer and the recycler interact strategically.

Furthermore, the literature generally integrates the collection decision into the recycling entities. In reality, while reprocessing entities are mostly private, the collection system relies heavily on the government's effort to scale it up. Playing a significant role in organizing the curb-side collection and subsidizing the collection entities, the government's commitments influence the recycling rate beyond the market-based mechanism. Therefore, we extend the literature by examining the impacts of exogenous variations of the recycling rate. To the best of our knowledge, Fabre et al. (2020) is the only other study doing this kind of analysis. However, they only consider an efficient recycling rate and a setting with a social planner's problem.⁶ In contrast, we study the optimal recycling rate with a setting allowing for strategic interaction among firms.

As mentioned above, the literature studying the problem of "remanufacturing" is also closely related to our work. In this strand of literature, extant studies focus mainly on the impact that remanufacturing has on the primary manufacturers' profitability. For instance, Atasu et al. (2008) investigate the conditions for the benefits of remanufacturing to outweigh the losses from cannibalization when manufacturers conduct remanufacturing themselves. They show that remanufacturing is more beneficial under competition than under monopoly. In another paper, Ferguson and Toktay (2009) analyze the competition between a manufacturer and a remanufacturing firm. They discuss the conditions for the manufacturer to choose to remanufacture its products or not. They also compare two entry-deterrent strategies: remanufacturing and preemptive collection. Webster and Mitra (2007) and Mitra and Webster (2008) develop two-period models where they consider a monopolist on the original market that competes with a remanufacturer. Assuming a fixed level of remanufacturability, they show the conditions under which take-back regulations as well as subsidies encourage remanufacturing activities. Örsdemir et al. (2014) study the competition between a manufacturer and a remanufacturer, incorporating the constraint that the remanufactured product quantity cannot exceed the quantity of the original product. Their model shares some features with ours but differs in important aspects: competition takes place in a single period and public policy is not considered.

In a broader view, our study also echoes recommendations from empirical studies that recycling should not be pushed too far. Kinnaman et al. (2014) use data in Japan to estimate the average social cost of waste management as a function of the recycling rate. Defining the social cost as the sum of all municipal costs and revenues, costs to recycling households, external disposal costs and external benefits of recycling, the authors suggest that the recycling rate that minimizes the average social costs in Japan should only be 10% and

⁶ Ba and Soubeyran (2023) also share a similar idea. However, their setting does not allow for a full static comparison. As a result, they only conduct numerical simulations with certain recycling rates.

concluded that “the 20% recycling rate in Japan is higher than the socially optimal rate” and that “the current recycling rates in the United States (35%) and the EU27 (34%) may also be too high.” In another study, Dijkgraaf and Gradus (2014) estimate the cost function resulting from different policies in waste recycling in the Netherlands and find that it seems nearly impossible for the Netherlands to reach the EU goal of 70% recycling rate because of the high cost of the recycling system.⁷

In Sect. 2, we analyse a baseline model with one manufacturer, one recycler, and linear demand and costs. In Sect. 3, we use this model to characterize the first-best allocation and the second-best policy. In Sect. 4, we show that our key results hold in more general settings with a general demand, product and cost differentiation, resource scarcity, several manufacturers and recyclers, manufacturers using their own scrap, or a for-profit scrap collector. We conclude in Sect. 5.

2 A Baseline Model

We analyze here a setting with one manufacturer, one recycler, and simple specifications for demand, costs, and recycling technology. This parsimonious model allows us to focus on the main strategic trade-off while leaving out unnecessary details. In Sect. 4, we discuss our assumptions and show the robustness of our results by extending the model in several directions.

We consider the market for some homogenous good (think of, e.g., aluminium cans). The manufacturer produces the good from primary material, whereas the recycler does so by using a reprocessed fraction of the manufacturer’s end-of-life products. The two firms play the following two-stage game. *In period 1*, the manufacturer chooses the quantity of production for this period, q_1 ; by the end of the period, all products in use wear out and a fraction $\tau \in [0, 1]$ of the scraps is collected and reprocessed (the rest of the scraps is dumped). *In period 2*, the recycler enters the market and uses the reprocessed scraps as input to compete with the manufacturer à la Cournot; we denote by r the quantity produced by the recycler and by q_2 the quantity produced by the manufacturer. In what follows, we call τ the *recycling rate* and we take it as a measure of the efficiency of the recycling system.⁸ Note that τ is common knowledge (in particular, it is known by the manufacturer in period 1). The other ingredients of the baseline model are as follows.

Demand. The inverse demand for the good is $p_1 = 1 - q_1$ in period 1 and $p_2 = 1 - q_2 - r$ in period 2. That is, we assume for now that consumers perceive the manufacturer’s and the recycler’s products as homogenous, and that the recycler’s entry does not contribute to increasing total demand (i.e., the maximum price that consumers are willing to pay is the same in both periods and is normalized to 1).

Production costs. We assume that both firms have a constant marginal cost of production and no fixed cost. Without loss of generality, we normalize the manufacturer’s production

⁷ In this stream of the literature, we can also cite Hamilton et al. (2013), Kinnaman (2013), Fullerton and Kinnaman (1995), Kinnaman and Fullerton (2000), Callan and Thomas (2001), Kinnaman (2006), Bohm et al. (2010), Kinnaman (2010), and Hamilton et al. (2013).

⁸ To adapt the model to the case of remanufacturing, we can simply interpret the parameter τ as the degree of product reparability. A larger value of τ means then that the primary product is easier to repair, which increases the remanufacturing possibilities. Policies promoting the reparability of goods aim to foster this process. For instance, in February 2024, the Council and the European Parliament reached a provisional deal on the so-called right-to-repair (or R2R) directive, which promotes the repair of broken or defective goods (see <https://tinyurl.com/bduacnx3>, last accessed April 4, 2024.)

cost to zero. Meanwhile, the total cost to produce a quantity r of recycled products from reprocessed scrap is equal to cr . We assume in the baseline model that $c \geq 0$, meaning that recycling is at least as expensive as primary production. Before the recycler's entry, the manufacturer does not know precisely the value of c ; it expects c to be drawn from a uniform distribution over the interval $[0, 1/2]$.⁹

We solve the game for its subgame-perfect equilibrium, assuming that the manufacturer does not discount its future profit when choosing its quantity in period 1.¹⁰ Before doing so, we briefly outline the benchmark case with no possibility of recycling. This is so, in our setting, when the recycling rate τ is equal to zero: with no scrap collected and/or reprocessed, the recycler cannot enter the market. In this case, the manufacturer would simply behave as an unconstrained monopolist in both periods: it would choose q_1 and q_2 to maximize $\pi = (1 - q_1)q_1 + (1 - q_2)q_2$, which yields $q_1 = q_2 = q^m = 1/2$. Over the two periods, the manufacturer would then produce a total quantity of primary products $2q^m = 1$ and earn a total profit of $\Pi(1/2, 1/2) = 1/2$.

We now turn to the situations in which $\tau > 0$: scraps are collected and reprocessed so that the recycler can enter the market in period 2. Solving the game backwards, we first analyse the Cournot competition in period 2; we then move to the manufacturer's choice in period 1.

2.1 Competition Between Manufacturer and Recycler

In period 2, the two firms simultaneously choose their quantity. The manufacturer chooses q_2 to maximize $\pi_2 = (1 - q_2 - r)q_2$; we derive the manufacturer's best-response function from the first-order condition:

$$q_2(r) = (1 - r)/2. \quad (1)$$

The recycler chooses r to maximize $\pi_r = (1 - q_2 - r)r - cr$ under the constraint $r \leq \tau q_1$ (as it cannot produce more than the amount of reprocessed scrap, i.e., τq_1). Solving the constrained maximization program, we find that the recycler's best-response function is kinked:

$$r^*(q_2) = \begin{cases} \frac{1}{2}(1 - c - q_2) & \text{if } \frac{1}{2}(1 - c - q_2) \leq \tau q_1, \\ \tau q_1 & \text{otherwise.} \end{cases} \quad (2)$$

Crossing the two best-response functions, we can identify two possible Cournot-Nash equilibria in period 2, depending on the amount of reprocessed scrap (τq_1) and the recycler's unit cost (c): an '*unconstrained equilibrium*' in which scraps are in large supply and/or the recycler is not efficient enough to reprocess them all, and a '*constrained equilibrium*' in

⁹ We make this assumption of stochastic costs purely for convenience, as it allows us to make the manufacturer's optimization problem continuous in period 1. We can establish our result equally—though less elegantly—if we assume instead that the manufacturer knows the recycler's cost with certainty. As we assume no entry cost, $c \leq 1/2$ guarantees that the recycler enters the market. For $c > 1/2$, the recycler stays out because entry is not profitable even when the manufacturer produces the monopoly quantity. Using the terminology of Bain (1956), we say that entry is 'blockaded' in this case. In our setting, the manufacturer cannot 'deter' entry and must 'accommodate' it when $c < 1/2$.

¹⁰ A discount factor strictly lower than 1 would attenuate the manufacturer's incentives to reduce production in the first period (as second-period profits would weigh relatively less). It is easily shown, however, that this would not affect our results.

which scraps are in short supply and/or the recycler is efficient enough to be bounded by the input availability. These two equilibria are characterized as follows:

- Quantities at the *unconstrained equilibrium* are found by solving the system of equations made of (1) and the top branch of (2):

$$q_2^u = \frac{1}{3}(1 + c) \text{ and } r^u = \frac{1}{3}(1 - 2c),$$

(with $r^u \geq 0$ as we assume $c \leq 1/2$). The equilibrium profits are then computed as:

$$\pi_2^u = \frac{1}{9}(1 + c)^2 \text{ and } \pi_r^u = \frac{1}{9}(1 - 2c)^2.$$

- In the *constrained equilibrium*, the recycler's quantity is bounded by the input constraint and the manufacturer reacts according to (1), so that:

$$q_2^c = \frac{1}{2}(1 - \tau q_1) \text{ and } r^c = \tau q_1;$$

equilibrium profits are then equal to:

$$\pi_2^c(q_1) = \frac{1}{4}(1 - \tau q_1)^2 \text{ and } \pi_r^c(q_1) = \frac{1}{2}\tau q_1(1 - 2c - \tau q_1).$$

Figure 1 depicts the two possible equilibria in period 2. Due to the input constraint, the recycler's reaction function is kinked at $r = \tau q_1$. If the scrap supply is large and/or the recycler is not efficient enough, we obtain the unconstrained equilibrium (q_2^u, r^u) in which $r^u < \tau q_1$ (Fig. 1a). Because the input constraint is not binding, the firms' outputs are independent of the recycling rate τ and the quantity of primary product in the first period (q_1). Instead, they depend on the marginal recycling cost c (a higher marginal cost c leads to lower recycling r^u and higher primary production q_2^u in period 2). In contrast, if the scrap supply is small and/or the recycler is efficient enough, its best-response function is shifted upward, as in Fig. 1b. Here, the quantity of recycled product is constrained by the initial primary production q_1 . The market then reaches the equilibrium (q_2^c, r^c) in which the recycler uses all the reprocessed scrap ($r^c = \tau q_1$), whereas the manufacturer produces a larger quantity q_2^c than if the recycler was not constrained (denoted by $\tilde{q}$). In this case, the manufacturer can control the scale of the recycler through its initial production q_1 (a lower q_1 leads to a lower r^c and a larger q_2^c).

In sum, the unconstrained equilibrium occurs if the quantity of reprocessed scrap is large enough, i.e., $\tau q_1 > r^u$; the constrained equilibrium occurs otherwise. Equivalently, for a given τq_1 , the unconstrained equilibrium occurs if r^u is small enough. Since r^u decreases with the recycler's marginal cost c , a larger value of this cost makes the unconstrained equilibrium more likely, as formalized in the following lemma.

Lemma 1 (1) For a given quantity of reprocessed scrap τq_1 , the unconstrained equilibrium ($r^u < \tau q_1$) obtains if the recycler's marginal cost c is above $\tilde{c} \equiv (1 - 3\tau q_1)/2$ and the constrained equilibrium ($r^c = \tau q_1$) obtains otherwise. (2) As the threshold $\tilde{c}$ decreases with τ and q_1 , only the unconstrained equilibrium can occur if $\tau q_1 \geq 1/3$.

Proof (1) The threshold $\tilde{c}$ is the value of c that separates the two types of equilibrium; that is, $\tilde{c}$ is such that $r^u(\tilde{c}) = r^c$, which is equivalent to $\frac{1-2\tilde{c}}{3} = \tau q_1$. For $c > \tilde{c}$, we have $r^u < \tau q_1$. (2) Given that $c \geq 0$, only the unconstrained equilibrium can occur if $\tilde{c} \leq 0$, which is

equivalent to $\tau q_1 \geq \frac{1}{3}$; for instance, if $q_1 = q_1^m = \frac{1}{2}$, then the condition becomes $\tau \geq \frac{2}{3}$. $\square$

2.2 Manufacturer's 'Limit Entry' Strategy

We now analyse whether and how the manufacturer wants to follow a 'limit entry' strategy, whereby the firm reduces its production in period 1 so as to limit the quantity of input that the recycler will be able to use in period 2. We are also interested in evaluating how the level of the recycling rate affects the manufacturer's decision.

In period 1, the manufacturer chooses the quantity q_1 to maximize its expected profits over the two periods. There are two possible courses of action. First, we know from Lemma 1 that if the manufacturer sets a sufficiently large quantity—namely, $q_1 \geq 1/(3\tau)$ —it can make sure that the equilibrium in period 2 will be unconstrained irrespective of the marginal cost drawn by the recycler. In that case, the manufacturer's profit in period 2 is $\pi_2^u = (1+c)^2/9$, which is independent of q_1 . Hence, the manufacturer's optimal quantity in period 1 is $q_1^m = 1/2$. This quantity satisfies the constraint as long as $q_1^m \geq 1/(3\tau)$, or $\tau \geq 2/3$.

Alternatively, the manufacturer can choose $q_1 < 1/(3\tau)$. Then, the equilibrium prevailing in period 2 depends on the cost drawn by the recycler: the manufacturer obtains the profit π_2^c in the constrained equilibrium if $c < \tilde{c}$, and obtains the profit π_2^u in the unconstrained equilibrium if $c > \tilde{c}$. Consequently, if $q_1 < 1/(3\tau)$, the manufacturer's expected profit function can be written as

$$\pi^e = \pi_1(q_1) + \hat{\pi}_2^c(q_1) + \hat{\pi}_2^u(q_1), \quad (3)$$

where $\pi_1(q_1) = q_1(1 - q_1)$ and, given the uniform distribution of c over the interval $[0, 1/2]$,

$$\hat{\pi}_2^c(q_1) = \int_0^{\tilde{c}} 2\pi_2^c(q_1)dc = \int_0^{\frac{1}{2}(1-3\tau q_1)} \frac{1}{2}(1 - \tau q_1)^2 dc = \frac{1}{4}(1 - \tau q_1)^2(1 - 3\tau q_1), \quad (4)$$

$$\hat{\pi}_2^u(q_1) = \int_{\tilde{c}}^{\frac{1}{2}} 2\pi_2^u dc = \int_{\frac{1}{2}(1-3\tau q_1)}^{\frac{1}{2}} \frac{2}{9}(1+c)^2 dc = \frac{1}{4}\tau q_1(\tau^2 q_1^2 - 3\tau q_1 + 3). \quad (5)$$

Because $\tilde{c}$ decreases with q_1 , the manufacturer faces a tradeoff when increasing q_1 . From (5), we observe that $\hat{\pi}_2^u(q_1)$ increases with q_1 as the probability that the unconstrained equilibrium occurs increases with q_1 while the manufacturer's profit remains constant. In contrast, we observe from (4) that $\hat{\pi}_2^c(q_1)$ decreases with q_1 for two reasons: not only does the constrained equilibrium become less likely but also the manufacturer gets a smaller profit (as $q_2^*(\tau q_1)$ decreases with q_1 because of strategic substitutability).

Clearly, the level of the recycling rate τ affects the balance between these two conflicting forces. As we now show, it does so in a non-monotonic way. Denote by $q_1^*(\tau)$ the quantity that maximizes expression (3) for a given τ . Note first that if τ is close to zero, the unconstrained equilibrium is very unlikely (as $\tilde{c}$ is close to $1/2$) and the manufacturer is hardly affected by the small scale of the recycler's operation in the constrained equilibrium. It follows that the manufacturer's choice of quantity $q_1^*(\tau)$ tends to $q_1^m = 1/2$ as τ tends to zero. Note also that we have just established that the manufacturer chooses

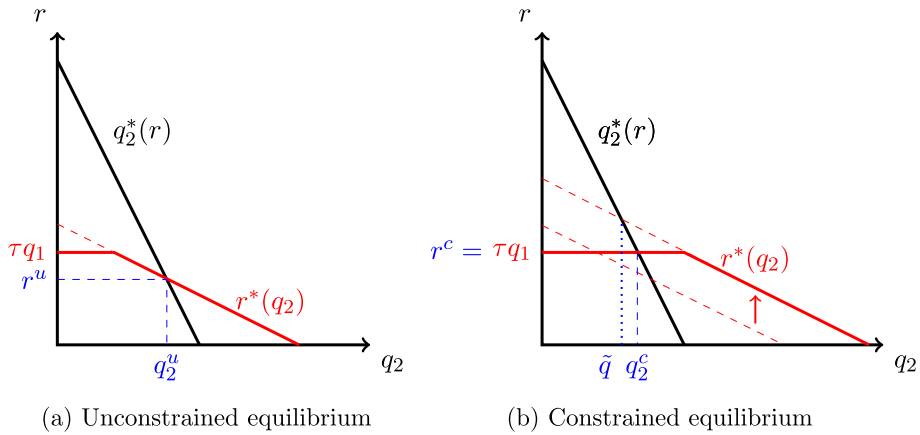


Fig. 1 Cournot-Nash equilibrium in period 2

$q_1^m = 1/2$ as well for $\tau \geq 2/3$. To understand how $q_1^*(\tau)$ evolves with τ for $0 < \tau < 2/3$, we use the implicit function theorem to write:

$$\frac{dq_1^*(\tau)}{d\tau} = -\frac{\partial^2 \Pi^e(q_1^*)}{\partial q_1 \partial \tau} \bigg/ \frac{\partial^2 \Pi^e(q_1^*)}{\partial q_1^2}.$$

Because $q_1^*(\tau)$ maximizes the firm's expected profit, $\partial^2 \pi^e(q_1^*)/\partial q_1^2 < 0$ by the second-order condition. So $dq_1^*(\tau)/d\tau$ takes the sign of

$$\frac{\partial^2 \pi^e(q_1^*)}{\partial q_1 \partial \tau} = \underbrace{\frac{\partial^2 \pi_1(q_1^*)}{\partial q_1 \partial \tau}}_{=0} + \underbrace{\frac{\partial^2 \hat{\pi}_2^c(q_1^*)}{\partial q_1 \partial \tau}}_{(i)} + \underbrace{\frac{\partial^2 \hat{\pi}_2^u(q_1^*)}{\partial q_1 \partial \tau}}_{(ii)}.$$

As τ only influences the first-period profit via its impact on q_1 , the first term is equal to zero. The variation of q_1 with respect to τ depends then on two factors: (i) the marginal impact of τ on the expected loss following an increase in q_1^* under the constrained equilibrium and (ii) the marginal impact of τ on the expected gain following an increase in q_1^* under the unconstrained equilibrium. Therefore, the profit-maximizing quantity in period 1, q_1^* , decreases with τ if the first impact dominates the second and increases with τ otherwise. As noted above, the former case certainly occurs when τ is close to zero (as the second impact vanishes), while the latter case certainly occurs when τ is close to $2/3$ (as the first impact vanishes). We expect thus $q_1^*(\tau)$ to be a U-shaped function of τ .

We now confirm our intuition by computing the exact value of $q_1^*(\tau)$. The first-order condition for profit-maximization is:

$$\frac{\partial \pi^e}{\partial q_1} = \frac{1}{2}(-3\tau^3 q_1^2 - 4(1 - \tau^2)q_1 + 2 - \tau) = 0. \quad (6)$$

At $\tau = 0$, it is equivalent to $1 - 2q_1 = 0$, which confirms that $q_1^*(0) = 1/2 = q_1^m$. For $\tau > 0$, the solution to Equation (6) is¹¹:

$$q_1^*(\tau) = \frac{\sqrt{4 - 8\tau^2 + 6\tau^3 + \tau^4} - 2(1 - \tau^2)}{3\tau^3}. \quad (7)$$

We check that $q_1^*(\tau) < 1/(3\tau)$ if and only if $\tau < 2/3$. We also observe that for $\tau < 2/3$, $q_1^*(\tau) < 1/2$ (while $q_1^*(2/3) = 1/2$). As represented in Fig. 2, $q_1^*(\tau)$ is a U-shaped function of τ : $q_1^* = 1/2$ at the two extreme values of the interval ($\tau = 0$ and $\tau = 2/3$), it decreases with τ for $0 < \tau < \bar{\tau} \approx 0.326$ and increases with τ for $\bar{\tau} < \tau < 2/3$. For $\tau \geq 2/3$, $q_1^*(\tau) = 1/2$: as explained above, the manufacturer can no longer constrain the recycler's input once the recycling rate becomes too large; it therefore maintains the monopolistic production q_1^m to maximize its profits in period 1.

The next proposition records our results.

Proposition 1 (1) *If the recycling rate τ is lower than $2/3$, then the manufacturer contracts its period 1 production, $q_1^*(\tau) < q_1^m$, to limit the recycler's scale of operation in period 2; the contraction is the largest for $\tau = \bar{\tau} \approx 0.326$.* (2) *If the recycling rate τ is larger than $2/3$, then the manufacturer maintains the monopolistic production level in period 1, $q_1^*(\tau) = q_1^m$.*

Intuitively, when the recycling rate is small, the manufacturer can constrain the recycler's scale by reducing slightly its production in period 1. Hence, in this case, the manufacturer finds it profitable to sacrifice part of its period-1 profits to increase its expected period-2 profits. As long as the recycling rate remains smaller than $\bar{\tau}$, the manufacturer reduces further its initial production. Yet, once the recycling rate becomes larger than $\bar{\tau}$, the manufacturer continues to apply the limit entry strategy, but it does so by reducing its initial production by smaller amounts; in fact, as the recycler can access a larger share of the initial production, the manufacturer must forgo more profits in period 1 to reach a given increase in expected profits in period 2. Eventually, the limit entry strategy becomes unprofitable (or is simply no longer a feasible option) when the recycling rate gets larger than $2/3$; the manufacturer, then, is no longer willing to contract its initial production and prefers to produce the monopoly output in period 1, as though the recycler was not to enter in period 2.

3 Policy Implications

We now address our research question: How far should we go in improving recycling? The policy instrument that we study is the recycling rate τ .¹² There are different ways through which public authorities can increase the recycling rate. For instance, the authorities can manage a centralized collection system and implement policies to encourage consumers and firms to participate in scrap collection. As a companion tool to enforce a given intended collection rate, authorities can also run a system of returnable goods with deposits (as is

¹¹ It can easily be checked that the other root is negative and that the second-order condition is satisfied.

¹² As our objective is to demonstrate the counter-intuitive impacts of modifying the recycling rate, we limit our analysis to this policy instrument, abstracting away other instruments—such as taxes on primary products or subsidies on recycled products—that the government could use to limit environmental damages. For a survey on the economics of environmental policy instruments, see, e.g., Sterner and Robinson (2018).

done for glass bottles in some European countries).¹³ Negative environmental externalities can result from four sources in our setting: (i) the extraction of the primary resource, (ii) the production of primary goods by the manufacturer; (iii) the production of recycled goods by the recycler, and (iv) the accumulation of disposed waste. Following the literature (see, e.g., Örsdemir et al. (2014) and the references therein), we assume that externalities are constant per unit of output. Accordingly, we define $e_p \geq 0$, $e_r \geq 0$, and $e_w \geq 0$ as the per-unit externality of, respectively, primary production (including the externality of primary production and primary resource extraction), r recycled production, and waste. The total environmental impact can then be defined as¹⁴:

$$E = e_p(q_1 + q_2) + e_r r + e_w(q_1 - r). \quad (8)$$

The other two components of the social welfare function are the consumer surplus (CS) and the firms' profits (Π). In our setting, they are computed as follows:

$$CS = \frac{1}{2}q_1^2 + \frac{1}{2}(q_2 + r)^2, \quad (9)$$

$$\Pi = \pi_m + \pi_r = [(1 - q_1)q_1 + (1 - q_2 - r)q_2] + (1 - q_2 - r - c)r. \quad (10)$$

As is also usually assumed in the literature, the social planner maximizes the unweighted sum of the three components, that is, $W = CS + \Pi - E$.¹⁵

3.1 First-Best Allocation

In a first-best world, the social planner chooses the quantities to be produced (q_1 , q_2 , r) as well as the recycling rate (τ) to maximize total welfare. The social planner's program is:

$$\max_{q_1, q_2, r, \tau} W \text{ subject to } r \leq \tau q_1.$$

Using expression (8)-(10) and deriving W with respect to r , we find:

$$\frac{dW}{dr} > 0 \Leftrightarrow 1 - r - q_2 > c + (e_r - e_w).$$

The left-hand side is the price of goods in period 2, while the right-hand side is the social cost of recycling (that is, the private cost c plus the net externality—one unit of recycled product entails an environmental impact of e_r but reduces waste by e_w). To give room to recycling in our setting, we assume that this inequality is satisfied. It follows that the social planner chooses to set $r = \tau q_1$. The social welfare function then becomes:

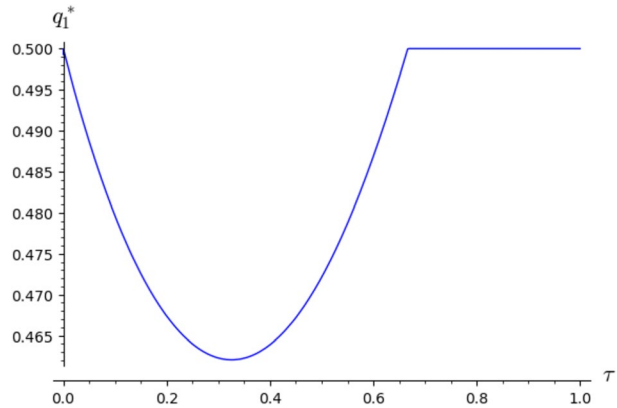
$$W = (1 - q_1)q_1 + (1 - q_2 - \tau q_1)q_2 + (1 - q_2 - \tau q_1 - c)\tau q_1 + \frac{1}{2}q_1^2 + \frac{1}{2}(q_2 + \tau q_1)^2 - (e_p(q_1 + q_2) + e_r \tau q_1 + e_w(1 - \tau)q_1).$$

¹³ To compare the merits of different organizations of collection systems, see, e.g., Beatty et al. (2007), Viscusi et al. (2012), Hamilton et al. (2013), Kinnaman (2013), or Kinnaman et al. (2014).

¹⁴ In this two-period model, we do not consider the potential waste externality of second-period production ($q_2 + r$).

¹⁵ All along, we assume that improving recycling is costless. This allows us to isolate the role of the strategic interaction described in the previous section (otherwise, a limited improvement of the recycling process could be attributed to cost reasons).

Fig. 2 Period-1 production as a function of the recycling rate



Solving for the first-order conditions with respect to q_1 and q_2 yields¹⁶:

$$\begin{cases} q_1^* = 1 - e_p - e_w - \tau(c + e_r - e_w - e_p), \\ q_2^* = 1 - e_p - \tau(1 - e_p - e_w) + \tau^2(c - e_p + e_r - e_w). \end{cases}$$

Substituting these values into the welfare function and deriving with respect to τ gives:

$$\left. \frac{dW}{d\tau} \right|_{q_1=q_1^*, q_2=q_2^*} = (1 - e_p - e_w - \tau(c + e_r - e_w - e_p))(e_p - c - e_r + e_w).$$

As the first bracketed term is equal to $q_1^* > 0$, we see that the derivative is either positive or negative, depending on the sign of the second bracketed term. This allows us to state the following result.

Proposition 2 *If the social cost of recycling ($c + e_r - e_w$) is lower than the social cost of primary production (e_p), then the first-best allocation is such that the first-period production is entirely recycled. Otherwise, there is no role for recycling at the first best.*

The intuition behind this result is straightforward. As the first-best is achieved by producing at the marginal social cost, one must choose, for the second period, the technology (primary production or recycling) with the lowest marginal social cost.

3.2 Second-Best Policy

We now consider a world in which quantities are not directly chosen by the social planner but, instead, by the manufacturer (q_1 and q_2) and the recycler (r). The planner can, nevertheless, influence the chosen quantities indirectly through the recycling rate. We saw indeed in the previous section that the recycling rate impacts the degree of competition in period 2 and, thereby, the manufacturer's decision in period 1. As recalled in Table 1, the quantities chosen by the two firms at the subgame-perfect equilibrium of the game depend on τ , and so do the various components of the social welfare function.¹⁷

¹⁶ It is easily checked that the second-order conditions are satisfied.

¹⁷ The detailed computations can be found in Appendix 6.1.

The social planner's objective is now written as:

$$\max_{\tau} \bar{W}(\tau) \equiv \pi_m(\tau) + \pi_r(\tau) + CS(\tau) - E(\tau).$$

An immediate observation from Table 1 is that $\bar{W}(\tau)$ is constant for values of the recycling rate above $2/3$. Recall that if $\tau \geq 2/3$, the competition between the manufacturer and the recycler always leads to the unconstrained equilibrium, in which scrap is only partially recycled. In this case, the equilibrium quantities are independent of the recycling rate and so are all components of the social welfare function.

For smaller values of the recycling rate, we cannot solve analytically for the maximum of $\bar{W}(\tau)$. However, we can draw useful insights by examining the impact of the recycling rate on the components of the social welfare function.

3.2.1 Impacts of Recycling on Firms and Consumers

Firms. Unsurprisingly, the firms' preferences regarding the level of the recycling rate are completely at odds with one another. It is easily shown that *the manufacturer's profit is the largest for $\tau = 0$, while the recycler's profit reaches its maximum level at $\tau = 2/3$* . If we take the point of view of total industry profits, we see in Panel (A) of Fig. 3 that they decrease with τ ; this follows from the fact that, in our model, the manufacturer earns profit over one more period than the recycler.¹⁸

Consumers. As the baseline model assumes homogeneous products, the consumer surplus increases with the level of total production (primary and recycled). A priori, recycling has ambiguous impacts on the consumer surplus: on the one hand, the recycler's entry in period 2 benefits consumers (because in a homogeneous product market, duopolists produce together a larger equilibrium quantity than a monopolist does); on the other hand, the prospect of the recycler's entry induces the manufacturer to (weakly) decrease its production in period 1. Panel (B) of Fig. 3 shows that the former effect always outweighs the latter, and even more so as the recycling rate increases. Hence, *consumer surplus increases with the recycling rate τ* , which means that consumers would vote for pushing the improvement of the recycling process to $\tau = 2/3$.

Social surplus. Combining the previous results, we can evaluate the impacts of recycling on the social surplus, defined as the sum of the firms' profits and the consumer surplus. We see in Panel (C) of Fig. 3 that the social surplus first decreases and then increases with the recycling rate. Comparing the values of the social surplus at $\tau = 0$ and $\tau = 2/3$, we find:

$$SS\left(\frac{2}{3}\right) = \frac{41}{54} = 0.759 > SS(0) = 0.75.$$

Hence, a second-best social planner with no concern for the environment (that is, only focused on the well-being of firms and consumers) would choose a recycling rate equal to $2/3$.¹⁹ This finding follows from the pro-competitive effect of recycling in our setting.

¹⁸ Even if the manufacturer had to bribe the recycler not to enter the market, it would push for the total absence of recycling.

¹⁹ In fact, the planner is indifferent between any $\tau \in [2/3, 1]$. Yet, if we introduce a tiny cost of improving recycling, choosing $\tau = 2/3$ is the dominant option.

Table 1 Quantities, profits, consumer surplus, and total environmental impact at the subgame-perfect equilibrium

	$\tau = 0$	$0 < \tau < 2/3$	$\tau \geq 2/3$
$q_1(\tau)$	$\frac{1}{2}$	$\frac{1}{3\tau^3} \left(\sqrt{4 - 8\tau^2 + 6\tau^3 + \tau^4} - 2(1 - \tau^2) \right)$	$\frac{1}{2}$
$q_2(\tau)$	$\frac{1}{2}$	$\frac{1}{2} (6\tau^2 q_1^2 - 4\tau q_1 + 1)$	$\frac{1}{6}$
$r(\tau)$	0	$\frac{1}{2} \tau q_1 (2 - 3\tau q_1)$	$\frac{1}{6}$
$\pi_m(\tau)$	$\frac{1}{2}$	$\frac{1}{4} (1 + 2(2 - \tau)q_1 - 4(1 - \tau^2)q_1^2 - 2\tau^3 q_1^3)$	$\frac{23}{54}$
$\pi_r(\tau)$	0	$\frac{1}{4} \tau q_1 (1 - \tau q_1)^2$	$\frac{1}{27}$
$CS(\tau)$	$\frac{1}{4}$	$\frac{1}{8} (1 + 5\tau q_1 + 2(2 - \tau^2)q_1^2 - 2\tau(6 + \tau^2)q_1^3)$	$\frac{8}{27}$
$E(\tau)$	$\frac{e_p}{2} + \frac{1}{2}e_w$	$\frac{1}{4} \tau (2e_r - 2e_w - e_p)(2 - 3\tau q_1)q_1 + (e_p + e_w)q_1 + \frac{1}{2}e_p$	$\frac{11}{12}e_p + \frac{1}{6}e_r + \frac{1}{3}e_w$

3.2.2 Impacts of Recycling on Environmental Externalities

Using the results recorded in Table 1 to compute the total environmental externality and deriving it with respect to the recycling rate, we obtain:

$$\begin{aligned} \frac{\partial E(\tau)}{\partial \tau} &= \omega_p(\tau)e_p + \omega_r(\tau)e_r + \omega_w(\tau)e_w, \text{ with} \\ \omega_p(\tau) &\equiv \frac{\partial q_1}{\partial \tau} - \frac{1}{2}(1 - 3\tau q_1) \left(q_1 + \tau \frac{\partial q_1}{\partial \tau} \right), \\ \omega_r(\tau) &\equiv (1 - 3\tau q_1) \left(q_1 + \tau \frac{\partial q_1}{\partial \tau} \right), \\ \omega_w(\tau) &\equiv \frac{\partial q_1}{\partial \tau} - (1 - 3\tau q_1) \left(q_1 + \tau \frac{\partial q_1}{\partial \tau} \right). \end{aligned}$$

Some lines of computations establish the following findings: (i) as τ tends to zero, $\omega_p(\tau)$, $\omega_r(\tau)$, and $\omega_w(\tau)$ tend, respectively, to $-\frac{1}{2}$, $\frac{1}{2}$, and $-\frac{3}{4}$; (ii) $\omega_p(\tau)$ and $\omega_w(\tau)$ increase with τ , while $\omega_r(\tau)$ decreases with τ ; (iii) $\omega_p(\tau)$, $\omega_r(\tau)$, and $\omega_w(\tau)$ are all positive at $\tau = \frac{2}{3}$. Hence, the function $E(\tau)$ is either increasing or U-shaped in τ . It is increasing in τ if the derivative is positive in the vicinity of $\tau = 0$, which occurs if $-\frac{1}{2}e_p + \frac{1}{2}e_r - \frac{3}{4}e_w > 0$, which is equivalent to $e_r > e_p + \frac{3}{2}e_w$. Otherwise, $E(\tau)$ reaches a minimum at $\hat{\tau}$ such that $\omega_p(\hat{\tau})e_p + \omega_r(\hat{\tau})e_r + \omega_w(\hat{\tau})e_w = 0$, with $0 < \hat{\tau} < \frac{2}{3}$.

In sum, if the social planner only cares about the environment, it chooses ‘partial recycling’ (that is, the recycling rate is positive but strictly lower than $2/3$), unless the externality from recycling is very large compared to the other two sources of externality (precisely, if $e_r > e_p + \frac{3}{2}e_w$), in which case the best is not to recycle at all.

The intuition is simple. Partial recycling induces the manufacturer to reduce its first-period production to limit the recycler’s scale of entry. From an environmental point of view, this has the advantage of reducing the extraction of primary resources, as well as the production of primary and recycled products.

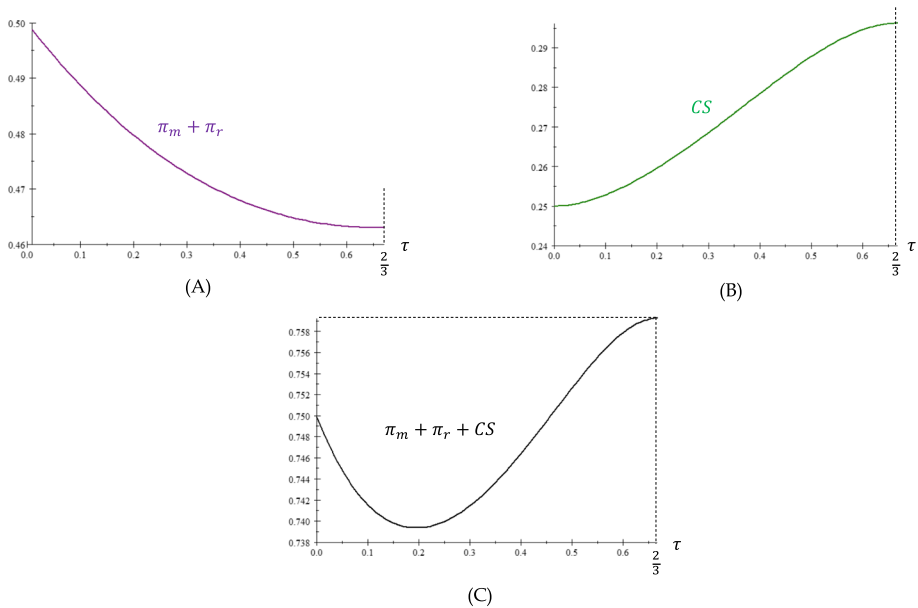


Fig. 3 Impact of the recycling rate on **A** total profits, **B** consumer surplus, and **C** social surplus

3.2.3 Combined Impacts of Recycling

Finally, we look at how the second-best social welfare function evolves with the recycling rate. We focus on values of τ comprised between 0 and $\frac{2}{3}$ (as $\bar{W}(\tau)$ is constant for $\frac{2}{3} \leq \tau \leq 1$). Recall that $\bar{W}(\tau) = SS(\tau) - E(\tau)$, where $SS(\tau) = \pi_m(\tau) + \pi_r(\tau) + CS(\tau)$. For $0 \leq \tau \leq \frac{2}{3}$, we just found that $SS(\tau)$ reaches its maximum at $\tau = \frac{2}{3}$, while $-E(\tau)$ reaches its maximum at a lower value of τ (possibly $\tau = 0$). Hence, in the presence of externalities ($E(\tau) > 0$), $\bar{W}(\tau)$ cannot be maximum at $\tau = \frac{2}{3}$. We check indeed that the derivative of $\bar{W}(\tau)$ with respect to τ is negative when evaluated at $\tau = \frac{2}{3}$:

$$\left. \frac{\partial \bar{W}(\tau)}{\partial \tau} \right|_{\tau=\frac{2}{3}} = -\frac{3}{14}(e_p + e_w) < 0.$$

This means that there exist $\bar{\tau}$ in the vicinity of $\frac{2}{3}$, such that $\bar{W}(\bar{\tau}) > \bar{W}(\frac{2}{3})$. Moreover, comparing the value of $\bar{W}(\tau)$ at the extremes, we find:

$$\begin{aligned} \bar{W}\left(\frac{2}{3}\right) &= \frac{41}{54} - \left(\frac{11}{12}e_p + \frac{1}{6}e_r + \frac{1}{3}e_w\right) > \bar{W}(0) = \frac{3}{4} - \left(e_p + \frac{1}{2}e_w\right) \\ &\Leftrightarrow e_r < \frac{1}{2}e_p + e_w + \frac{1}{18}. \end{aligned}$$

Hence, if the latter condition is fulfilled, we have that $\bar{W}(\bar{\tau}) > \bar{W}(\frac{2}{3}) = \bar{W}(1) > \bar{W}(0)$, with $0 < \bar{\tau} < \frac{2}{3}$. Figure 4 illustrates this result. It depicts the social welfare function in the second-best, assuming that $e_p = e_r = 0.1$ and $e_w = 0.05$. As $e_r < e_p/2 + e_w + 1/18$, we see

that the maximum is reached at a value of τ that is inferior to $2/3$. We have thus proved the following result.

Proposition 3 *From a second-best perspective, partial recycling is optimal if the negative externality stemming from recycled production is relatively smaller than the externalities stemming from primary production and waste (precisely if $e_r < \frac{1}{2}e_p + e_w + \frac{1}{18}$).*

The rationale underlying this result can be succinctly articulated as follows. The second-best social planner faces a delicate trade-off stemming from the divergent effects that changes in the recycling rate exert on social surplus and environmental externalities. In striving to maximize social surplus, the planner is inclined to enhance recycling to the fullest extent feasible, given that the benefits accruing to consumers and recyclers outweigh the drawbacks experienced by manufacturers. Nonetheless, the imperative to mitigate environmental externalities necessitates a nuanced approach, wherein partial recycling emerges as preferable. This preference arises from the incentivization of manufacturers to curtail primary resource extraction, thereby limiting the recycler's entry. Insofar as recycling yields relatively lower environmental harm compared to the utilization of primary resources and waste disposal, the planner's prioritization is directed towards mitigating the latter effects, leading to a propensity to constrain recycling enhancements. Consequently, from a second-best perspective, the response to our initial question “*Recycling: How far should we go?*” is aptly articulated as “*Not too far!*”.

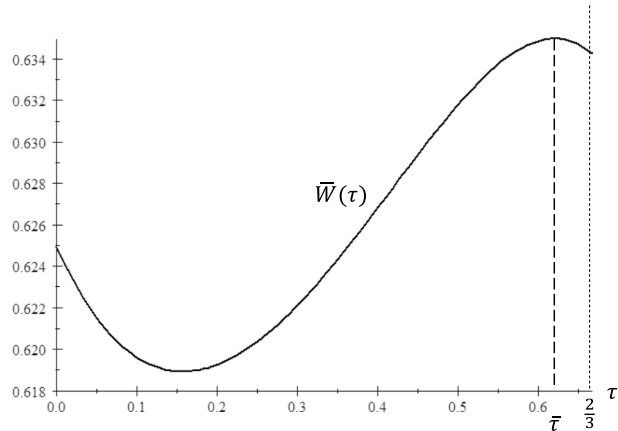
4 Extensions

In this section, we show that the results obtained in our baseline model continue to hold in more general settings. We first stick to the ‘one manufacturer/one recycler’ setting but we generalize the demand function (4.1), allow for differentiated products and costs (4.2), or introduce resource scarcity (4.3). Next, we complexify the strategic interaction by assuming an arbitrary number of manufacturers and recyclers (4.4), letting the manufacturer be present in the recycling market (4.5), and introducing an independent scrap collector (4.6). For each extension, we present the modified model and focus on the results and economic intuition, leaving most of the technical analysis in the appendix.

4.1 General Demand Function

In the baseline model, the demand for the products was, for simplicity, assumed to be linear. We take now a general demand function, $P = P(Q)$. This function is strictly decreasing, twice differentiable in $\mathbb{R}^+$, and satisfies the following assumptions: (i) $P(Q) = 0$ for a finite Q ; (ii) $P''(Q)Q + P'(Q) < 0$ for all $Q > 0$; and (iii) $P(Q) > 0$. Under these assumptions, the best-response functions are downward sloping with the slope belonging to the interval $(-1, 0]$. These are the sufficient conditions to assure the existence of a unique and

Fig. 4 Social welfare function at the second best ($e_p = e_r = 0.1$, $e_w = 0.05$)



locally stable Cournot equilibrium in period 2.²⁰ These conditions also ensure that products are substitutes so that per-firm outputs decrease with the number of firms in the symmetric equilibrium.²¹

In Appendix 6.2, we characterize the subgame-perfect Nash equilibrium of the game. We show that the results of Lemma 1 and Proposition 1 still hold with the general demand $P(Q)$. In particular, we establish that $q_1^* = q^m$ for $\tau \geq \bar{\tau}$ and $q_1^* < q^m$ for $\tau < \bar{\tau}$, with q_1^* decreasing with τ when τ is close to zero, and increasing in τ when τ is close to $\bar{\tau}$.²² We also show that the expected quantity produced by the manufacturer in period 2 decreases with τ . This allows us to state that the results of Proposition 1 continue to hold in the general case, and so do the policy implications of Sect. 3.

4.2 Product and Cost Differentiation

In the baseline model, we suppose for simplicity that the products of the recycler and the manufacturer are perfect substitutes. This relies on two related assumptions: the two products have the same technical properties and consumers are indifferent between them. Arguably, both assumptions can be verified in some contexts but certainly not in general. For certain materials such as glass, paper, and some metals, it is reasonable to consider that recycled and primary products can be used in the same way. Yet, recycled materials may also produce goods of inferior quality or, simply, other goods (for instance, plastic from recycled bottles is used for certain textiles or garden furniture). Moreover, even if recycled and primary products are similar from a technical viewpoint, it is not clear whether consumers will perceive them as equivalent. For some

²⁰ See Novshek (1985) for the existence, Kolstad and Mathiesen (1987) on the uniqueness and Dastidar (2000) on the local stability of Cournot equilibrium. See Vives (2001) for the discussion of these conditions.

²¹ In fact, Amir and Lambson (2000) prove that the necessary condition can be weaker: $P(Q)$ is log-concave, i.e. $P''(Q)P(Q) - P'^2 < 0$. However, the existence of a unique Cournot equilibrium requires strictly increasing, convex cost functions. Therefore, we use the assumption of declining marginal revenue to cover the case with zero production cost.

²² The threshold $\bar{\tau} < 1$ is such that $r''(0) = \bar{\tau}$ and hence, $r''(c) < \bar{\tau}q^m$ for all $c \in [0, \bar{\tau}]$. (In the linear case, we had $\bar{\tau} = 2/3$.)

products (such as cars, electronic goods, or domestic appliances), consumers may be reluctant to trust recycled products or components. Conversely, environmentally conscious consumers may be attracted to recycled products of other types (such as textiles, packaging, or luggage). As for costs, we postulate in the baseline model that recycling is at least as expensive as primary production. This assumption is also restrictive, as in some industries, more energy is needed for primary production than for recycling (think, for instance, of the aluminium industry).

We show here that our model can be extended to account for these alternative scenarios while preserving the main results. On the demand side, we now let recycled and primary products be differentiated (vertically and horizontally). In period 2 (when both products are on the market), consumers are assumed to have the following net utility:

$$U(q_2, r) = a_m q_2 + a_r r - \frac{1}{2}(q_2^2 + r^2 + 2\gamma q_2 r) - p_2 q_2 - p_r r.$$

Maximizing with respect to q_2 and r yields the inverse demands for two goods: $p_2 = a_m - q_2 - \gamma r$ and $p_r = a_r - r - \gamma q_2$. In this formulation, a_k is the maximum price that consumers are willing to pay for product k ($k = m, r$); this parameter can also be interpreted as an indicator of perceived quality. Hence, any difference between a_m and a_r denotes vertical differentiation. For instance, $a_m > a_r$ means that consumers are willing to pay more for the primary product than for the recycled one, other things being equal. The parameter γ is an inverse measure of horizontal differentiation between the two products: if $\gamma = 0$, the two products are seen as completely different; if $\gamma = 1$, they are seen as perfect substitutes. In period 1, as only the manufacturer's product is available, the inverse demand is simply $p_1 = a_m - q_1$.

On the supply side, we denote the constant unit costs by $c_m > 0$ for the manufacturer and by $c_r \geq 0$ for the recycler. Under this formulation, producing from recycled material can be more or less expensive than producing from primary material. Note that we can recover the baseline model by setting $a_m = a_r = 1$, $\gamma = 1$, $c_m = 0$ and $c_r = c$.

In Appendix 6.3, we repeat the analysis of Sect. 2. We characterize the equilibrium quantity of the manufacturer in the constrained equilibrium, which depends not only on the recycling rate τ but also on the demand and cost parameters $(a_r, a_m, \gamma, c_r, c_m)$. To gain additional insights, we perform two comparative statics exercises. We consider first the effect of horizontal differentiation between the primary and the recycled products. To this end, we set $a_r = a_m = 1$, $c_m = 0$ (as in the baseline model) but let γ vary. We examine next the effect of vertical differentiation: What happens if consumers are environmentally conscious and value the recycled product relatively more than the primary product? Here, we set $a_m = 1$, $c_m = 0$, and $\gamma = 1$ (as in the baseline model) but we let a_r be larger than $a_m = 1$.

The numerical simulations that we perform suggest that the manufacturer reduces further its first-period output to limit entry as products become more substitutable (γ increases) or as the recycled product becomes more valuable for consumers (a_r increases). The intuition is clear: in both cases, the manufacturer faces stronger competition from the recycler and finds it more profitable to limit the recycler's scale in period 2. From a policy point of view, one observes that the recycling rate that generates the largest output reduction becomes smaller as γ increases but larger as a_r increases.

4.3 Resource Scarcity

As we noted in the introduction, we implicitly assume in the baseline model that the manufacturer does not internalize the scarcity of the resource that it uses in its production process. To account for resource scarcity, we extend the baseline model in the following way. We let the manufacturer's total cost of production be given by $c_m q_1$ in period 1 and $c_m(\theta q_1 + q_2)$ in period 2, with $c_m, \theta > 0$. The formulation of the costs in period 2 captures the idea that the cost of exploiting the scarce resource increases over time with the stock of what has been used so far (in the baseline model, $c_m = \theta = 0$). In the benchmark case with no recycling, the manufacturer's maximization programme is:

$$\max_{q_1, q_2} (1 - q_1)q_1 - c_m q_1 + (1 - q_2)q_2 - c_m(\theta q_1 + q_2).$$

The profit-maximizing quantities are found as:

$$q_1^m = \frac{1 - c_m(1 + \theta)}{2} \leq q_2^m = \frac{1 - c_m}{2}.$$

We observe that in the absence of any competition, the manufacturer already has an incentive to reduce its first-period production. As underlined by, e.g., Ba and Mahenc (2019), reducing production (extraction) in the first period contributes to lowering the cost of production (extraction) in the second period.

Consider now the entry of the recycler in the second period. As we show in the baseline model, this entry may also incentivize the manufacturer to reduce its production in the first period. We want to know (i) how the two channels (scarcity costs and entry limitation) interact and (ii) how the equilibrium is affected by a change in the recycling rate. In Appendix 6.4, we show that (i) the two channels reinforce one another and (ii) the manufacturer's first-period production continues to be U-shaped in the recycling rate. In sum, *resource scarcity does not challenge our main results*. In fact, resource scarcity gives the manufacturer another motive to decrease its first-period quantity: on top of reducing the recycler's entry potential, the manufacturer also wants to save on second-period costs.

To conclude this section, let us note that the baseline model remains a reasonable approximation if we consider a local market. Within this local market, the firms (manufacturer and recycler) are (relatively) large, which explains why they enjoy market power. However, from a global perspective, these firms are very small players. As a result, the manufacturer does not perceive that its production contributes to the exhaustion of the resource. This does not prevent the local authority from taking into account the negative global externality that resource exhaustion exerts (see the parameter e_p that we introduced in Sect. 3). A case in point is the recycling of plastics in Belgium. First, the market for

plastic recycling is increasingly local.²³ Second, Belgium is a small producer of plastics at the global level.²⁴ Finally, the Belgian government cares about plastic recycling.²⁵

4.4 Several Manufacturers and Recyclers

We consider now an arbitrary number of symmetric firms in each sector: m identical manufacturers and n identical recyclers. We adjust our notation as follows. First, we let q_{i1} and q_{i2} denote the quantities produced by manufacturer $i = 1 \dots m$ in period 1 and 2 respectively; Q_1 and Q_2 are the corresponding total quantities, summing over all m manufacturers. Second, we let r_j denote the quantity produced by recycler $j = 1 \dots n$ in period 2; R denote the total quantity produced by the n recyclers, with $R \leq \tau Q_1$. Finally, the inverse demand is written as $P = 1 - Q_1$ in period 1 and $P = 1 - Q_2 - R$ in period 2.

As in the baseline model, we assume that all firms produce at a constant marginal cost; this cost is normalized to zero for manufacturers and equal to c for all recyclers, with c drawn from a uniform distribution over $[0, 1/(m+1)]$. In Appendix 6.5, we solve the game by backward induction for its subgame-perfect equilibrium. We sketch the main results here.

Define:

$$Q_1^{\text{lim}} \equiv \frac{1}{\tau} \frac{n(1 - (m+1)c)}{m+n+1}.$$

The Nash equilibrium at the second stage of the game is characterized as follows: for $Q_1 < Q_1^{\text{lim}}$, all recyclers are constrained while for $Q_1 \geq Q_1^{\text{lim}}$, no recycler is constrained. The condition for the unconstrained equilibrium ($Q_1 \geq Q_1^{\text{lim}}$) can be rewritten as:

$$c \geq \frac{n - \tau(m+n+1)Q_1}{n(m+1)} \equiv \tilde{c}(m, n).$$

We observe that $\tilde{c}(m, n)$ decreases with m and increases with n , implying that, other things being equal, the unconstrained equilibrium is more likely if there are more manufacturers or fewer recyclers. We also note that the unconstrained equilibrium is the only possible equilibrium if Q_1 is sufficiently large, that is:

²³ For instance, a new recycling plant has recently started to operate in Belgium. This “new recycling centre is the last of five new facilities being built across Belgium, with three new operational—the simultaneous efforts of all five are expected to see a 75% domestic recycling rate for plastic packaging from 2025. (...) [The operator] plans to provide the centre with 24,000 tonnes of PMD waste sourced from Belgian households. (...) These will be converted into recycled plastic granules to be used in the production of new packaging. It is hoped that the recytrate will be of such high quality that it can be reused in its entirety and that it will be supplied to the local Belgian market as much as possible (see *Packaging Europe*, 21 March 2023, <https://tinyurl.com/yckmmdpa>; emphasis added; last accessed April 4, 2024).

²⁴ We can roughly estimate that Belgium accounts for 0.6% of global plastic materials production (Belgium’s GDP is about 4% of EU-27 GDP and EU-27 accounted for 15% of global plastic materials production in 2021; see Statista.com).

²⁵ “Overall, the country is particularly performant in the collection, sorting and recycling of household packaging with Belgium firmly taking on more ambitious targets than the EU itself, establishing a target of 70% plastics recycling rate for 2030 (compared to 55% for the EU) and a 95% household packaging recycling rate (vs. 65% for the EU)” (see *The Brussels Time*, 15 June 2023, <https://tinyurl.com/3322fymj>; emphasis added; last accessed April 4, 2024).

$$\tilde{c}(m, n) \leq 0 \Leftrightarrow Q_1 \geq \frac{n}{\tau(m+n+1)}. \quad (11)$$

If this equilibrium prevails, the manufacturers' profits in the two periods are independent of one another. It follows that the equilibrium in period 1 is the classic Cournot-Nash equilibrium. In the present setting, each firm produces a quantity $q_1 = 1/(m+1)$. Then, condition (11) is satisfied as long as

$$Q_1 = \frac{m}{m+1} \geq \frac{n}{\tau(m+n+1)} \Leftrightarrow \tau \geq \frac{n(m+1)}{m(m+n+1)} \equiv \tilde{\tau}(m, n).$$

We note that (i) $\tilde{\tau}(1, 1) = 2/3$ (as we found in the baseline model), (ii) $\tilde{\tau}(m, n)$ decreases with m and increases with n , and (iii) $\tilde{\tau}(m, n) < 1$ if and only if $n < m(m+1)$. We can thus conclude that *the symmetric 'unconstrained equilibrium' occurs if the recycling rate is above some threshold and becomes more likely as the number of manufacturers increases and the number of recyclers decreases.*

In the symmetric 'limit equilibrium', we show that each manufacturer produces a quantity $q_1^*(\tau, m, n) < 1/(m+1)$. We can then compute the value of τ that minimizes $q_1^*(\tau, m, n)$ and assess how this value, which we denote $\tilde{\tau}(m, n)$, changes with the numbers of manufacturer and recyclers in the market. Given the complexity of the expressions, we only consider cases with one or two firms in each group; we find:

$$\tilde{\tau}(2, 1) = 0.178 < \tilde{\tau}(2, 2) = 0.272 < \tilde{\tau}(1, 1) = 0.326 < \tilde{\tau}(1, 2) = 0.474,$$

which suggests that $\tilde{\tau}(m, n)$ decreases with m and increases with n .

4.5 Manufacturer Using Its Own Scrap

In the baseline model, we assume that the manufacturer produces the good in both periods by using primary material exclusively. To relax this assumption, suppose now that the manufacturer is forced to use its scrap along with primary material to produce in period 2. The reuse of scrap entails two contrasting effects on the manufacturer's profits. On the one hand, there is a direct negative effect stemming from the increase in the unit cost of production in period 2. Supposing for simplicity that the production process mixes a share α of scrap (which costs c per unit) with a share $(1-\alpha)$ of primary material (which costs 0 per unit), the manufacturer's unit cost is now equal to $\alpha c > 0$. On the other hand, there is potentially a positive strategic effect as the manufacturer can further limit the recycler's capacity by using part of the scrap for its own production. Now, the quantity r that the recycler can produce cannot be larger than $\tau q_1 - \alpha q_2$.²⁶

In Appendix 6.6, we analyse the manufacturer's limit entry strategy under these new assumptions. We compute the manufacturer's profit-maximizing quantity in period 1, $q_1^*(\tau, \alpha)$, and we analyse its sensitivity to changes in α . We observe first that $q_1^*(\tau, \alpha)$ continues to be U-shaped in τ even for $\alpha > 0$, meaning that our main result is preserved. The additional insight that we can draw from this extension of the model is the following: *If the manufacturer must include a larger ratio of reprocessed scrap in its production, it tends to decrease its first-period production further and the recycling rate that induces the lowest first-period production becomes larger.* This indicates that the positive effect of

²⁶ The available scrap from period 1, τq_1 , is reduced by the scrap that the manufacturer uses for its second-period production, αq_2 .

constraining further the recycler's entry outweighs the negative effect of facing a larger production cost in period 2.

4.6 Independent Scrap Collector

In the baseline model (and its extensions so far), we assume a direct link between the manufacturer's scrap production in the first period and the recycler's activity in the second period. In reality, this link is less direct: between scrap production and recycling, there is the intermediary step of scrap collection. Another useful extension of the model consists thus in introducing a third type of actors, namely scrap collectors, who first retrieve discarded material from manufacturers and/or consumers and, next, sell it to recyclers. As these intermediaries act strategically, they affect the manufacturer's behavior.

In this more realistic context, is the manufacturer still willing to reduce its first-period production now that it no longer directly controls how much scrap is available for recycling? And if it still does, how is its behavior affected by public policy? We show here that our previous results carry over if we introduce an independent, for-profit, scrap collector in the model. In particular, the manufacturer still reduces its first-period production below the myopic optimum to limit entry and this reduction is still a non-monotonic function of the efficiency of the collection/recycling process.

To account for scrap collection and resell, let us divide period 1 into two sub-periods. In period 1a, the manufacturer produces q_1 ; in period 1b, the scrap collector chooses the intensity of scrap collection $\phi \in [0, 1]$ to produce a quantity of scrap $s = \phi q_1$ and sell it to the recycler at a price c per unit. As before, in period 2, the recycler produces r from scrap at cost c and the manufacturer produces q_2 from primary material at cost 0. We assume that the scrap collector's cost function is concave in ϕ and increasing in q_1 : $C(\phi, q_1) = \frac{1}{2}\sigma\phi^2q_1$, where $\sigma > 0$ can be seen as an inverse measure of the efficiency of the collection process (the lower σ , the lower the cost of scrap collection for any intensity ϕ and any production q_1). We also assume that the recycler can produce a quantity of final good $r = \mu s$ from a quantity s of scrap, where $0 < \mu \leq 1$ measures the efficiency of the recycling process. In this extended model, a public authority can use two instruments to improve recycling: it can decrease σ to have a larger share of discarded products being collected and/or improve μ to have a larger share of collected scrap being transformed into final goods.

In Appendix 6.7, we demonstrate that the manufacturer can improve its second-period profit by decreasing its first-period output below the myopic optimum. In other words, the manufacturer is still able to limit the recycler's entry even if the quantity of available scrap is now chosen by an intermediary. We also show that the profit-maximising quantity in period 1 first decreases and eventually increases with τ (with $\tau \equiv \mu^2/\sigma$ measuring the global efficiency of the collection/recycling process). This non-monotonicity is similar to the one we find in the baseline model.

5 Conclusion

We show in this paper that increasing the rate of scrap collection/reprocessing for recycling (or the degree of product reparability to foster remanufacturing) does not reduce monotonically the quantity of primary production. This is due to the strategic reaction of manufacturers when anticipating the entry by recyclers (or remanufacturers). In fact, increasing

the recycling rate from a low level reduces the quantity of primary production as manufacturers constrain the recyclers' scale of operation to soften competition in the next period. However, if the initial recycling rate is higher than a certain threshold, increasing the rate will lead to an *increase* in the quantity of primary production as constraining the recyclers' entry becomes too expensive for manufacturers (because they need to reduce further their current production—and thus their current profit). Consequently, it may be counterproductive from an environmental point of view (and even a societal point of view) to make the recycling process too efficient because, above some level, manufacturers would prefer to increase their extraction of primary material.

Although we show that our results continue to hold in richer settings, future research should aim at extending our model further. An interesting direction would be to abandon the simplifying assumption of symmetry within the two categories of firms (manufacturers and recyclers). If manufacturers are different (for instance, because they have different costs of production), it is unclear how the efforts to reduce the recyclers' entry would be allocated among them. Manufacturers would indeed tend to free-ride and let other firms bear the cost of reducing their production.²⁷ Also, given the manufacturers' first-period decisions, the recyclers' entry could be affected not only on the intensive margin (each entrant producing less) but also on the extensive margin (the less efficient recyclers staying out altogether). Additional insights could then be gained regarding the impacts of changes in the recycling rate.

Appendix

Second Best

Recall:

- Unconstrained equilibrium (for $c \geq \tilde{c} \equiv (1 - 3\tau q_1)/2$):

$$q_2^u = \frac{1}{3}(1 + c), r^u = \frac{1}{3}(1 - 2c), \pi_2^u = \frac{1}{9}(1 + c)^2, \pi_r^u = \frac{1}{9}(1 - 2c)^2$$

- Constrained equilibrium (for $c \leq \tilde{c} \equiv (1 - 3\tau q_1)/2$):

$$q_2^c = \frac{1}{2}(1 - \tau q_1), r^c = \tau q_1, \pi_2^c = \frac{1}{4}(1 - \tau q_1)^2, \pi_r^c = \frac{1}{2}\tau q_1(1 - 2c - \tau q_1).$$

Equilibrium quantities

- **Manufacturer**

– *Period 1*

$$q_1 = \begin{cases} \frac{1}{2} & \text{if } \tau = 0 \\ \frac{\sqrt{4 - 8\tau^2 + 6\tau^3 + \tau^4} - 2(1 - \tau^2)}{3\tau^3} & \text{if } 0 < \tau < \frac{2}{3} \\ \frac{1}{2} & \text{if } \frac{2}{3} \leq \tau \leq 1 \end{cases}$$

– *Period 2*

²⁷ See, e.g., Gilbert and Vives (1986).

$$q_2 = \begin{cases} \frac{1}{2} & \text{if } \tau = 0 \\ \int_0^{\frac{1}{2}(1-3\tau q_1)} 2\left(\frac{1}{2}(1-\tau q_1)\right)dc & \\ + \int_{\frac{1}{2}(1-3\tau q_1)}^{\frac{1}{2}} 2\left(\frac{1}{3}(1-2c)\right)dc & \text{if } 0 < \tau < \frac{2}{3} \\ = \frac{1}{2}(6\tau^2 q_1^2 - 4\tau q_1 + 1) & \\ \int_0^{\frac{1}{2}} 2\left(\frac{1}{3}(1-2c)\right)dc = \frac{1}{6} & \text{if } \frac{2}{3} \leq \tau \leq 1 \end{cases}$$

• **Recycler**

$$r = \begin{cases} 0 & \text{if } \tau = 0 \\ \int_0^{\frac{1}{2}(1-3\tau q_1)} 2(\tau q_1)dc + \int_{\frac{1}{2}(1-3\tau q_1)}^{\frac{1}{2}} 2\left(\frac{1}{3}(1-2c)\right)dc & \text{if } 0 < \tau < \frac{2}{3} \\ = \frac{1}{2}\tau q_1(2-3\tau q_1) & \\ \int_0^{\frac{1}{2}} 2\left(\frac{1}{3}(1-2c)\right)dc = \frac{1}{6} & \text{if } \frac{2}{3} \leq \tau \leq 1 \end{cases}$$

Equilibrium profits

• **Manufacturer:** $\pi_m = (1 - q_1)q_1 + (1 - q_2 - r)q_2$

$$\pi_m = \begin{cases} \left(1 - \frac{1}{2}\right)\frac{1}{2} + \left(1 - \frac{1}{2}\right)\frac{1}{2} = \frac{1}{2} & \text{if } \tau = 0 \\ (1 - q_1)q_1 + \int_0^{\frac{1}{2}(1-3\tau q_1)} 2\left(\frac{1}{4}(1-\tau q_1)^2\right)dc & \\ + \int_{\frac{1}{2}(1-3\tau q_1)}^{\frac{1}{2}} 2\left(\frac{1}{9}(1+c)^2\right)dc & \text{if } 0 < \tau < \frac{2}{3} \\ = \frac{1}{4}(1 + 2(2-\tau)q_1 - 4(1-\tau^2)q_1^2 - 2\tau^3 q_1^3) & \\ \left(1 - \frac{1}{2}\right)\frac{1}{2} + \int_0^{\frac{1}{2}} 2\left(\frac{1}{9}(1+c)^2\right)dc = \frac{23}{54} & \text{if } \frac{2}{3} \leq \tau \leq 1 \end{cases}$$

• **Recycler:** $\pi_r = (1 - q_2 - r - c)r$

$$\pi_r = \begin{cases} 0 & \text{if } \tau = 0 \\ \int_0^{\frac{1}{2}(1-3\tau q_1)} 2\left(\frac{1}{2}\tau q_1(1-2c-\tau q_1)\right)dc & \\ + \int_{\frac{1}{2}(1-3\tau q_1)}^{\frac{1}{2}} 2\left(\frac{1}{9}(1-2c)^2\right)dc = \frac{1}{4}\tau q_1(1-\tau q_1)^2 & \text{if } 0 < \tau < \frac{2}{3} \\ \int_0^{\frac{1}{2}} 2\left(\frac{1}{9}(1-2c)^2\right)dc = \frac{1}{27} & \text{if } \frac{2}{3} \leq \tau \leq 1 \end{cases}$$

Consumer surplus

$$CS = \frac{1}{2}q_1^2 + \frac{1}{2}(q_2 + r)^2$$

$$CS = \begin{cases} \frac{1}{2}\left(\frac{1}{2}\right)^2 + \frac{1}{2}\left(\frac{1}{2}\right)^2 = \frac{1}{4} & \text{if } \tau = 0 \\ \int_0^{\frac{1}{2}(1-3\tau q_1)} 2\left(\frac{1}{2}q_1^2 + \frac{1}{2}\left(\frac{1}{2}(1-\tau q_1) + \tau q_1\right)^2\right)dc \\ + \int_{\frac{1}{2}(1-3\tau q_1)}^{\frac{1}{2}} 2\left(\frac{1}{2}\left(\frac{1}{2}\right)^2 + \frac{1}{2}\left(\frac{1}{3}(1+c) + \frac{1}{3}(1-2c)\right)^2\right)dc & \text{if } 0 < \tau < \frac{2}{3} \\ = \frac{1}{8}(1+5\tau q_1 + 2(2-\tau^2)q_1^2 - 2\tau(6+\tau^2)q_1^3) \\ \int_0^{\frac{1}{2}} 2\left(\frac{1}{2}\left(\frac{1}{2}\right)^2 + \frac{1}{2}\left(\frac{1}{3}(1+c) + \frac{1}{3}(1-2c)\right)^2\right)dc = \frac{8}{27} & \text{if } \frac{2}{3} \leq \tau \leq 1 \end{cases}$$

Total environmental externality

$$E = e_p(q_1 + q_2) + e_r r + e_w(q_1 - r)$$

$$E = \begin{cases} e_p\left(\frac{1}{2} + \frac{1}{2}\right) + e_w\left(\frac{1}{2}\right) = e_p + \frac{1}{2}e_w & \text{if } \tau = 0 \\ \int_0^{\frac{1}{2}(1-3\tau q_1)} 2\left(e_p\left(q_1 + \frac{1-\tau q_1}{2}\right) + e_r \tau q_1 + e_w(1-\tau)q_1\right)dc \\ + \int_{\frac{1}{2}(1-3\tau q_1)}^{\frac{1}{2}} 2\left(e_p\left(q_1 + \frac{1+c}{3}\right) + e_r \frac{1-2c}{3} + e_w\left(q_1 - \frac{1-2c}{3}\right)\right)dc & \text{if } 0 < \tau < \frac{2}{3} \\ = \frac{1}{4}\tau(2e_r - 2e_w - e_p)(2-3\tau q_1)q_1 + (e_p + e_w)q_1 + \frac{1}{2}e_p \\ \int_0^{\frac{1}{2}} 2\left(e_p\left(\frac{1}{2} + \frac{1+c}{3}\right) + e_r \frac{1-2c}{3} + e_w\left(\frac{1}{2} - \frac{1-2c}{3}\right)\right)dc & \text{if } \frac{2}{3} \leq \tau \leq 1 \\ = \frac{1}{12}(11e_p + 2e_r + 4e_w) \end{cases}$$

General Demand Function

Period 2 equilibrium. In period 2, the manufacturer chooses q_2 to maximize its profit $\pi_2 = P(q_2 + r)q_2$, while the recycler chooses r to maximize its profit $\pi_r = P(q_2 + r)r - cr$ under the constraint that $r \leq \tau q_1$. Letting $r^*(q_2) = \arg\max_r \pi_r$, we can write the recycler's best-response function as:

$$r^* = \begin{cases} r^*(q_2) & \text{if } r^*(q_2) \leq \tau q_1, \\ \tau q_1 & \text{otherwise.} \end{cases}$$

Hence, the unconstrained and constrained equilibria, $(r^u(c), q_2^u(c))$ and $(r^c(\tau q_1), q_2^c(\tau q_1))$, are respectively given by

$$\begin{cases} P(Q) - q_2^u P'(Q) = 0 \\ P(Q) + r^u P'(Q) - c = 0 \end{cases} \quad \text{where } Q = r^u + q_2^u,$$

and

$$\begin{cases} P(Q) - q_2^c P'(Q) = 0 \\ r^c = \tau q_1 \end{cases} \quad \text{where } Q = \tau q_1 + q_2^c.$$

Using the fact that q_2^c satisfies the first-order condition for profit maximization (i.e., $\frac{d\pi_2}{dq_2} = P'(Q)q_2^c + P(Q) = 0$, with $Q = \tau q_1 + q_2^c$), along with the implicit function theorem, we can compute the derivative of q_2^c with respect to q_1 as

$$\frac{dq_2^c}{dq_1} = -\frac{\frac{\partial \pi_2}{\partial^2 q_2 \partial q_1}}{\frac{\partial^2 \pi_2}{\partial q_2^2}} = -\tau \frac{P''q_2^c + P'}{P''q_2^c + 2P'}.$$

Because $P''q_2^c + P' < 0$ and $P''q_2^c + 2P' < 0$ under our assumptions, we obtain that $\frac{dq_2^c}{dq_1} < 0$; that is, q_2^c decreases with q_1 .

From there, we can show that the results of Lemma 1 still hold with the general demand $P(Q)$. The quantities of recycled and primary product in the unconstrained equilibrium $r^\mu(c)$ and $q_2^\mu(c)$ are indeed such that

$$\begin{cases} P'q_2^\mu(c) + P = 0, \\ P + P'r^\mu(c) - c = 0. \end{cases}$$

Because $P' < 0$ by assumption, $r^\mu(c)$ decreases in c , equals zero at $c = \bar{c}$, and reaches its maximum at $c = 0$, where the two firms are symmetric.²⁸ We then obtain $r^\mu(c) < r^\mu(0) = q_2^\mu(0)$ for all $c \in [0, \bar{c})$. As per-firm outputs decrease with the number of firms under our assumptions, we also have that $q_2^\mu(0) < q^m$.²⁹ Therefore, there exists a threshold $\bar{\tau} < 1$ such that $r^\mu(0) = \bar{\tau}$ and hence, $r^\mu(c) < \bar{\tau}q^m$ for all $c \in [0, \bar{c})$. (In the linear case, we had $\bar{\tau} = 2/3$.) Moreover, for any $\tau < \bar{\tau}$ and $q_1 < q^m$, there must exist a value $\tilde{c} \in (0, \bar{c})$ such that $r^\mu(\tilde{c}) = \tau q_1$. Because $r^\mu(c)$ decreases in c , we have $\tilde{c}$ decreasing with q_1 and τ , such that

$$\begin{cases} r^\mu(c) \leq \tau q_1 & \text{if } c \geq \tilde{c}(q_1) \\ r^\mu(c) > \tau q_1 & \text{otherwise.} \end{cases}$$

Manufacturer's maximization problem in period 1. We compute the total differentiation of the manufacturer's expected profit function with respect to q_1 :

$$\frac{d\Pi^e(q_1)}{dq_1} = \frac{d\pi_1(q_1)}{dq_1} + \frac{d\hat{\pi}_2^c(q_1)}{dq_1} + \frac{d\hat{\pi}_2^\mu(q_1)}{dq_1}.$$

The impact of q_1 on the expected profit in the second period is computed as

$$\begin{aligned} \frac{d\hat{\pi}_2^c(q_1)}{dq_1} + \frac{d\hat{\pi}_2^\mu(q_1)}{dq_1} &= \frac{1}{\bar{c}} \frac{d}{dq_1} \int_0^{\tilde{c}(q_1)} \pi_2^c(q_1) dc + \frac{1}{\bar{c}} \frac{d}{dq_1} \int_{\tilde{c}(q_1)}^{\bar{c}} \pi_2^\mu(c) dc \\ &= \frac{1}{\bar{c}} \left[\underbrace{\frac{d\tilde{c}(\tau q_1)}{dq_1} (\pi_2^c(q_1) - \pi_2^\mu(\tilde{c}))}_{(a)} + \underbrace{\tilde{c} \frac{d\pi_2^c(q_1)}{dq_1}}_{(b)} \right]. \end{aligned}$$

²⁸ By definition, $\bar{c}$ is such that $\pi_r^\mu(\bar{c}), q_2^\mu(\bar{c}) = 0$; in a Cournot competition without degeneration following our assumption, this is equivalent to $r^\mu(\bar{c}) = 0$.

²⁹ See Amir and Lambson (2000).

Because $r^u(\tilde{c}) = r^c = \tau q_1$, we obtain $\pi_2^c(q_1) = \pi_2^u(\tilde{c})$, which makes $(a) = 0$. Therefore, we obtain

$$\frac{\partial \pi_2^c(q_1)}{\partial v q_1} + \frac{\partial \hat{\pi}_2^u(q_1)}{\partial q_1} = \frac{1}{\tilde{c}} \left[\tilde{c}(q_1) \frac{\partial \pi_2^c(q_1)}{\partial q_1} \right]. \quad (12)$$

Given that the profit of the manufacturer under the constrained equilibrium is $\pi_2^c(q_1) = P(\tau q_1 + q_2^*) q_2^*$, with $q_2^* = q_2^*(\tau q_1)$ the best response of the manufacturer when the recycler produces τq_1 , we have

$$\begin{aligned} \frac{\partial \pi_2^c(q_1)}{\partial q_1} &= \left(\tau + \frac{\partial q_2^*}{\partial q_1} \right) P' q_2^* + P \frac{\partial q_2^*}{\partial q_1} \\ &= \tau P' q_2^* + \frac{\partial q_2^*}{\partial q_1} (P' q_2^* + P). \end{aligned} \quad (13)$$

Because q_2^* maximizes π_2^c , according to the first-order condition of the profit-maximization problem, $P' q_2^* = -P$. Replacing in (13), we obtain

$$\frac{\partial \pi_2^c(q_1)}{\partial q_1} = -P\tau < 0. \quad (14)$$

The first derivative of the manufacturer's profit function can then be written as

$$\frac{d\Pi^e}{dq_1} = P'(q_1)q_1 + P(q_1) - \frac{\tilde{c}}{c} P(q_2 + r)\tau. \quad (15)$$

Since $\frac{\tilde{c}}{c} P(\cdot)\tau$ is positive and $P'(q_1)q_1 + P(q_1)$ is negative by assumption, there can be a value q_1^* so that $\frac{d\Pi^e}{dq_1} = 0$. Furthermore, $P'(q_1)q_1 + P(q_1)$ decreases with all $q_1 > 0$ as $\pi_1(q_1)$ is concave and $\frac{\tilde{c}}{c} P\tau$ increases with all $q_1 > 0$ as both P and $\tilde{c}$ decrease with q_1 . Therefore, q_1^* is unique if it exists.

Profit-maximizing primary production in period 1. When q_1 converges to 0, $\frac{d\Pi^e}{dq_1}$ converges to $P'(0)0 + P(0)$, which is strictly positive under our assumptions (i). Furthermore, at $q_1 = q^m$, the manufacturer's period 1 profit is separately maximized, i.e., $P'(q_m)q_m + p(q_m) = 0$ by the first-order condition. Equation (15) then becomes

$$\frac{d\Pi^e}{dq_1} = -\frac{\tilde{c}}{c} P\tau. \quad (16)$$

Since $\frac{\tilde{c}}{c} P\tau > 0$, $\frac{d\Pi^e}{dq_1}$ is strictly negative at $q_1 = q^m$ (ii). Together, (i) and (ii) impose that, if $\tau < \bar{\tau}$, the profit function increases with q_1 , reaches a unique maximum then decreases with q_1 when q_1 tends to q^m . Therefore, for $\tau < \bar{\tau}$, choosing $q_1^* \in (0, q^m)$ is the optimal choice for the manufacturer.

At $\tau = \bar{\tau}$, because $\tilde{c}(\bar{\tau}q^m) = 0$, Equation (15) is equivalent to

$$P'(q_1)q_1 + P(q_1) = 0.$$

Thus, the firm's profit is maximized at $q_1^* = q^m$ if $\tau = \bar{\tau}$. Because q_1^* is unique, this is also the global optimal choice of the manufacturer.

For $\tau > \bar{\tau}$, $\tilde{c}(\tau q^m)$ is negative, imposing that the constrained equilibrium does not obtain. The manufacturer's profit is independent of τ . The firm then chooses $q_1^* = q^m$.

Impact of the recycling rate on primary production in period 1. To formalize the impact of $\tau \in (0, \bar{\tau})$ on q_1^* , we use the implicit function theorem to write

$$\frac{dq_1^*(\tau)}{d\tau} = -\frac{\frac{\partial^2 \pi(q_1^*)}{\partial q_1 \partial \tau}}{\frac{\partial^2 \pi(q_1^*)}{\partial q_1^2}}.$$

Because q_1^* maximizes the firm's expected profit, $\frac{\partial^2 \pi(q_1^*)}{\partial q_1^2} < 0$ by the second-order condition. So $\frac{dq_1^*(\tau)}{d\tau}$ takes the sign of

$$\frac{\partial^2 \pi(q_1^*)}{\partial q_1 \partial \tau} = \frac{\partial^2 \pi_1(q_1^*)}{\partial q_1 \partial \tau} + \underbrace{\frac{\partial^2 \hat{\pi}_2^c(q_1)}{\partial q_1 \partial \tau}}_{(i)} + \underbrace{\frac{\partial^2 \hat{\pi}_2^u(q_1)}{\partial q_1 \partial \tau}}_{(ii)}.$$

From (12), we obtain

$$\begin{aligned} \frac{\partial^2 \pi(q_1^*)}{\partial q_1 \partial \tau} &= \frac{\partial^2 \hat{\pi}_2^c(q_1)}{\partial q_1 \partial \tau} + \frac{\partial^2 \hat{\pi}_2^u(q_1)}{\partial q_1 \partial \tau} = \frac{1}{\tilde{c}} \frac{\partial}{\partial \tau} \left[\tilde{c}(q_1^*) \frac{\pi_2^c(q_1^*)}{\partial q_1} \right] \\ &= \tilde{c}(q_1^*) \frac{\partial^2 \pi_2^c(q_1^*)}{\partial q_1 \partial \tau} + \frac{\partial \tilde{c}(q_1^*)}{\partial \tau} \frac{\partial \pi_2^c(q_1^*)}{\partial q_1} = -\frac{1}{\tilde{c}} \frac{\partial}{\partial \tau} [\tilde{c} \tau P] \\ &= -\frac{1}{\tilde{c}} \left[P \tilde{c} + \tau \left(\frac{\partial \tilde{c}}{\partial \tau} P + \frac{\partial P}{\partial \tau} \tilde{c} \right) \right]. \end{aligned}$$

Because both $\tilde{c}$ and P decrease with τ , the sign of $\frac{\partial^2 \pi(q_1^*)}{\partial q_1 \partial \tau}$ is ambiguous.

Consider τ close to 0, we have

$$\lim_{\tau \rightarrow 0} \frac{\partial}{\partial \tau} \left[\tilde{c} \frac{\pi_2^c}{\partial q_1} \right] = [-P \tilde{c}]_{\tau=0} < 0.$$

Furthermore, when $\tau \rightarrow 0$, $q_1^* \rightarrow \operatorname{argmax}_{q_1} (\pi_1 + \pi_2^c)$ but $\pi_2^c(\tau q_1, q_2^*(\tau q_1)) \rightarrow \pi_2^c(0, q_2^*(0))$, which is independent of q_1 , thus $q_1^* \rightarrow \operatorname{argmax}_{q_1} \pi_1 = q^m$.

Consider $\tau = \bar{\tau}$, we have $q_1 = q^m$, leading to $\tilde{c} = 0$. In this case,

$$\lim_{\tau \rightarrow \bar{\tau}} \frac{\partial}{\partial \tau} \left[\tilde{c} \frac{\pi_2^c}{\partial q_1} \right] = -\bar{\tau} P \frac{\partial \tilde{c}}{\partial \tau} > 0.$$

As $\frac{\partial}{\partial \tau} \left[\tilde{c} \frac{\pi_2^c}{\partial q_1} \right]$ is negative for τ close to zero, whereas $q_1^* \rightarrow q^m > 0$ when $\tau \rightarrow \bar{\tau}$, we can deduce that the initial production of the manufacturer decreases from the monopolistic value when τ is small and increases with τ when τ is close to $\bar{\tau}$ to reach the monopolistic level $q_1^* = q^m$ again at this threshold.

Recall that the threshold $\tilde{c}$ is determined at $r^u(\tilde{c}) = \tau q_1$, from the first-order condition of profit maximization of the recycler, we obtain

$$\tilde{c} = P'(Q) \tau q_1 + P(Q), \quad (17)$$

with $Q = \tau q_1 + q_2^c(\tau q_1)$.

To study the variation of $\tilde{c}$ with respect to $\tau \in (0, \bar{\tau})$, we take the total differentiation of equation (17) with respect to τ and rearrange the terms to obtain

$$\begin{aligned} \frac{d\tilde{c}}{d\tau} &= \left(q_1 + \frac{\partial q_2}{\partial \tau} \right) P' + P'' \tau q_1 \left(q_1 + \frac{\partial q_2}{\partial \tau} \right) + P' q_1 \\ &= \left(q_1 + \frac{\partial q_2}{\partial \tau} \right) (P'' \tau q_1 + P') + P' q_1 \\ &= P' q_1 \left(\frac{P'' \tau q_1 + P'}{P'' q_2 + 2P'} + 1 \right) < 0. \end{aligned}$$

Hence, given a level of q_1 , we have

$$\begin{aligned} \frac{d\tilde{c}}{d\tau} &= q_1 P' + \tau P' \frac{dq_1}{d\tau} + \left(q_1 + \tau \frac{dq_1}{d\tau} + \frac{dq_2}{d\tau} \right) (P'' \tau q_1 + P') \\ &= P' \left(\tau \frac{dq_1}{d\tau} + q_1 \right) \left(\frac{P'' \tau q_1 + P'}{P'' q_2 + 2P'} + 1 \right). \end{aligned}$$

For $\frac{d\tilde{c}}{d\tau} \geq 0$, we should have $\frac{dq_1}{d\tau} \leq -\frac{q_1}{\tau}$. Intuitively, this inequality means that, at an initial level of τ , to compensate for the marginal effect of an increase in τ on the reduction of $\tilde{c}$, the manufacturer has to reduce its initial production by more than q_1/τ , which is larger than q_1 . That means that the manufacturer has to reduce more than what it is producing. Since this is impossible, we can conclude that $\tilde{c}$ always decreases with τ .

Impact of the recycling rate on primary production in period 2. In period 2, the manufacturer's profits in the constrained equilibrium is given by $\pi_2^c = P(\tau q_1 + q_2)q_2$. Applying the implicit function theorem on the first-order condition $\frac{\partial \pi_2^c}{\partial q_2} = P' q_2 + P = 0$, we obtain the variation of q_2 with respect to τ due to the substitution effect in period 2 as

$$\frac{\partial q_2}{\partial \tau} = -\frac{\partial \pi_2}{\partial^2 q_2 \partial q_1} / \frac{\partial^2 \pi_2}{\partial q_2^2} = -\tau q_1 \frac{P'' q_2 + P'}{P'' q_2 + 2P'}.$$

Hence, the total variation of q_2 with respect to τ , taking into account both the substitution effect in period 2 and the strategic effect in period 1 is given by

$$\begin{aligned} \frac{dq_2}{d\tau} &= \frac{\partial q_2}{\partial \tau} + \frac{\partial q_2}{\partial q_1} \frac{dq_1}{d\tau} \\ &= -\tau q_1 \frac{P'' q_2 + P'}{P'' q_2 + 2P'} - \tau \frac{P'' q_2 + P'}{P'' q_2 + 2P'} \frac{dq_1}{d\tau} \\ &= -\frac{P'' q_2 + P'}{P'' q_2 + 2P'} \left(\frac{dq_1}{d\tau} + q_1 \right) \tau. \end{aligned}$$

Similar to the logic above, since $\frac{dq_1}{d\tau} > q_1$, we have $\frac{dq_2}{d\tau} < 0$; that is, the quantity of primary product in the constrained equilibrium decreases in τ .

We know that $\tilde{c}$ decreases in τ ; that is, the probability of occurrence of the constrained equilibrium is smaller. Moreover, given the same recycling cost c , we have $q_2^c > q_2^u$. Hence, the expected quantity of primary product in period 2 decreases τ . Now given that q_1^* decreases with τ when τ is small, the total quantity of primary production decreases when τ

is small. However, since q_2^u is independent of τ , the higher the weight of q_2^u in the computation of expected primary production in period 2, the smaller the variation of $\hat{q}_2$ with respect to τ . Hence, when τ is large, the negative impact of increasing τ on the total primary production via $\hat{q}_2$ converge to zero while the positive impact via q_1^* is larger. Therefore, the total primary production decreases, then increases with τ , that is, it also has an interior minimum with respect to τ .

Product and Cost Differentiation

To ease the exposition, we define $\mu_k \equiv a_k - c_k$ ($k = m, r$); this variable can be seen as a measure of the ‘social value’ of one unit of product k (as it is the difference between the maximum willingness to pay and the marginal cost). If the manufacturer was not constrained by the potential entry of the recycler, it would, in period 1, maximize $(\mu_m - q_1)q_1$ and choose $q_1^m = \mu_m/2$. Under entry, the manufacturer’s profit in period 2 is given by $(\mu_m - q_2 - \gamma r)q_2$, leading to the following reaction function: $q_2(r) = (\mu_m - \gamma r)/2$. The recycler chooses r to maximize $(\mu_r - r - \gamma q_2)r$ under the constraint that $r \leq \tau q_1$. The resulting reaction function is: $r(q_2) = (\mu_r - \gamma q_2)/2$ if $(\mu_r - \gamma q_2)/2 \leq \tau q_1$ or τq_1 otherwise. We can now derive the two candidate Nash equilibria:

$$\begin{cases} \text{Unconstrained equilibrium : } q_2^u = \frac{2\mu_m - \gamma\mu_r}{4 - \gamma^2}, r^u = \frac{2\mu_r - \gamma\mu_m}{4 - \gamma^2}, \\ \text{Constrained equilibrium : } q_2^c = \frac{1}{2}(\mu_m - \gamma\tau q_1), r^c = \tau q_1. \end{cases}$$

For the constrained equilibrium to emerge (and our results to follow), it must be that:

$$\tau q_1 < r^u \Leftrightarrow \mu_r > \frac{\gamma}{2}\mu_m + \frac{4 - \gamma^2}{2}\tau q_1 \equiv \tilde{\mu}_r.$$

Note that we assume here that $\frac{\gamma}{2}\mu_m < \mu_r < \frac{2}{\gamma}\mu_m$ to guarantee positive quantities for both firms in the unconstrained equilibrium,³⁰ It is obvious that $\tilde{\mu}_r > \frac{\gamma}{2}\mu_m$. We can also show that $\tilde{\mu}_r < \frac{2}{\gamma}\mu_m$. This condition is equivalent to $\mu_m > \gamma\tau q_1$, which is the most stringent when $q_1 = q_1^m = \mu_m/2$; in that case, the condition becomes $2 > \gamma\tau$, which is satisfied as γ and τ are inferior to 1.

In the constrained equilibrium of period 2, both firms produce a positive quantity as long as

$$\frac{2}{\gamma}\mu_m > \mu_r > \frac{\gamma}{2}\mu_m \Leftrightarrow a_r - \frac{2}{\gamma}\mu_m < c_r < a_r - \frac{\gamma}{2}\mu_m.$$

Let us assume that $a_r - \frac{2}{\gamma}\mu_m < 0 < a_r - \frac{\gamma}{2}\mu_m$. We, therefore, suppose that c_r is uniformly distributed over $[0, a_r - \frac{\gamma}{2}\mu_m]$.

In period 1, when the manufacturer decides to limit entry, it chooses q_1 to maximize $\Pi^e = q_1(\mu_m - q_1) + \hat{\pi}_2^c(q_1) + \hat{\pi}_2^u(q_1)$, where:

³⁰ We also assume that $\gamma > 0$ so that the two firms interact strategically.

$$\begin{aligned}
 \hat{\pi}_2^c(q_1) &= \int_0^{a_r - \frac{\gamma}{2}\mu_m - \frac{4-\gamma^2}{2}\tau q_1} \frac{1}{a_r - \frac{\gamma}{2}\mu_m} \frac{1}{4} (\mu_m - \tau\gamma q_1)^2 dc_r \\
 &= \frac{1}{4} (\mu_m - \tau\gamma q_1)^2 \frac{2a_r - \gamma\mu_m - 4\tau q_1 + \tau\gamma^2 q_1}{2a_r - \gamma\mu_m}, \\
 \hat{\pi}_2^u(q_1) &= \int_{a_r - \frac{\gamma}{2}\mu_m - \frac{4-\gamma^2}{2}\tau q_1}^{a_r - \frac{\gamma}{2}\mu_m} \frac{1}{a_r - \frac{\gamma}{2}\mu_m} \left(\frac{2\mu_m - \gamma(a_r - c_r)}{4 - \gamma^2} \right)^2 dc_r \\
 &= \frac{4 - \gamma^2}{12} \frac{3\mu_m^2 + \tau^2\gamma^2 q_1^2 - 3\tau\gamma\mu_m q_1}{2a_r - \gamma\mu_m} \tau q_1.
 \end{aligned}$$

The profit-maximizing value of q_1 is found as:

$$\begin{aligned}
 q_1^*(\tau; a_r, \mu_m, \gamma) &= \frac{\sqrt{(2-\tau\gamma)^2(2+\tau\gamma)^2 a_r^2 - 4\gamma(\tau^2 + \tau\gamma + 1)(2-\tau\gamma)^2 a_r \mu_m + 2\gamma^2(4\tau^2 + 2\tau^4 - 2\tau^2\gamma^2 + \tau^3\gamma^3 - 4\tau^3\gamma + 2)\mu_m^2}}{\tau^3\gamma^2(4-\gamma^2)} \\
 &\quad - \frac{((4-\tau^2\gamma^2)a_r - \gamma(2\tau^2 - \tau^2\gamma^2 + 2)\mu_m)}{\tau^3\gamma^2(4-\gamma^2)}.
 \end{aligned}$$

It is easily shown that $q_1^*(\tau; a_r, \mu_m, \gamma) < q_1^m = \mu_m/2$. As explained in the text, we perform two comparative statics exercises.

1. *Effects of horizontal differentiation.* We set $a_r = a_m = 1$, $c_m = 0$ but let γ vary.
2. *Effects of vertical differentiation.* We set $a_m = 1$, $c_m = 0$, and $\gamma = 1$ but we let a_r be larger than $a_m = 1$.

Table 2 reports the results of some numerical simulations. These results suggest that the manufacturer reduces further its first-period output to limit entry as products become more substitutable (γ increases) or as the recycled product becomes more valuable for consumers (a_r increases).

Resource Scarcity

If we redo the analysis of Sect. 2, assuming $c_m < \frac{1}{2}$ and c (the recycler's constant marginal cost) uniformly distributed on $[0, \frac{1}{2}(1 + c_m)]$, we find the following profits, respectively in the unconstrained and constrained cases:

$$\begin{aligned}
 \pi_2^u &= \frac{1}{9} (1 - 2c_m + c)^2 - c_m \theta q_1, \quad \pi_r^u = \frac{1}{9} (1 - 2c + c_m)^2, \\
 \pi_2^c &= \frac{1}{4} (1 - c_m - \tau q_1)^2 - c_m \theta q_1, \quad \pi_r^c = \frac{1}{2} \tau q_1 (1 - 2c + c_m - \tau q_1).
 \end{aligned}$$

The threshold in Lemma 1 becomes: $\tilde{c} = \frac{1}{2}(1 + c_m - 3\tau q_1)$. This threshold is negative when the manufacturer produces its first-period unconstrained quantity, $q_1^m = (1 - c_m(1 + \theta))/2$ if $\tau > \frac{2(1+c_m)}{3(1-c_m(1+\theta))}$. If the manufacturer sets $q_1 < (1 + c_m)/(3\tau)$, the unconstrained equilibrium occurs for $c > \tilde{c}$ and the constrained equilibrium otherwise. The

Table 2 Effects of product differentiation on the manufacturer's limit strategy

Horizontal differentiation			Vertical differentiation		
γ	$\bar{\tau}$	$q_1^m - q_1^*(\bar{\tau})$	a_r	$\bar{\tau}$	$q_1^m - q_1^*(\bar{\tau})$
1	0.326	0.038	1	0.326	0.038
0.9	0.338	0.036	1.1	0.387	0.045
0.8	0.351	0.033	1.2	0.445	0.051

first-period maximization programme is then given by $\max_{q_1} (1 - q_1)q_1 - c_m q_1 + \hat{\pi}_2^c(q_1) + \hat{\pi}_2^u(q_1)$, where:

$$\begin{aligned}\hat{\pi}_2^c(q_1) &= \int_0^{\frac{1}{2}(1+c_m-3\tau q_1)} \left(\frac{1}{4}(1-c_m-\tau q_1)^2 - c_m \theta q_1 \right) \frac{2}{1+c_m} dc \\ &= (1+c_m-3\tau q_1) \frac{\tau^2 q_1^2 - 2(\tau + (2\theta - \tau)c_m)q_1 + (1-c_m)^2}{4(1+c_m)}, \\ \hat{\pi}_2^u(q_1) &= \int_{\frac{1}{2}(1+c_m-3\tau q_1)}^{\frac{1}{2}(1+c_m)} \left(\frac{1}{9}(1-2c_m+c)^2 - c_m \theta q_1 \right) \frac{2}{1+c_m} dc \\ &= \tau q_1 \frac{\tau^2 q_1^2 - 3(\tau + (4\theta - \tau)c_m)q_1 + 3(1-c_m)^2}{4(1+c_m)}.\end{aligned}$$

The profit-maximizing quantity is found as:

$$q_1^*(\tau, \theta) = \frac{\sqrt{(1-2c_m)^2 \tau^4 + 2(1+c_m)(3(1-(1+\theta)c_m)\tau^3 - 2(2-c_m)\tau^2 + 2(1+c_m)) - (2+\tau^2)c_m - 2(1-\tau^2)}}{3\tau^3}.$$

It can be shown that $q_1^*(\theta, \tau) < q_1^m(\theta)$, meaning that *the manufacturer reduces its first-period quantity below the monopoly level*. Moreover, in Fig. 5, we plot $q_1^*(\tau, \theta)$ against τ for different values of θ (and setting $c_m = 1/4$). We observe that $q_1^*(\tau, \theta)$ remains a U-shaped function of τ for all values of θ . In sum, *resource scarcity does not challenge our main results*. In fact, resource scarcity gives the manufacturer another motive to decrease its first-period quantity: the manufacturer wants to reduce the recycler's entry potential and also its second-period cost. We have indeed that $q_1^*(\theta, \tau) < q_1^m(\theta) < q_1^m(0)$.

Several Manufacturers and Recyclers

Period 2. Suppose that $n \geq 1$ recyclers have entered the market. The maximization problem of recycler j is $\max_{r_j} (1 - c - r_j - r_{-j} - Q_2)r_j$ subject to $r_j + r_{-j} \leq \tau Q_1$, where r_{-j} denotes the total quantity produced by the other recyclers. We derive recycler j 's reaction function as follows. From the first-order condition, we find the quantity that recycler j would choose if it were unconstrained: $r_j = \frac{1}{2}(1 - c - r_{-j} - Q_2)$. This quantity is valid as long as the constraint is satisfied, i.e.,

$$\frac{1}{2}(1 - c - r_{-j} - Q_2) + r_{-j} \leq \tau Q_1 \Leftrightarrow r_{-j} - Q_2 \leq 2\tau Q_1 - (1 - c).$$

In sum, we have

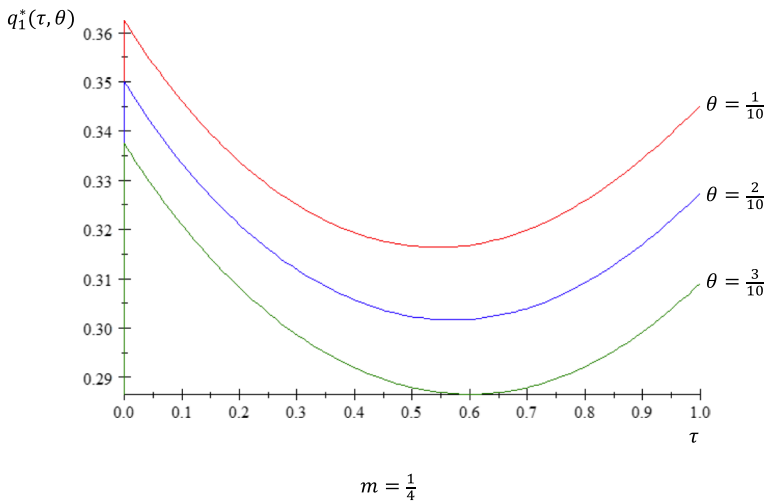


Fig. 5 Manufacturer's first-period quantity ($c_m = 1/4$)

$$r_j(r_{-j}, Q_2) = \begin{cases} \frac{1}{2}(a - c - r_{-j} - Q_2) & \text{if } r_{-j} - Q_2 \leq 2\tau Q_1 - (a - c) \\ \tau Q_1 - r_{-j} & \text{otherwise.} \end{cases}$$

Define:

$$Q_1^{\text{lim}} \equiv \frac{1}{\tau} \frac{n(1 - (m + 1)c)}{m + n + 1}.$$

We now show that *there cannot be an equilibrium where some but not all recyclers are constrained*. Suppose, by contradiction, that we have an equilibrium with a strict subset of recyclers being in the constrained part of their reaction function. Suppose that recyclers 1 to k are in the unconstrained part, while recyclers k to n are in their constrained part (with $1 < k < n$). Define

$$R_u \equiv \sum_{s=1}^k r_s \text{ and } R_c \equiv \sum_{t=k+1}^n r_t.$$

We can sum up the first-order conditions of the unconstrained recyclers:

$$\begin{aligned} \sum_{s=1}^k r_s &= \sum_{s=1}^k \frac{1}{2}(1 - c - r_{-s} - Q_2) \Leftrightarrow R_u = \frac{1}{2}k(1 - c - Q_2 - R_c) - \frac{1}{2}(k - 1)R_u \\ &\Leftrightarrow (k + 1)R_u + kR_c = k(1 - c - Q_2). \end{aligned}$$

Proceeding in the same way for the constrained recyclers, we have:

$$\begin{aligned} \sum_{t=k+1}^n r_t &= \sum_{t=k+1}^n (\tau Q_1 - r_{-t}) \Leftrightarrow R_c = (n - k)(\tau Q_1 - R_u) - (n - k - 1)R_c \\ &\Leftrightarrow R_c + R_u = \tau Q_1 \end{aligned}$$

Solving the system of the last two equations gives:

$$\begin{aligned} R_u &= k(1 - c - Q_2 - \tau Q_1), \\ R_c &= (k + 1)\tau Q_1 - k(1 - c - Q_2). \end{aligned}$$

We need to check if the condition for being in the unconstrained part of the reaction function is satisfied for all recyclers $s \in \{1, k\}$. If it is, then we have:

$$\begin{aligned} \sum_{s=1}^k (r_{-s} - Q_2) &\leq k(2\tau Q_1 - (1 - c)) \Leftrightarrow k\tau Q_1 - R_u \leq k(2\tau Q_1 - (1 - c)) \\ &\Leftrightarrow \tau Q_1 - (1 - c - Q_2 - \tau Q_1) \leq 2\tau Q_1 - (1 - c) \\ &\Leftrightarrow 2\tau Q_1 - (1 - c) - Q_2 \leq 2\tau Q_1 - (1 - c) \Leftrightarrow Q_2 \leq 0, \end{aligned}$$

a contradiction.

It follows that the only two equilibria are such that either none or all recyclers are constrained. Take first the case such that *no recycler is constrained*. Summing up the reaction functions of the n recyclers, we have $R_u(Q_2) = n(1 - c - Q_2)/(n + 1)$. As for manufacturer i , its problem is $\max_{q_{i2}} (a - q_{i2} - q_{-i2} - R_u)q_{i2}$, where q_{-i2} is the sum of the quantities produced by the other manufacturers. The first-order condition yields $q_{i2}(q_{-i2}, R_u) = (1 - q_{-i2} - R_u)/2$. Summing up the m previous expressions, we have

$$Q_2 = \frac{1}{2}(ma - (m - 1)Q_2 - mR_u) \Leftrightarrow Q_2(R_u) = \frac{m}{m+1}(1 - R_u).$$

At the Nash equilibrium, we have $Q_2^* = Q_2(R_u^*)$ and $R_u^* = R_u(Q_2^*)$; solving and assuming $c < 1/(m + 1)$, we obtain

$$Q_2^* = m \frac{1 + nc}{m + n + 1}, R_u^* = n \frac{1 - (m + 1)c}{m + n + 1}.$$

At the symmetric equilibrium, each manufacturer produces Q_2/m and each recycler produces R_u/n . This equilibrium is valid as long as all recyclers are indeed in the unconstrained part of their reaction function, which supposes

$$\begin{aligned} \sum_{j=1}^n (r_{-j} - Q_2^*) &\leq n(2\tau Q_1 - (1 - c)) \Leftrightarrow (n - 1)R_u^* - nQ_2^* \leq n(2\tau Q_1 - (1 - c)) \\ &\Leftrightarrow Q_1 \geq \frac{1}{\tau} \frac{n}{m + n + 1} (1 - (m + 1)c) \equiv Q_1^{\text{lim}}. \end{aligned}$$

Consider now the case in which *all recyclers are constrained*. Summing up the reaction functions of the n recyclers, we have $R_c = \tau Q_1$. As $Q_2(R_c) = m(1 - R_c)/(m + 1)$, we find that $Q_2^{**} = m(1 - \tau Q_1)/(m + 1)$ and $R_c^{**} = \tau Q_1$. At the symmetric equilibrium, each manufacturer produces Q_2/m and each recycler produces R_c/n . This equilibrium is valid as long as all recyclers are indeed in the constrained part of their reaction function, which supposes that $(n - 1)R_c^{**} - nQ_2^{**} > n(2\tau Q_1 - (1 - c))$. A few lines of computations establish that the latter condition is equivalent to $Q_1 < Q_1^{\text{lim}}$.

We can now compute the equilibrium profits in both cases. In the unconstrained case, we have

$$\begin{aligned}
 \pi_2^u &= (1 - Q_2^* - R_u^*) \frac{1}{m} Q_2^* \\
 &= \left(1 - m \frac{1 + nc}{m + n + 1} - n \frac{1 - (m + 1)c}{m + n + 1} \right) \frac{1}{m} m \frac{1 + nc}{m + n + 1} \\
 &= \frac{(1 + nc)^2}{(m + n + 1)^2}, \\
 \pi_r^u &= (1 - c - Q_2^* - R_u^*) \frac{1}{n} R_u^* \\
 &= \left(1 - c - m \frac{1 + nc}{m + n + 1} - n \frac{1 - (m + 1)c}{m + n + 1} \right) \frac{1 - (m + 1)c}{m + n + 1} \\
 &= \frac{(1 - (m + 1)c)^2}{(m + n + 1)^2}.
 \end{aligned}$$

In the constrained case, we have

$$\begin{aligned}
 \pi_2^c &= (1 - Q_2^{**} - R_u^{**}) \frac{1}{m} Q_2^{**} \\
 &= \left(1 - \frac{m(1 - \tau Q_1)}{m + 1} - \tau Q_1 \right) \frac{1 - \tau Q_1}{m + 1} \\
 &= \frac{(1 - \tau Q_1)^2}{(m + 1)^2}, \\
 \pi_r^c &= (1 - Q_2^{**} - R_u^{**}) \frac{1}{n} R_u^{**} \\
 &= \left(1 - c - \frac{m(1 - \tau Q_1)}{m + 1} - \tau Q_1 \right) \frac{1}{n} \tau Q_1 \\
 &= \frac{1 - (m + 1)c - \tau Q_1}{n(m + 1)} \tau Q_1.
 \end{aligned}$$

Period 1. Consider the limit strategy in period 1. If $Q_1 < Q_1^{\lim}$, a manufacturer's profit in period 2 is π_2^c if $c < \tilde{c}(m, n)$, and π_2^u if $c > \tilde{c}$. Letting $q_{-i1} = Q_1 - q_{i1}$, we can write manufacturer i 's expected profit function as

$$\Pi^e(Q_1) = \pi_1(Q_1) + \hat{\pi}_2^c(Q_1) + \hat{\pi}_2^u(Q_1),$$

where $\pi_1(Q_1) = (1 - q_{i1} - q_{-i1})q_{i1}$ and, given the uniform distribution of c over the interval $[0, 1/(m + 1)]$,

$$\begin{aligned}
 \hat{\pi}_2^c(Q_1) &= \int_0^{\frac{n - \tau(m + n + 1)Q_1}{n(m + 1)}} \frac{(1 - \tau Q_1)^2}{m + 1} dc = \frac{1}{n(m + 1)^2} (1 - \tau Q_1)^2 (n - \tau(m + n + 1)Q_1), \\
 \hat{\pi}_2^u(Q_1) &= \int_{\frac{n - \tau(m + n + 1)Q_1}{n(m + 1)}}^{\frac{1}{m + 1}} \frac{(m + 1)(1 + nc)^2}{(m + n + 1)^2} dc = \frac{m + n + 1}{3n(m + 1)^2} \tau Q_1 (\tau^2 Q_1^2 - 3\tau Q_1 + 3).
 \end{aligned}$$

The first-order condition for profit-maximization evaluated at $q_{i1} = q_1$ for all i can be written as

$$-2m^2\tau^3(m+n+1)q_1^2 + (2m(m+2n+1)\tau^2 - n(m+1)^3)q_1 + n((m+1)^2 - 2\tau) = 0.$$

Solving for q_1 , we find

$$q_1^*(\tau, m, n) = \frac{(m+1)\sqrt{4m^2\tau^4 + 8m^2n(m+n+1)\tau^3 - 4mn(m+1)(m+2n+1)\tau^2 + n^2(m+1)^4}}{4m^2(m+n+1)\tau^3} - \frac{n(m+1)^3 - 2m(m+2n+1)\tau^2}{4m^2(m+n+1)\tau^3},$$

and we check that the total quantity $mq_1^*(\tau, m, n)$ is inferior to $n/(\tau(m+n+1))$ if and only if $\tau < \tilde{\tau}(m, n)$.

Own Scrap Use

For the sake of comparability, we continue to assume that the manufacturer does not know the exact realization of c when it chooses q_1 in period 1 but expects c to be uniformly distributed over $[0, 1/2]$.

In period 2, the manufacturer chooses q_2 to maximize $(1 - \alpha c - q_2 - r)q_2$ and the recycler chooses r to maximize $(1 - c - r - q_2)r$. Using the first-order conditions for profit-maximization, we derive the quantities and profits at the unconstrained equilibrium as:

$$q_2^u = \frac{1}{3}(1 + c - 2c\alpha) \text{ and } r^u = \frac{1}{3}(1 - 2c + c\alpha),$$

$$\pi_2^u = \frac{1}{9}(1 + c - 2c\alpha)^2 \text{ and } \pi_r^u = \frac{1}{9}(1 - 2c + c\alpha)^2.$$

To guarantee positive equilibrium quantities, we impose $c \leq 1/(2 - \alpha)$. This equilibrium obtains as long as $r^u + \alpha q_2^u \leq \tau q_1$, which is equivalent to:

$$c \geq \frac{(1 + \alpha) - 3\tau q_1}{2(1 - \alpha + \alpha^2)} = \tilde{c}(\alpha),$$

with $\tilde{c}(\alpha) \geq 0$ if and only if $q_1 \leq (1 + \alpha)/3\tau$.

If $c < \tilde{c}(\alpha)$, then the constrained equilibrium prevails, with $r = \tau q_1 - \alpha q_2^c$. The value of q_2^c is found by inserting $r = \tau q_1 - \alpha q_2^c$ into the manufacturer's first-order condition:

$$\left. \frac{\partial \pi_2}{\partial q_2} \right|_{r=\tau q_1 - \alpha q_2^c} = 0 \Leftrightarrow q_2^c = \frac{1}{2 - \alpha}(1 - \alpha c - \tau q_1).$$

It follows that:

$$r^c = \frac{1}{2 - \alpha}(2\tau q_1 + \alpha^2 c - \alpha), \pi_2^c = \frac{(1 - \tau q_1 - \alpha c)^2}{(2 - \alpha)^2},$$

$$\text{and } \pi_r^c = \frac{(2\tau q_1 + \alpha^2 c - \alpha)(1 - \tau q_1 - (2 - 2\alpha + \alpha^2)c)}{(2 - \alpha)^2}.$$

When the manufacturer chooses $q_1 < (1 + \alpha)/(3\tau)$, the equilibrium prevailing in period 2 depends on the cost drawn by the recycler: the manufacturer obtains the profit π_2^c if $c < \tilde{c}$ and π_2^u if $c > \tilde{c}$. Consequently, the manufacturer's expected profit function can be written as

$$\pi^e = \pi_1(q_1) + \hat{\pi}_2^c(q_1) + \hat{\pi}_2^u(q_1),$$

where $\pi_1(q_1) = q_1(1 - q_1)$ and, given the uniform distribution of c over the interval $[0, 1/(2 - \alpha)]$,

$$\begin{aligned} \hat{\pi}_2^c(q_1) &= \int_0^{\tilde{c}} 2\pi_2^c(q_1)dc = \int_0^{\frac{(1+\alpha)-3\tau q_1}{2(1-\alpha+\alpha^2)}} \frac{2(1-\alpha c - \tau q_1)^2}{(2-\alpha)^2} dc \\ &= \frac{(1+\alpha-3\tau q_1)(3\tau^2(4-14\alpha+21\alpha^2-14\alpha^3+4\alpha^4)q_1^2)}{12(2-\alpha)^2(1-\alpha+\alpha^2)^3} \\ &\quad - \frac{(1+\alpha-3\tau q_1)(6\tau(2-4\alpha+3\alpha^2)(2-2\alpha+\alpha^2)q_1 + (12-30\alpha+37\alpha^2-22\alpha^3+7\alpha^4))}{12(2-\alpha)^2(1-\alpha+\alpha^2)^3}, \\ \hat{\pi}_2^u(q_1) &= \int_{\tilde{c}}^{\frac{1}{2-\alpha}} 2\pi_2^u dc = \int_{\frac{(1+\alpha)-3\tau q_1}{2(1-\alpha+\alpha^2)}}^{\frac{1}{2-\alpha}} \frac{2}{9}(1+c-2c\alpha)^2 dc \\ &= \frac{(\tau(2-\alpha)q_1 - \alpha(1-\alpha))q_1((2-\alpha)^2(2\alpha-1)^2\tau^2 q_1 + 2\tau(1-\alpha)(2-\alpha)(2\alpha-1)(3-2\alpha+\alpha^2))}{4(2-\alpha)^3(1-\alpha+\alpha^2)^3} \\ &\quad + \frac{(\tau(2-\alpha)q_1 - \alpha(1-\alpha))(12-18\alpha+19\alpha^2-10\alpha^3+4\alpha^4)(1-\alpha)^2}{4(2-\alpha)^3(1-\alpha+\alpha^2)^3}. \end{aligned}$$

In period 1, the manufacturer chooses q_1 to maximize π^e . From the first-order condition, we find:

$$q_1^*(\tau, \alpha) = \frac{(2-\alpha)(1-\alpha+\alpha^2)\sqrt{2K} - (9\alpha-3\alpha^2-2\alpha^3-8)\tau^2 + 2(2-\alpha)^2(1-\alpha+\alpha^2)^2}{3(4-7\alpha+4\alpha^2)\tau^3}$$

with $K \equiv 2\tau^4 + 3(4 - 7\alpha + 4\alpha^2)\tau^3 - 2(8 - 9\alpha + 3\alpha^2 + 2\alpha^3)\tau^2 + 2(2 - \alpha)^2(1 - \alpha + \alpha^2)^2$.

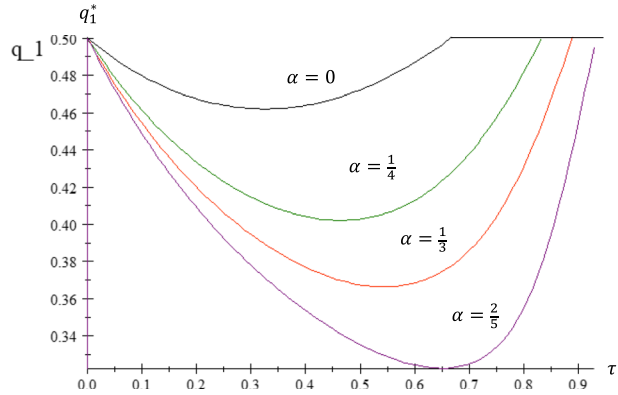
A sufficient condition to have $K > 0$ for all $\tau \in [0, 1]$ (and so, for the second-order condition to be met) is $\alpha < 0.441$, which we assume from now on.

In Fig. 6, we depict the manufacturer's profit-maximizing quantity in period 1, $q_1^*(\tau, \alpha)$, against τ for different values of α .

Independent Scrap Collector

Let us derive the subgame-perfect equilibrium of this game. In period 2, the manufacturer chooses q_2 to maximize $\pi_2 = (1 - q_2 - r)q_2$, while the recycler chooses r to maximize $\pi_r = (1 - q_2 - r)r - c(r/\mu)$. Their respective reaction functions are $q_2(r) = (1 - r)/2$ and $r(q_2) = (\mu - c - \mu q_2)/(2\mu)$. The Cournot-Nash equilibrium in period 2 is then found as $q_2 = (\mu + c)/(3\mu)$ and $r = (\mu - 2c)/(3\mu)$. In period 1b, the scrap collector faces the demand $s = r/\mu = (\mu - 2c)/(3\mu^2)$ or, equivalently, the inverse demand $c = \mu(1 - 3\mu s)/2$. Given that $s = \phi q_1$, we can write the scrap collector's maximization problem as:

Fig. 6 First-period production for different rates of scrap re-use



$$\max_{\phi} \frac{\mu}{2} (1 - 3\mu\phi q_1) \phi q_1 - \frac{\sigma}{2} \phi^2 q_1 \text{ such that } \gamma \leq 1.$$

Solving for the first-order condition (and checking that the second-order condition is met), we find:

$$\phi^* = \frac{\mu}{6\mu^2 q_1 + 2\sigma}.$$

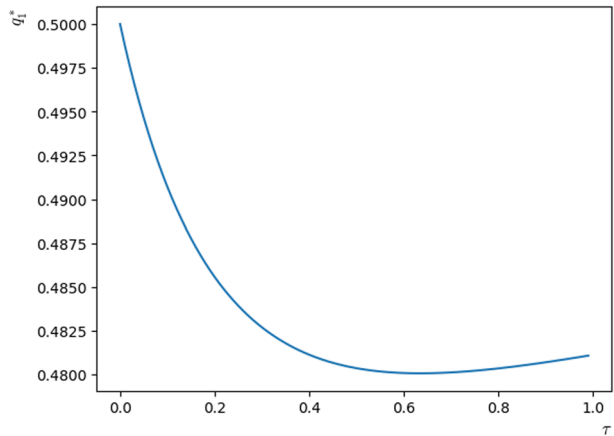
A sufficient condition for $\phi^* \leq 1$ is $\sigma \geq \mu/2$. Introducing ϕ^* into the price of scrap (c) and the quantities produced at the equilibrium of period 2 (q_2 and r), we can express the equilibrium profit of the manufacturer in period 2 as:

$$\pi_2(q_1) = \frac{(5\tau q_1 + 2)^2}{16(3\tau q_1 + 1)^2},$$

where $\tau \equiv \mu^2/\sigma$ measures the global efficiency of the collection/recycling process.

It is easily seen that $\pi_2(q_1)$ is a decreasing function of q_1 , which means that the manufacturer can improve its second-period profit by decreasing its first-period output below the myopic optimum. In other words, the manufacturer is still able to limit the recycler's entry even if the quantity of available scrap is now chosen by an intermediary. The remaining question is how the manufacturer's limit entry strategy is affected by changes in τ . To answer this question, we solve the manufacturer's problem in period 1. The manufacturer chooses q_1 to maximize $\Pi = q_1(1 - q_1) + \pi_2(q_1)$. In Fig. 7, we report the optimal quantity for values of τ ranging from 0 to 1. We observe that the optimal quantity first decreases but eventually increases with τ . This non-monotonicity is similar to the one we find in the baseline model.

Fig. 7 Manufacturer's profit-maximizing quantity in period 1



Acknowledgements The authors gratefully acknowledge financial support from the Belgian Science Policy, Research Project BR/143/A5/IECOMAT. They thank Thierry Bréchet, Johan Eyckmans, Johannes Johnen, Sandra Rousseau, Bernard Sinclair-Desagné, and four anonymous reviewers for useful comments on earlier drafts.

Funding When writing this paper, both authors were employed by Université catholique de Louvain, Belgium; they also both received financial support from Belgian Science Policy, Research project BR/143/A5/IECOMAT.

Declarations

Conflict of interest Both authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Amir R, Lambson V (2000) On the effects of entry in Cournot markets. *Rev Econ Stud* 67(2):235–254
- Atasu A, Sarvary M, Van Wassenhove LN (2008) Remanufacturing as a marketing strategy. *Manag Sci* 54(10):1731–1746
- Ba BS (2022) Recyclage d'une ressource primaire et pouvoir de marché?: le cas Alcoa. *Revue économique* 73(2):303–324
- Ba BS, Mahenc P (2019) Is recycling a threat or an opportunity for the extractor of an exhaustible resource? *Environ Resour Econ* 73(4):1109–1134
- Ba BS, Motel PC, Schwartz S (2020) Challenging pollution and the balance problem from rare earth extraction: how recycling and environmental taxation matter. *Environ Dev Econ* 25(6):634–656
- Ba BS, Soubeyran R (2023) Hotelling and recycling. *Resour Energy Econ* 72(C)
- Bain JS (1956) Barriers to new competition: their character and consequences. Harvard University Press, Cambridge

- Beatty TKM, Berck P, Shimshack JP (2007) Curbside recycling in the presence of alternatives. *Econ Inq* 45(4):739–755
- Bernard S (2011) Remanufacturing. *J Environ Econ Manag* 62:337–351
- Bohm RA, Folz DH, Kinnaman TC, Podolsky MJ (2010) The costs of municipal waste and recycling programs. *Resour Conserv Recycl* 54(11):864–871
- Callan SJ, Thomas JM (2001) Economies of scale and scope: a cost analysis of municipal solid waste services. *Land Econ* 77(4):548–560
- Dastidar KG (2000) Is a unique Cournot equilibrium locally stable? *Games Econom Behav* 32(2):206–218
- de Beir J, Ha-Huy T, Sourisseau S (2023) Recycling vs mining: competition for market shares, collusion for market power. *Revue économique* 74(1):81–113
- Dijkgraaf E, Gradus RHJM (2014) The effectiveness of Dutch municipal recycling policies. *SSRN Electron J*
- Eichner T (2005) Imperfect competition in the recycling industry. *Metroeconomica* 56(1):1–24
- Fabre A, Fodha M, Ricci F (2020) Mineral resources for renewable energy: optimal timing of energy production. *Resour Energy Econ* 59:101131
- Ferguson ME, Toktay LB (2009) The effect of competition on recovery strategies. *Prod Oper Manag* 15(3):351–368
- Fullerton D, Kinnaman TC (1995) Garbage, recycling, and illicit burning or dumping. *J Environ Econ Manag* 29:78–91
- Gaskins DW (1974) Alcoa revisited: the welfare implications of a secondhand market. *J Econ Theory* 7(3):254–271
- Gaudet G, Van Long N (2003) Recycling redux: a Nash–Cournot approach. *Jpn Econ Rev* 54(4):409–419
- Gilbert R, Vives X (1986) Entry deterrence and the free rider problem. *Rev Econ Stud* 53(1):71–83
- Grant D (1999) Recycling and market power: a more general model and re-evaluation of the evidence. *Int J Ind Org* 22
- Hamilton SF, Sproul TW, Sunding D, Zilberman D (2013) Environmental policy with collective waste disposal. *J Environ Econ Manag* 66(2):337–346
- Hoel M (1984) Extraction of a resource with a substitute for some of its uses. *Can J Econ* 17(3):593
- Hollander A, Lasserre P (1988) Monopoly and the preemption of competitive recycling. *Int J Ind Organ* 6(4):489–497
- Honma S, Chang M-C (2010) A model for recycling target policy under imperfect competition with and without cooperation between firms. Working Paper 45, Kyushu Sangyo University, Faculty of Economics
- International Aluminium Institute (2009) Global aluminium recycling: a cornerstone of sustainable development. Technical report
- Kinnaman T (2013) Waste disposal and recycling. In: *Encyclopedia of energy, natural resource, and environmental economics*, pp 109–113. Elsevier
- Kinnaman TC (2006) Policy watch: examining the justification for residential recycling. *J Econ Perspect* 20(4):219–232
- Kinnaman TC (2010) The costs of municipal curbside recycling and waste collection. *Resour Conserv Recycl* 54(11):864–871
- Kinnaman TC, Fullerton D (2000) Garbage and recycling with endogenous local policy. *J Urban Econ* 48(3):419–442
- Kinnaman TC, Shinkuma T, Yamamoto M (2014) The socially optimal recycling rate: evidence from Japan. *J Environ Econ Manag* 68(1):54–70
- Kolstad CD, Mathiesen L (1987) Necessary and sufficient conditions for uniqueness of a Cournot equilibrium. *Rev Econ Stud* 54(4):681
- Mitra S, Webster S (2008) Competition in remanufacturing and the effects of government subsidies. *Int J Prod Econ* 111(2):287–298
- Novshek W (1985) On the existence of Cournot equilibrium. *Rev Econ Stud* 52(1):85–98
- Örsdemir A, Kemahlioğlu-Ziya E, Parlaktürk AK (2014) Competitive quality choice and remanufacturing. *Prod Oper Manag* 23(1):48–64
- Stern T, Robinson EJ (2018) Selection and design of environmental policy instruments. In: Dasgupta P, Pattanayak SK, Smith VK (Eds.) *Handbook of Environmental Economics*, Volume 4, Chapter 8, pp. 231–284. Amsterdam: Elsevier
- Suslow VY (1986) Estimating monopoly behavior with competitive recycling: an application to Alcoa. *Rand J Econ* 17(3):389
- Swan PL (1977) Product durability under monopoly and competition: comment. *Econometrica* 45(1):229
- Viscusi WK, Huber J, Bell J (2012) Alternative policies to increase recycling of plastic water bottles in the United States. *Rev Environ Econ Policy* 6(2):190–211
- Vives X (2001) Oligopoly pricing: old ideas and new tools. MIT Press Books, The MIT Press
- Walter A (1951) The aluminum case: legal victory—economic defeat. *Am Econ Rev* 41(5):915–922

Webster S, Mitra S (2007) Competitive strategy in remanufacturing and the impact of take-back laws. *J Oper Manag* 25(6):1123–1140

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.