Circular Business Models: Product Design and Consumer Participation

Stefan Buehler, Rachel Chen, Daniel Halbheer

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Abstract

This paper develops an analytical framework to study how firms should design a product by choosing its recyclability and price when consumers adopt a life-cycle approach and decide whether to recycle an end-of-life product. We show that, under a linear business model, the firm offers a non-recyclable product even if consumers care about recyclability. Under a circular business model, the firm generates revenue from both sales and recycling, and determines recyclability by balancing the marginal changes in the consumers' expected end-of-life utility and the unit production cost net of the expected value of the recovered resources. We identify conditions under which the firm offers a fully recyclable product and all consumers return the product for recycling. In addition, we show that stronger consumer concerns about recyclability and a higher market value of the recovered resources increase recyclability, but have an ambiguous impact on price, demand, profit, and the waste footprint of the firm. Further, we characterize conditions under which transitioning from a linear to a circular business model is profitable and socially desirable. Finally, we examine how the firm can boost circularity by leveraging deposit-refund systems, product buyback, or retaining product ownership.

Keywords: Circular business model, waste footprint, resource footprint, recycling, reverse supply chain, pricing.

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1 Introduction

Business leaders, consumers, and governments alike are increasingly becoming aware of the enormous resource and waste footprints resulting from the "take-make-dispose" approach of the *linear economy*, which extracts resources to make products that are discarded as waste when they reach end-of-life. In 2020, supply chains sourced over 100 billion tons of materials, while only 8.6% were cycled back into the global economy.[1] The resulting circularity gap of over 90% is a key driver of the world's most pressing environmental problems, including global warming, biodiversity loss, and pollution. To tackle these problems, firms must urgently develop innovations across product design, recovery of end-of-life products, and recycling technologies that enable the transition from a linear to a *circular economy* to reduce the environmental footprint of doing business.[2]

There is evidence that consumers increasingly care about environmental sustainability. A survey among global consumers found that more than 51% of the respondents say that sustainability is more important to them today than it was a year ago (IBM Institute for Business Value 2022). More broadly, research by The Economist Intelligence Unit (2021) on eco-awakening shows that an increasing number of people are concerned about the natural environment. To cater to consumers who care about sustainability and recycling, many firms are beginning to embrace circularity. For example, Nespresso offers free home pickup services to recover and recycle coffee capsules.[3] Similarly, HP uses material from returned cartridges to produce new cartridges (HP 2022), and Apple's iPhone recycling robot Daisy can disassemble up to 1.2 million phones each year, supporting the recovery of valuable resources via the Apple Trade In program (Apple 2022). Electric car makers are also heavily investing in circular initiatives to recover rare materials and put them into new batteries (The Economist 2022).

[1]The Circularity Gap Report (Circle Economy 2022).

[2]The foundations of the circular economy are laid out in the report "Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition" (Ellen MacArthur Foundation 2013) and Stahel (2016, 2019). The circular movement has gained momentum by highlighting opportunities for green business (Accenture 2017; McKinsey 2017).

[3]For details on the 'Recycling at Home' option, see the report "The Positive Cup" (Nespresso 2021).

This paper develops an analytical framework to study the mechanics of circular business models that attempt to close the loop and thereby reduce a firm's resource and waste footprint.[4] To this end, we formalize three core pillars of circularity, illustrated in Figure 1: *Reduce*—design out waste by optimizing products for recycling; *Recover*—build a reverse supply chain to collect end-of-life products; and *Recycle*—convert recovered products into raw materials. The firm chooses the product design—recyclability and price—and decides whether or not to build a reverse supply chain to recover end-of-life products. Specifically, recyclability captures the extent to which a recovered end-of-life product can be recycled by the firm. At the heart of our analysis is the interplay between product design decisions by the firm and disposal decisions by consumers who care about recyclability. Going circular creates an opportunity for the firm to tap into a new source of revenue from recovering and recycling the resources embedded in end-of-life products, which reduces the unit production cost. In addition, going circular may allow the firm to benefit from the consumers' higher willingness to pay for products with higher recyclability. Our analysis highlights that full circularity is hard to reach as it requires that the product is fully recyclable by design and all consumers choose to return the product for recycling when it reaches end-of-life. Otherwise, there is a waste footprint that may result in a market externality caused by buyers who do not fully account for the environmental impact of their purchase decision.

We derive the following key results. First, under a linear business model without a reverse supply chain, the firm produces a non-recyclable product and all the resources embedded in end-of-life products are going to waste. Intuitively, recyclability is costly but has no impact on demand because consumers cannot return the product for recycling. Second, under a circular business model with a reverse supply chain, recyclability is determined by balancing the marginal changes in the expected end-of-life utility perceived by consumers and the "net unit cost," where the latter is defined as the unit production cost net of the expected value of the recovered resources. However, if the marginal increase in

[4]See Guide and Van Wassenhove (2009) on the fundamentals of closed-loop supply chains. For a recent practitioner article on circular business models, see Atasu, Dumas, and Van Wassenhove (2021).

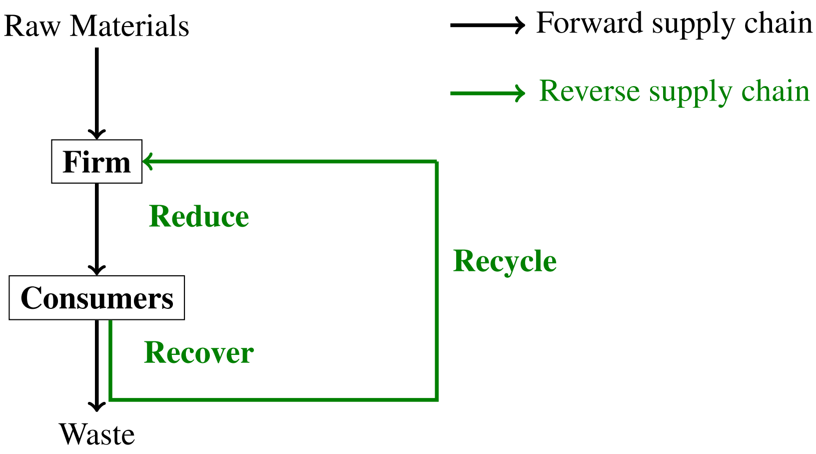

Figure 1: From linearity to circularity.

end-of-life utility outweighs the change in net unit cost, the firm offers a fully recyclable product, and a fully circular model arises if all consumers choose to recycle the product. If consumers do not care about recyclability, then the circular product design coincides with the linear product design. The comparative statics results show that stronger concerns about recyclability or a higher value of the resources embedded in end-of-life products (e.g., because of increasing scarcity) increase recyclability, but have an ambiguous impact on price, demand, profit, and the overall waste footprint when the firm offers a partially recyclable product—an in-between non-recyclable and fully recyclable product. Third, we identify the conditions under which the transition from a linear to a circular business model is profitable and socially desirable. Intuitively, the firm has an incentive to strategically distort recyclability to exploit its pricing power under circularity, which may result in an economically inefficient choice of business model.

To leverage our key results, we study how firms can boost the performance of circular business models. We show that coupling a circular business model with a deposit-refund system, where the firm collects a deposit at the time of purchase that is refunded when the product is recycled, cannot decrease profit but does not necessarily increase recyclability. In addition, we find that a buyback strategy, where the firm repurchases end-of-life products from consumers to induce recovery and recycling, yields an outcome equivalent to a deposit-refund system. Finally, we show that retaining product ownership, which allows the firm to eliminate "leakage" on the part of consumers, increases recyclability.[5] Again, profitability does not suffer as the firm has an additional contractual instrument for product design.

This is the first paper that integrates disposal decisions by consumers who care about recyclability into a model of profit-maximizing product design with respect to recyclability and price, accounting for the impact on the firm's unit cost, demand, and waste footprint. Our analytical framework has three key ingredients. First, it provides a utility foundation for the consumers' decision whether or not to participate in the recycling system. This foundation allows us to focus on a cradle-to-grave perspective where consumers adopt a life-cycle approach. Second, product recovery and recycling allows the firm to tap into a new source of revenue, the size of which depends on recyclability, consumer participation in the recycling network, and the market value of recovered resources. Integrating the reverse supply chain into the analysis also allows us to understand how the value of the resources embedded in end-of-life products affects unit cost and the market outcome. Third, our framework allows us to analyze the interplay between the firm's product design decisions and its waste footprint as well as the waste externality created by buyers in the market.

Our paper contributes to three strands of literature. First, the results add to the literature on green product design in marketing (Bertini et al. 2022; Chen 2001; Sudhir, Shankar, and Jin 2022) by showing how recyclability and price are determined by the interplay of consumers' concerns about recyclability and the value of the resources embedded in end-of-life products. The most closely related paper to ours is Bertini et al. (2022), which studies product carbon footprinting and pricing by firms that face consumers with climate concerns. The novelty of our paper is that consumers care about recyclability and derive an endogenous utility from making a discrete choice between recycling and trashing an end-of-life product, which may either enhance or reduce demand. Considering the

[5]Renting and leasing has gained momentum in business-to-consumer markets, including cars, fashion, furniture, and electronics.

end-of-life utility allows us to extend the analysis of product design to circular business models, thereby adding to classic work on the returns on quality in linear business models (Rust, Moorman, and Dickson 2002; Rust and Zahorik 1993; Rust, Zahorik, and Keiningham 1995). The difference to a standard model where the firm chooses price and (environmental) quality is that consumers make both purchase *and* disposal decisions, which determine not only demand and profit, but also the firm's waste footprint and the environmental externality. By studying the impact of product design on the environmental footprint of the firm, we further add to the sustainability literature in marketing (Chandy et al. 2021; Cronin et al. 2011; Huang and Rust 2011; Luo and Bhattacharya 2006; Papadas, Avlonitis, and Carrigan 2017). Specifically, we show how going circular affects the triple bottom line of profit, people, and planet (Elkington 1999).

Second, we add to the literature on circular production. Savaskan, Bhattacharya, and Van Wassenhove (2004) focus on closed-loop supply chain models and study how to best organize the reverse channel structure. They show that product recovery should be undertaken by the retailer (rather than the manufacturer or a third party). We consider a vertically integrated forward supply chain, but let consumers endogenously decide whether or not to recycle the end-of-life product, which provides a novel foundation for the "reverse channel performance." Recently, Agrawal, Atasu and Ülkü (2021) investigated two prominent circular economy strategies, leasing and modularity, in a durable goods monopoly. They find that adopting one of these strategies does not necessarily make the adoption of the other strategy more profitable, and that adopting both strategies can actually lead to higher environmental impact than leasing or modularity alone. However, they argue that other "circular design strategies" such as durability, repairability, and recyclability should be studied. We focus on the choice of recyclability and show that under a circular business model, a firm may gain from adopting a leasing strategy that eliminates leakage on the part of consumers. Our paper also adds to the literature on sustainable operations (Agrawal, Atasu, and Van Wassenhove 2019; Geng, Sarkis and Bleischwitz 2019; Santibanez Gonzalez, Koh, and Leung 2019; Tang and Zhou 2012) by modeling the return decisions of consumers to efficiently manage goods in the post-production stage. Furthermore, by analyzing the role of financial incentives to stimulate consumer participation in recycling, our paper extends the literature on deposit-refund systems (Fullerton and Wolverton 2000; Walls 2011) and extended producer responsibility (Gui et al. 2016; Huang, Atasu and Toktay 2019). We show how such financial incentives to stimulate consumer participation in recycling affect product design.

Finally, our paper contributes to the emerging literature on the impact of morally or environmentally concerned consumers on market outcomes in economics (Dewatripont and Tirole 2022; Herweg and Schmidt 2022). We show how concerns about recyclability affect the end-of-life utility of a product, and thereby the firm's profit-maximizing product design. Our analysis shows that consumer concerns about the end-of-life properties of a product force the firm to adopt a life-cycle perspective, which may induce a purely profit-maximizing firm to switch from a linear to a circular business model.

The remainder of the paper is organized as follows. Section 2 introduces the analytical framework. Section 3 studies product design in the linear business model, our benchmark case. Section 4 examines the mechanics of circular business models, characterizes product design, and performs comparative statics. Section 5 studies the conditions under which it is profitable or desirable from a welfare perspective to switch from a linear to a circular business model. Section 6 considers managerial strategies to improve the performance of the circular business model, including the implementation of a deposit-refund system, product buyback, and retaining product ownership. Section 7 discusses the implications of the research, highlights its limitations, and offers directions for future work.

2 Analytical framework

2.1 The firm

Consider a firm that designs a product with a fixed lifetime by choosing the recyclability index $r \in [0,1]$ and the price $p \geq 0$. The index of recyclability captures the extent to which the resources embedded in an end-of-life product can be recycled by the firm.

Specifically, the product is non-recyclable if $r = 0$, partially recyclable if $r \in (0,1)$, and fully recyclable if $r = 1$. For example, Nespresso's aluminium capsules and HP's toner cartridges are fully recyclable, and The Coca-Cola Company pledged to make 100% of its packaging recyclable by 2025.[6] Renault estimates that around 85% of a car is recyclable (The Economist 2022), whereas wind turbine blades can't be recycled (Bloomberg 2020). Throughout, we assume that recyclability r is truthfully communicated to consumers by the firm to focus on the mechanics of circular business models and avoid issues of "greenwashing," whereby firms make unsubstantiated environmental claims to affect consumer behavior (Wu, Xang, and Xie 2020).

Improving product recyclability is costly. Specifically, the unit cost of a product with recyclability index r is $c(r)$, where $c'(r) > 0$ and $c''(r) > 0$ for $r \in (0,1]$, with $c(0) \geq 0$ and $c'(0) \geq 0$. Building a reverse supply chain involves a fixed cost $K \geq 0$. Letting $\omega \geq 0$ denote the market price for the resources embedded in one unit of product, the value of a recovered product to the firm is ωr.

2.2 Consumers

Consider a market with a unit mass of consumers who care not only about the intrinsic features and price of the product but also its recyclability—a life-cycle approach. When the product reaches end-of-life, consumers make a discrete choice: return the product for recycling or dispose of it as waste (Viscusi, Huber, and Bell 2011). Specifically, buyers incur the idiosyncratic hassle cost $\kappa \geq 0$ of returning the product for recycling, which is realized when the product reaches end-of-life, and derive a corresponding benefit $b(r;\lambda) \geq 0$ that captures the warm glow of participating in a pro-environmental action (Andreoni 1995), where $\lambda \geq 0$ indicates the strength of concerns about recyclability. Assuming that consumers do not know the hassle cost at the time of making the purchase is natural because of unforeseeable circumstances of returning the product for recycling. The hassle cost κ is distributed across consumers according to the cumulative distribution

[6] For Coca Cola's packaging solutions for a "World Without Waste," see http://bit.ly/3iIUOmC.

function $G(\kappa)$ with associated density $g(\kappa)$ over the interval $[0,+\infty)$, with $G(0)=0$ and $\lim_{\kappa\to\infty} G(\kappa)=1$. Instead, when disposing of the product as waste, consumers receive the disutility $\bar{u}(\lambda)\leq 0$ that captures the cold prickle of participating in an anti-environmental action. To put additional structure on the costs and benefits associated with the end-of-life disposal decision, we impose the following assumption.

Assumption 1 (Disposal decision)**.** *(i) The benefit of recycling $b(r;\lambda)$ satisfies $b_r(r;\lambda)\geq 0$, $b_\lambda(r;\lambda)\geq 0$, and $b_{\lambda r}(r;\lambda)\geq 0$ for all (r,λ), with $b(r;0)=0$; (ii) The disutility $\bar{u}(\lambda)\leq 0$ from discarding the product as waste satisfies $\bar{u}'(\lambda)\leq 0$ for all λ, with $\bar{u}(0)=0$.*

To intuitively understand this assumption, note that part (i) requires that consumers value recyclability, that the benefit increases in concerns about recyclability, and that the marginal benefit from recyclability is non-decreasing in λ. The normalization $b(r;0)=0$ means that consumers who do not care about recyclability derive zero benefit from participating in a pro-environmental action. Part (ii) states that the disutility is higher when consumers have stronger concerns about recyclability and zero if they do not care about recyclability.

When considering the disposal alternatives, consumers return the product for recycling if the utility from recycling $b(r;\lambda)-\kappa$ exceeds the disutility $\bar{u}(\lambda)$ of trashing the product, that is, if the hassle cost of recycling the product κ is smaller than the net benefit of recycling $b(r;\lambda)-\bar{u}(\lambda)$. Because the hassle cost is not known until the product reaches end-of-life, consumers must form an expectation of the utility of an end-of-life product by considering the disposal options across different realizations of κ.[7] The following result holds (for ease of exposition, all proofs are relegated to the Appendix).

Lemma 1 (End-of-life utility)**.** *The expected utility of an end-of-life product is given by*

$$e(r;\lambda)=\int_0^{b(r;\lambda)-\bar{u}(\lambda)} G(\kappa)d\kappa+\bar{u}(\lambda) \tag{1}$$

and satisfies $e(r;\lambda)\gtrless 0$, $e_r(r;\lambda)\geq 0$, $e_\lambda(r;\lambda)\gtrless 0$, and $e_{r\lambda}(r;\lambda)\geq 0$.

[7]Alternatively, one could consider heterogeneity in λ rather than κ, which would imply that consumers do not know their environmental preferences when making purchase decisions.

Lemma 1 highlights that the expected utility of an end-of-life product can be positive or negative depending on the costs and benefits associated with the two disposal options. Specifically, if $\bar{u}(\lambda) = 0$, then the expected end-of-life utility is positive, whereas if $\bar{u}(\lambda) < 0$, then the expected end-of-life utility is positive if $\int_0^{b(r;\lambda)-\bar{u}(\lambda)} G(\kappa)d\kappa \geq -\bar{u}(\lambda)$ and negative otherwise. In addition, marginally increasing recyclability translates into higher end-of-life utility. However, the impact of stronger concerns about recyclability on $e(r;\lambda)$ is ambiguous because it affects both the warm glow and the cold prickle component. Finally, Lemma 1 shows that the marginal increase in expected end-of-life utility from recycling is non-decreasing in λ.

When considering whether to purchase, consumers take the expected end-of-life utility of the product into account. Specifically, a buyer derives utility

$$u(r,p;\lambda) = v - p + e(r;\lambda) - E(r,p;\lambda),$$

where $v \in [0,\infty)$ is the valuation of the intrinsic product features, distributed across consumers according to the cumulative distribution function $F(v)$, with $F(0) = 0$, and $\lim_{v\to\infty} F(v) = 1$, and density $f(v) > 0$ for all v; $e(r;\lambda)$ is the expected end-of-life utility in (1); and $E(r,p;\lambda) \geq 0$ is the externality caused by other buyers that affects all consumers in the market. Normalizing the intrinsic utility of the outside option to zero, a consumer purchases the product if $v \geq p - e(r;\lambda)$ because an individual buyer has no impact on the externality. The demand for the product therefore is

$$D(r,p;\lambda) = 1 - F(p - e(r;\lambda)), \tag{2}$$

where $p - e(r;\lambda)$ can be interpreted as the generalized purchase price, which can be higher or lower than p depending on whether consumers derive a positive or negative end-of-life utility (see Lemma 1). Stated differently, if $e(r;\lambda) > 0$, then the expected end-of-life utility is demand-enhancing, whereas it is demand-reducing whenever $e(r;\lambda) < 0$. In addition, demand has the natural properties that it decreases in price and increases in recyclability as $e_r(r;\lambda) \geq 0$. In turn, stronger concerns about recylability have an ambiguous impact on demand as $e_\lambda(r;\lambda) \gtreqless 0$. Overall, this shows that the impact of concerns about recyclability on demand is not clear-cut. If the disutility $\bar{u}(\lambda)$ is sufficiently negative, then environmental preferences reduce demand—a form of "deconsumption." On the other hand, if the warm-glow component dominates the cold prickle, then concerns about recyclability have a demand-enhancing effect. We impose the following standard assumption on demand.

Assumption 2 (Demand)**.** *The demand function $D(r,p;\lambda)$ is log-concave in price p.*

Intuitively, log-concavity of demand ensures that the purchase probability increases as the price decreases. Finally, note that in the absence of concerns about recyclability ($\lambda = 0$), the expected end-of-life utility satisfies $e(r;0) = 0$, and demand takes the standard form $D(r,p;0) = 1-F(p)$.

2.3 Waste footprint and externality

The firm's waste footprint measures the amount of resources that are going to waste. In our setting, there are two sources of waste: (i) products that are disposed of as waste, and (ii) recovered products that are not fully recyclable. Based on their end-of-life decision, buyers with hassle cost $\kappa \leq b(r;\lambda) - \bar{u}(\lambda)$ return the product for recycling, which results in the endogenous recycling probability

$$\phi(r;\lambda) \equiv G(b(r;\lambda) - \bar{u}(\lambda)) \tag{3}$$

that satisfies $\phi_r(r;\lambda) \geq 0$ and $\phi_\lambda(r;\lambda) \geq 0$ by Assumption 1. Stated differently, higher recyclability and stronger concerns about recyclability increase the probability that buyers return the product for recycling.

Without loss of generality, we normalize the amount of resources embedded in an end-of-life product to unity. Assuming that the resources cannot be recovered from waste, the expected waste footprint per unit of product is

$$\begin{aligned} w(r;\lambda) &= \phi(r;\lambda)(1-r) + (1-\phi(r;\lambda)) \\ &= 1-\phi(r;\lambda)r, \end{aligned}$$

where $w_r(r;\lambda) \leq 0$ and $w_\lambda(r;\lambda) \leq 0$. That is, the waste footprint $w(r;\lambda)$ per unit of product decreases in the recyclability index r and the concerns about recyclability λ. Note that $\phi(r;\lambda)r$ can be interpreted as the "effective recycling rate." Importantly, the waste footprint per unit of product is zero if and only if both the return probability and the index of recyclability are equal to unity, hereafter referred to as "full circularity."

The firm's waste footprint results from adding up the per-unit waste footprint $w(r;\lambda)$ across buyers:

$$\Phi(r,p;\lambda) = [1-\phi(r;\lambda)r]D(r,p;\lambda). \tag{4}$$

Note that the firm's waste footprint mirrors its resource footprint: If the effective recycling rate is $\phi(r;\lambda)r$, then the net resource footprint per unit of product is given by $1-\phi(r;\lambda)r$, and the overall resource footprint coincides with $\Phi(r,p;\lambda)$. Therefore, the firm leaves no footprint when it reaches full circularity—neither in terms of waste nor resources used.

Because disposing of the product creates waste, buyers exert an externality if they do not fully internalize their expected waste footprint. Assuming a one-to-one correspondence between the expected per-unit waste footprint and the associated monetary damage, a buyer creates an externality whenever $e(r;\lambda) > -w(r;\lambda)$, that is, if the end-of-life utility exceeds the environmental damage. Note that for given r, buyers fully internalize their waste footprint if

$$\bar{u}(\lambda) = -\left[w(r;\lambda) + \int_0^{b(r;\lambda)-\bar{u}(\lambda)} G(\kappa)d\kappa\right]$$

by (1). That is, the cold prickle must offset both the waste footprint *and* the warm glow from participating in recycling to internalize the environmental damage. Finally, the market externality can be calculated by summing up the non-internalized waste footprints across buyers:

$$E(r,p;\lambda) = [w(r;\lambda) + e(r;\lambda)]D(r,p;\lambda). \tag{5}$$

In the absence of concerns about recyclability, the market externality equals the overall waste footprint, $E(r,p;\lambda) = \Phi(r,p;\lambda)$, as the expected end-of-life utility is zero.

3 The linear business model

In this benchmark case, the firm does not build a reverse supply chain, and consumers must therefore dispose of the end-of-life product as waste, irrespective of their concerns about recyclability λ. Hence, the expected end-of-life benefit simplifies to $e(r;\lambda) = \bar{u}(\lambda) \leq 0$, and consumers with $v \geq p - \bar{u}(\lambda)$ purchase the product. Therefore, the firm's profit under the linear business model is given by

$$\pi(r, p; \lambda) = [p - c(r)][1 - F(p - \bar{u}(\lambda))]. \tag{6}$$

Note that if $\bar{u}(\lambda) < 0$, the consumers' disutility associated with the trashing option reduces demand. Assuming that the profit function is strictly concave in r and p and thus has unique global maximizer, the following result holds.

Proposition 1 (Take-make-dispose)**.** *Under the linear business model, the profit-maximizing product design* $(\hat{r}, \hat{p})$ *satisfies*

$$\hat{r} = 0 \text{ and } \hat{p} = c(0) + \frac{1 - F(\hat{p} - \bar{u}(\lambda))}{f(\hat{p} - \bar{u}(\lambda))}$$

and yields the waste footprint $\Phi(\hat{p};\lambda) = 1 - F(\hat{p} - \bar{u}(\lambda))$*. If* $\bar{u}'(\lambda) = 0$*, then stronger concerns about recyclability* λ *have no impact on pricing, firm profitability, and the waste footprint. Instead, if* $\bar{u}'(\lambda) < 0$*, then stronger concerns about recyclability* λ *reduce the profit-maximizing price* $\hat{p}$*, profit, and the waste footprint.*

Proposition 1 shows that a profit-maximizing firm provides a non-recyclable product in the absence of a reverse supply chain, even if consumers care about recyclability. The reason is that recyclability is costly but has no impact on demand. The result also implies that all resources embedded in the end-of-life product are going to waste. In addition, Proposition 1 shows that, if the disutility depends on λ, then stronger concerns about recyclability yield a lower profit and waste footprint. Intuitively, the lower waste footprint follows from the demand-reducing effect of stronger concerns about recycling, which outweighs the price-mediated effect.

The result suggests two reasons why a profit-maximizing firm might want to build a reverse supply chain. First, the firm may benefit from extracting utility of consumers who care about recyclability. Second, the firm may tap into a new source of revenue from recycling the resources embedded in end-of-life products.

4 The circular business model

Under the circular business model, the firm operates a reverse supply chain, and generates revenue from sales and resource recovery.[8] For example, Nespresso uses recovered and recycled aluminium to produce new capsules (Nespresso 2021), and HP uses material from returned cartridges to produce new cartridges (HP 2022). Importantly, under a circular business model, the firm must adopt a life cycle perspective by taking into account the end-of-life decisions made by consumers. Formally, the firm's profit is given

$$\pi(r,p;\lambda,\omega,K) = [p-c(r)]D(r,p;\lambda) + \phi(r;\lambda)\omega r D(r,p;\lambda) - K, \tag{7}$$

where $\phi(r;\lambda)\omega r$ is the expected value of a recovered product and K is the fixed cost of setting up the reverse supply chain. Intuitively, $[p-c(r)]D(r,p;\lambda)$ is the profit contribution from sales—the standard forward supply chain—whereas $\phi(r;\lambda)\omega r D(r,p;\lambda)-K$ is the expected profit contribution from resource recovery and recycling—the reverse supply chain. Due to recycling, the unit cost $c(r)$ is reduced to the "net unit cost" $c(r)-\phi(r;\lambda)\omega r$, which satisfies the following properties.

Lemma 2 (Net unit cost)**.** *Suppose that the unit cost $c(r)$ is sufficiently convex and that $\frac{d\log g(\kappa)}{d\kappa}$ is not too negative. Then, the net unit cost function*

$$z(r;\lambda,\omega) \equiv c(r) - \phi(r;\lambda)\omega r \tag{8}$$

satisfies the properties $z(r;\lambda,\omega)\geq 0$, $z_r(r;\lambda,\omega)\geq 0$, $z_{rr}(r;\lambda,\omega)\geq 0$, $z_\lambda(r;\lambda,\omega)\leq 0$, $z_{r\lambda}(r;\lambda,\omega)\leq 0$, $z_\omega(r;\lambda,\omega)\leq 0$, and $z_{r\omega}(r;\lambda,\omega)\leq 0$ for admissible values of (λ,ω).

[8]The collection of end-of-life products can also be outsourced to a third party (Savaskan, Bhattacharya, and Van Wassenhove 2004). However, this would not qualitatively change the analysis.

Intuitively, the convexity assumption in Lemma 2 rules out a "perpetuum mobile" by ensuring that the unit cost $c(r)$ exceeds the product's expected end-of-life value $\phi(r;\lambda)\omega r$ for all r. The result shows that the net unit cost function $z(r;\lambda,\omega)$ is convex in r, and that a higher λ and ω decrease both $z(r;\lambda,\omega)$ and the marginal net unit cost $z_r(r;\lambda,\omega)$. The regularity condition on the density function $g(\kappa)$ ensures that the marginal net unit cost is decreasing in λ, a natural property as the return probability $\phi(r;\lambda)$ is higher when consumers have stronger concerns about recyclability. Finally, Lemma 2 shows that the marginal net unit cost is also decreasing in the market value ω of the recovered resources.

4.1 Product design

Under a circular business model, the firm chooses the recyclability index r and the price p by considering the unit cost function in (8) to solve

$$\max_{r,p} \quad \pi(r,p;\lambda,\omega,K) = [p-z(r;\lambda,\omega)][1-F(p-e(r;\lambda))]-K \tag{9}$$
$$\text{s.t. } 0 \le r \le 1.$$

Assuming that the profit function is strictly concave, the profit-maximizing price p^* and the recyclability index r^* satisfy the following necessary and sufficient first-order conditions (the multipliers $\mu_1 \ge 0$ and $\mu_2 \ge 0$ are associated with the inequality constraints):

$$-z_r(r^*;\lambda,\omega)[1-F(\cdot)]+[p^*-z(r^*;\lambda,\omega)]f(\cdot)e_r(r^*;\lambda)+\mu_1-\mu_2=0, \tag{10}$$
$$1-F(\cdot)-[p^*-z(r^*;\lambda,\omega)]f(\cdot)=0, \tag{11}$$
$$\mu_1 r^* = 0 \text{ and } \mu_2(r^*-1)=0.$$

The terms in the first equation capture the marginal changes in profit due to higher net unit cost and a higher end-of-life utility, respectively, whereas the second equation determines the firm's "pricing power" captured by $p^*-z(r^*;\lambda,\omega)$. We derive the following result.

Proposition 2 (Circular design)**.** *Under the circular business model, the firm offers a non-recyclable product with* $r^*=0$ *if* $-z_r(0;\lambda,\omega)+e_r(0;\lambda)\le 0$*, and a fully recyclable product* *with $r^* = 1$ if $-z_r(1;\lambda,\omega) + e_r(1;\lambda) \geq 0$. Otherwise, the firm offers a partially recyclable product with $r^* \in (0,1)$, characterized by the condition $-z_r(r^*;\lambda,\omega) + e_r(r^*;\lambda) = 0$. The profit-maximizing price p^* solves $p^* = z(r^*;\lambda,\omega) + \frac{1-F(p^*-e(r^*;\lambda))}{f(p^*-e(r^*;\lambda))}$.*

The result highlights that a profit-maximizing firm does not necessarily offer a fully recyclable product under the circular business model. Specifically, at an interior solution, the firm offers a partially recyclable product with $r^* \in (0,1)$, chosen to balance the marginal changes in net unit cost and end-of-life utility, that is $z_r(r^*;\lambda,\omega) = e_r(r^*;\lambda)$. At a corner solution with $r^* = 0$, the firm offers a non-recyclable product, which mirrors the product design under the linear business model. If in addition $b(0;\lambda) = \bar{u}(\lambda) = 0$, then a "throw-away society" emerges with $\phi^*(0;\lambda) = 0$. On the other hand, at a corner solution with $r^* = 1$, the marginal change in net unit cost is smaller than the corresponding increase in end-of-life utility, and the firm offers a fully recyclable product. In this limiting case, if consumers strongly care about recyclability, then $\phi^* \to 1$, and a fully circular business model emerges. Irrespective of the choice of r^*, the profit-maximizing price p^* is characterized by the standard inverse-elasticity pricing rule for given net unit cost $z(r^*)$.

4.2 Comparative statics

Our next result studies how stronger concerns about recyclability λ and a higher market value ω of the resources embedded in end-of-life products affect the firm.

Proposition 3 (Impact on firm)**.** *If the firm offers a partially recyclable product, then stronger concerns about recyclability λ increase the recyclability index r^*. In addition, they decrease demand and profit if $e_\lambda(r^*;\lambda) < z_\lambda(r^*;\lambda,\omega)$, and increase demand and profit if the inequality is reversed. A higher market value ω of the recovered resources increases the recyclability index r^*, demand, and profit. The impact of changes in λ and ω on pricing is ambiguous.*

Proposition 3 shows that a profit-maximizing firm increases recyclability in response to stronger concerns about recyclability and a higher value of recycled resources. Even though higher recyclability translates into higher net unit cost, the impact on pricing is ambiguous due to the change in the firm's pricing power. If $e_\lambda(r^*;\lambda) < z_\lambda(r^*;\lambda) \leq 0$, then stronger concerns about recyclability reduce both demand and profit. However, if the reduction in the end-of-life utility is relatively small or if the end-of-life utility increases in λ, then the change in product design leads to an increase in equilibrium demand and profit. Finally, while the impact of a higher value of recovered resources on price is generally ambiguous, the impact on demand and profit is always positive. Intuitively, the profit impact is positive as the firm cannot lose from recovering more valuable products. We next consider the impact on the waste footprint.

Proposition 4 (Impact on waste footprint)**.** *If the firm offers a partially recyclable product with* $r^* \in (0,1)$*, then stronger concerns about recyclability* λ *reduce the waste footprint per unit of product,* $w(r^*;\lambda) = 1 - \phi(r^*;\lambda)r^*$*. If* $e_\lambda(r^*;\lambda) < z_\lambda(r^*;\lambda,\omega)$*, then the overall waste footprint* $\Phi(r^*,p^*;\lambda) = w(r^*;\lambda)D(r^*,p^*;\lambda)$ *decreases; otherwise the overall waste footprint may increase. The impact of a higher market value* ω *of recovered resources on the overall waste footprint is generally ambiguous.*

The result shows that stronger concerns about recyclability unambiguously reduce the waste footprint per unit of product. Intuitively, the result follows from the associated increases in recyclability and the probability of recycling. The impact on the overall waste footprint, in turn, depends on the impact on demand. If demand decreases, the impact on the overall waste footprint is unambiguously negative. However, if demand increases, the impact on the overall waste footprint may be positive—a rebound effect (Alcott 2005). Similarly, the impact of a higher market value of the recycled resources is ambiguous due to a positive demand effect.

5 Going circular

In this section, we compare the outcomes under the linear and the circular business model, and derive conditions under which going circular is profitable and socially desirable.

5.1 Profitability

Operating a circular business model is viable if $\pi(r^*, p^*; \lambda, \omega, K) \geq 0$ but not necessarily profit maximizing when considering the linear alternative. The next result characterizes the conditions under which the circular business model yields a higher profit than its linear counterpart.

Proposition 5 (Profitability)**.** *(i) If* $-z_r(0;\lambda,\omega) + e_r(0;\lambda) \leq 0$*, then the profit-maximizing product design is invariant across business models,* $(r^*, p^*) = (0, \hat{p})$*, and going circular is not profitable for any* $K > 0$*. (ii) If* $-z_r(0;\lambda,\omega) + e_r(0;\lambda) > 0$*, then the circular product design satisfies* $(r^*, p^*) > (0, \hat{p})$*, and going circular increases profit if and only if* $K < K^*$*, where* K^* *is defined by the condition* $\pi(r^*, p^*; \lambda, \omega, K^*) - \pi(0, \hat{p}; \lambda) = 0$*.*

This result highlights that, for a profitable transition to a circular business model, it is necessary (but not sufficient) that the change in product design increases the combined profit from sales and recycling. If the consumers' concerns about recyclability or the value of the recovered resources are sufficiently high, then the increase in the combined profit from sales and recycling outweighs the cost of building the reverse supply chain, which makes the adoption of a circular business model profitable. Intuitively, going circular is attractive because it allows the firm to raise its price and tap into a new source of revenue. Importantly, adopting a circular business model is not viable in a throw-away society because the firm can neither raise price nor generate profit from recycling, and thus cannot recover K.

5.2 Social desirability

Next, we characterize the conditions under which switching from a linear to a circular business model improves social welfare. Following convention, we define welfare as the sum of profit and utilities that accrue to buyers and non-buyers,

$$\begin{aligned} W(r,p;\lambda,\omega,K) &= \pi(r,p;\lambda,\omega,K) \\ &\quad + \int_{p-e(r;\lambda)}^{\infty} u(r,p;\lambda)dF(v) + \int_{0}^{p-e(r;\lambda)} [-E(r,p;\lambda)]dF(v), \end{aligned}$$

which can equivalently be written as the triple bottom line of profit, people, and planet (Elkington 1999):

$$W(r,p;\lambda,\omega,K) = \pi(r,p;\lambda,\omega,K) + S(r,p;\lambda) - \Phi(r,p;\lambda), \tag{12}$$

where $S(r,p;\lambda) \equiv \int_{p-e(r;\lambda)}^{\infty} v dF(v) - pD(r,p;\lambda)$ is the standard consumer surplus absent the externality and $\Phi(r,p;\lambda)$ is the overall waste footprint defined in (4). We derive the following result.

Proposition 6 (Welfare)**.** *(i) If* $-z_r(0;\lambda,\omega)+e_r(0;\lambda) \leq 0$*, then the profit-maximizing choice of the linear business model is socially optimal. (ii) If* $-z_r(0;\lambda,\omega)+e_r(0;\lambda) > 0$*, then going circular is socially desirable if and only if* $K < \bar{K}$*, where* $\bar{K}$ *is defined by the condition* $W(r^*,p^*;\lambda,\omega,\bar{K}) - W(0,\hat{p};\lambda) = 0$*.*

This result shows that the profit-maximizing choice between the linear and the circular business model does not necessarily coincide with the welfare-maximizing choice. Intuitively, the firm has an incentive to strategically distort recyclability to exploit its pricing power in a circular model, which has an impact on consumer surplus and the overall waste footprint that is ignored by the firm. As a result, if $K^* < K < \bar{K}$, the firm refrains from making the circular transition based on profitability considerations, even though adopting a circular business model would be socially desirable. On the other hand, if $\bar{K} < K < K^*$, then the profit-maximizing choice of the circular business models reduces welfare.

More broadly, part (i) shows that it is optimal from a welfare perspective to adopt a linear business model if $r^* = 0$. The reason is that the linear business model results in the same product design but saves the fixed cost of setting up the reverse supply chain, leaving the bottom line for consumers and the planet unaffected. Part (ii) shows that if $r^* > 0$, then the profit-maximizing choice of the business model ignores the impact on people and the planet. Hence, the firm's profit-maximizing choice between the linear and the circular business model may not be optimal from a welfare perspective.

6 Boosting circularity

This section studies three managerial strategies that have the objective of improving the performance of circular business models with partially recyclable products. Importantly, we focus on voluntary strategies that can be implemented by the firm rather than schemes imposed by a regulator.[9] First, we analyze how coupling a circular business model with a deposit-refund system or a product buyback strategy affects recyclability and profit. Next, we examine the impact of a product-as-a-service strategy, where the firm retains ownership of the product instead of selling it to the consumer. While these strategies have been studied before, the novelty of this section is to apply them to circular settings and analyze their impact on product design.

6.1 Deposit-refund system

Under a deposit-refund system, the firm collects a deposit $d \geq 0$ as a surcharge at the time of purchase that is refunded to the buyer when the product is returned for recycling. Intuitively, the deposit can be viewed as a tax on trashing end-of-life products, an economic incentive commonly used for beverage containers, lead-acid batteries, motor oil, tires, various hazardous materials, and consumer electronics (Fullerton and Wolverton 2000, Walls 2011). Using the superscript D to index the relevant expressions under the deposit-refund system, the firm chooses the deposit d, as well as the index of recyclability r and the purchase price p to

$$\begin{aligned}\max_{d,r,p} \quad \pi^D =& [p+d-z^D(r,d;\lambda,\omega)][1-F(p+d-e^D(r,d;\lambda))] \\ & -\phi^D(r,d;\lambda)d[1-F(p+d-e^D(r,d;\lambda))]-K \qquad (13)\\ \text{s.t. } & 0 \leq r \leq 1,\end{aligned}$$

where $z^D(r,d;\lambda,\omega) \equiv c(r)-\phi^D(r;\lambda)\omega r$ is the net unit cost, $\phi^D(r,d;\lambda)d$ is the expected refund, and $e^D(r,d;\lambda)$ is the end-of-life utility. Note that a deposit-refund system makes

[9] We address regulation in the discussion section.

$e^D(r,d;\lambda)$ as well as the return probability $\phi^D(r,d;\lambda)$ dependent on d because consumers receive $b(r;\lambda)+d$ when returning the product for recycling. Note that the profit function π^D nests the circular business model for $d=0$. We derive the following result.

Proposition 7 (Deposit refund)**.** *The profit-maximizing deposit in a circular business model with a deposit-refund system equals the value of a recovered product, $d^D = \omega r^D$. Coupling a circular business model with a deposit-refund system cannot decrease profit, and increases recyclability to $r^D > r^*$ only if the additional number of consumers who recycle the product is sufficiently large.*

This result first shows that the profit-maximizing deposit corresponds to the value of the resources embedded in the end-of-life product. Intuitively, if $d < d^D$, then there are unexploited gains of trade, whereas the firm overpays for the value of the resources embedded in the product if $d > d^D$. Second, Proposition 7 shows that introducing a deposit-refund system cannot reduce profit because the firm has an additional contractual instrument and can always choose to set $d=0$. In effect, the deposit-refund system allows the firm to discriminate the ex-post-prices paid by recycling and non-recycling buyers. Finally, the result shows that introducing a deposit-refund system does not necessarily increase recyclability. To see this, consider introducing a deposit-refund system into a circular model when recyclability is given by r^*. Then, there is an incentive to increase recyclability beyond r^* only if $\omega(\phi^D-\phi)+(e_r^D-e_r) > \omega\phi_r r^*$, that is, if the additional benefit from marginally raising recyclability (a higher value of the recovered resource and a higher marginal end-of-life utility) exceeds the additional cost (a higher expected refund). The proof establishes that this condition is satisfied if introducing a deposit-refund system induces a sufficiently large number of additional consumers to recycle the product.

6.2 Product buyback

Similar to a deposit-refund scheme, a buyback strategy provides financial incentives for buyers to return the product for recycling when it reaches end of life. Specifically, we assume that the firm repurchases end-of-life products from consumers at price $s \geq 0$.

Whereas buyback strategies are often used in trade-in programs and refurbishing markets, the incentive to buy back products in a circular model may come from the value of the resources embedded in end-of-life products.[10] Letting the superscript B index the variables under a buyback strategy, the firm chooses the buyback price s, as well as the index of recyclability r and the purchase price p to

$$\max_{s,r,p} \quad \pi^B = [p - z^B(r,s;\lambda,\omega) - \phi^B(r,s;\lambda)s][1 - F(p - e^B(r,s;\lambda))] - K \qquad (14)$$
$$\text{s.t. } 0 \leq r \leq 1,$$

where $z^B(r,s;\lambda,\omega) \equiv c(r) - \phi^B(r;\lambda)\omega r$ is the net unit cost, $\phi^B(r,s;\lambda)s$ is the expected payment for recovering a product, and $e^B(r,s;\lambda)$ is the end-of-life utility. Repurchase results in adjusted unit cost $c(r) - \phi^B(r,s;\lambda)\,[\omega r - s]$ and makes the end-of-life utility $e^B(r,s;\lambda)$ as well as the return probability $\phi^B(r,s;\lambda)$ dependent on s as consumers receive $b(r;\lambda) + s$ when returning the product for recycling. We derive the following result.

Proposition 8 (Product buyback)**.** *Coupling a circular business model with a product buyback strategy is equivalent to introducing a deposit-refund system with* $r^B = r^D$ *and* $p^B = p^D + d^D$.

This result shows that the product design in terms of recyclability and purchase price is the same under a deposit-refund system and a buyback strategy, which translates into identical demand and waste footprint. Intuitively, when dumping the product, the consumer either gives up the deposit d^D or forgoes the buyback price s^B. Because the buyback price can be viewed as an implicit deposit that is collected upfront, consumers incur the same transaction price at the time of purchase. Note that introducing a buyback strategy cannot decrease profit and does not necessarily increase recyclability—mirroring the properties of a deposit-refund system.

[10]For example, the Apple Trade In program offers credit toward the next purchase, and Back Market buys back electronics devices from consumers to sell them on their marketplace of refurbished electronics.

6.3 Retaining product ownership

Deposit-refund systems and buyback strategies create "leakage" because consumers do not necessarily return the product for recycling. In contrast, retaining product ownership (RPO) is an effective strategy for the firm to ensure that all products being sold can be recovered for recycling. Typical examples of RPO strategies include rentals and leasing—the idea of "product as a service." For example, Xerox has for a long time leased its printers and photocopiers to corporate customers, Michelin Fleet Solutions proposes tire lease programs with fixed price per mile rates, and On's running shoe made from the oil of castor beans is available on subscription only "to ensure your old pair of Cyclons goes back to the company, so that the recycling loop actually works."[11] Using the superscript O to index the variables under an RPO strategy, the firm chooses the index of recyclability r and the purchase price p to

$$\max_{r,p} \quad \pi^O = [p - z^O(r;\omega)][1 - F(p - e^O(r;\lambda))] - K \qquad (15)$$
$$\text{s.t.} \quad 0 \leq r \leq 1,$$

where $e^O(r;\lambda) = b(r;\lambda) - E[\kappa]$ is the expected end-of-life utility in the absence of a trash disposal option, with $E[\kappa] = \int_0^\infty \kappa dG(\kappa) > 0$ denoting the expected cost of recycling and the superscript O indexing the variables under product ownership. As $\phi^O(r;\lambda) = 1$ by construction, the net unit cost $z^O(r;\omega)$ is independent of λ. We derive the following result.

Proposition 9 (Product Ownership)**.** *Coupling a circular business model with an RPO strategy increases recyclability and profitability.*

This result shows that retaining product ownership leads to better recyclable products and higher profit compared to the circular model without any boosting mechanism. Intuitively, an RPO strategy leads to lower net unit cost because the return probability is higher. At the same time, the better recyclability expands demand and therefore profit at $p = p^*$. Because profit cannot decrease if the firm adjusts its price from p^* to the new

[11] For details on On's running shoe, see `https://bit.ly/33ioyPs`.

optimal price p^O, the profit under RPO is higher compared to the benchmark case. Finally, by eliminating leakage on the part of consumers, an RPO strategy leads to a fully circular product design if $r^O = 1$, a dual win for the firm and the planet.

7 Discussion

This paper developed an analytical framework to study the mechanics of circular business models operated by profit-maximizing firms. Specifically, we analyzed how firms should design a product by choosing its recyclability and price if consumers have concerns about recyclability and decide whether to recycle or trash an end-of-life product. We also studied the impact of stronger concerns about recyclability and a higher value of the resources embedded in end-of-life products on product design, profit, and the firm's waste footprint. In addition, we studied the profitability and desirability of switching from a linear to a circular business model. Finally, we examined managerial strategies to boost circularity, including a deposit-refund system, product buyback, and retaining product ownership.

Our analysis suggests that it is a daunting task for a firm to reach full circularity, which requires that the product is fully recyclable by design and returned for recycling by all consumers to eliminate the firm's resource and waste footprint. Yet, a profit-maximizing firm may want to operate a partially circular business model if consumers strongly care about recyclability, the value of the recovered resourced embedded in end-of-life products is high, and the cost of setting up the reverse supply chain is not prohibitively high. Circularity is further supported when the hassle cost of consumers to return the product for recycling can be lowered by the firm. We now discuss the implications of our analysis for firms, consumers, and policy makers.

7.1 Implications for firms

The consumers' concerns about recyclability offer new opportunities for firms: They may not only benefit from a higher willingness to pay for products with better recyclability, but also tap into a new source of revenue from recovering and recycling the resources embedded in end-of-life products. However, to seize these opportunities, a firm must adjust its product design and operate a reverse supply chain, that is, it must adopt a circular business model.

While the profitability of switching from a linear to a circular business model will depend on market specifics and the managerial strategies adopted (e.g., whether the firm operates a deposit-refund system or offers the product as a service), it is driven by three generic effects: First, the demand effect resulting from the change in the appropriate product design; second, the unit cost effect due to the "flow-back" of valuable resources embedded in end-of-life products; and third, the fixed cost effect of setting up the reverse supply chain. Therefore, even a purely profit-maximizing firm should take the environmental concerns of consumers into account and choose its business model accordingly. To further boost circularity, firms should also consider reducing the hassle cost of consumers to participate in the reverse supply chain.

There are indications that the circular business model will become more profitable in the future. For instance, policies that raise consumer awareness, such as the European Union's Circular Economy Action Plan (European Commission 2020), might lead to "deconsumption" for non-recyclable products as consumers increasingly dread the prospect of having to trash end-of-life products, thereby making the linear business model less attractive. Increasing prices of raw materials and more intense competition over rare earth materials, in turn, suggest that recovering and recycling the resources embedded in end-of-life products (or sourcing from other secondary markets) becomes more profitable. Finally, it seems plausible that technological progress will not only reduce the cost of setting up the reverse supply chain but also the cost of producing a better recyclable product.

7.2 Implications for consumers

Our analysis highlights that the consumers' concerns about recyclability enter the objective function of a profit-maximizing firm via their impact on the revenues from sales and recycled resources, respectively, thereby affecting the firm's product design decisions. In other words, consumers can impose their environmental preferences even on firms that narrowly focus on profit maximization.

Yet, consumers should be aware that their choices not only affect the firm's profit but also impose a negative externality on society if they do not fully account for the waste footprint caused by their purchase decisions. Full internalization requires that the cold prickle from throwing away an end-of-life product offsets the waste footprint and the warm glow from participating in the recycling system. Otherwise, the expected end-of-life utility is "too large," which results in an excessively high demand and overall waste footprint.

7.3 Implications for policy makers

There are many ways in which policy makers can support the circular economy movement: taxation, command-and-control regulation, and "realpolitik." Resource and waste taxes are classical tools to correct for under-priced environmental externalities (Pigou 1932). Our analysis suggests that correcting for externalities by taxation requires that the adjusted end-of-life utility corresponds to the environmental damage measured by the per-unit waste footprint. This can be achieved, for instance, by imposing an appropriate unit waste tax on consumers. If their tax burden is higher under the linear business model than under the circular business model (e.g., because of the higher per-unit waste footprint), firms may be induced to go circular to avoid the higher waste tax imposed on their consumers under the linear model. Similarly, regulators can pressure firms to adopt a circular business model by making the waste tax part of their cost.

Command-and-control regulation in the form of Extended Producer Responsibility (EPR) often have the objective of making producers responsible for the environmental impact of their products across the lifecycle (OECD 2016, 2018). For instance, a regulator may impose a minimum level of recyclability, which places an additional restriction on the firm's profit maximization problem. A minimum recyclability requirement, for example, may boost the incentive to go circular, because it reduces profit under the linear business model, whereas it is not necessarily binding under the circular model. Similar arguments apply for minimum requirements on the share of recovered products or the share of recycled materials embedded in new products.

Finally, regarding realpolitik, the European Commission (2019, 2020) and the Chinese National Development and Reform Commission (NDRC 2021) have proposed several measures to accelerate the circular transition of the economy.[12] The Circular Economy Action Plan adopted in March 2020, one of the main building blocks of the European Green Deal (European Commission 2019), targets how products are designed, and aims to ensure that waste is prevented and resources are used as long as possible. The action mainly focuses on resource-intensive sectors such as textiles, construction, electronics and plastics. Likewise, China's development plan (NDRC 2021) focuses on recycling and reusing materials and resources, and will make circular economy a national priority.[13]

7.4 Limitations and future research

Future research could study how firms can go beyond closing the loop by extending the loop through additional "R-levers" including reuse, repair, and remanufacture to further reduce resource extraction and waste production. An important avenue will be to explore how product design interacts with levers to extend the loop. Another fruitful avenue could be to study settings that allow for several life cycles of a product, similar to Patagonia's Worn Wear Program to buy and trade in used gear.

Second, future research could explore the potential for greenwashing when consumers care about product recyclability. We assumed that consumers take recyclability claims made by firms at face value. However, firms may be tempted to make unsubstantiated green claims to affect consumer behavior, and it would therefore be interesting to examine the conditions under which greenwashing can prevail in market equilibrium. By extending the model to competition, one could also study how to best organize recycling at the industry

[12]For an overview of the circular economy in China, see Bleischwitz et al. (2022).
[13]For details, see `https://bit.ly/3PBAnE0`.

level. In addition, one could explore how the capacity of the public waste management system to recycle end-of-life products affects recyclability and waste footprints.

Third, it would be important to develop a better understanding of how consumers value recyclability, and to empirically quantify the "attitude-behavior gap" between consumer's stated sustainability intentions and actual behaviors. Another avenue is to define "circular metrics" at the firm and industry level and empirically measure the progress towards a circular economy. Overall, our paper highlights some consequences of concerns about recyclability on product design, waste footprints, and the incentives for a firm to transition from a linear to a circular business model. Hopefully, it will spur further research on how to integrate circularity across the value chain to tackle the "circularity gap" and align business models with planetary boundaries.

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Appendix

Proof of Lemma 1. To establish (1), note that

$$\begin{aligned} e(r;\lambda) &= \int_0^{b-\bar{u}} (b-\kappa)\, g(\kappa) d\kappa + \int_{b-\bar{u}}^{\infty} \bar{u} g(\kappa) d\kappa \\ &= \int_0^{b-\bar{u}} (b-\kappa)\, g(\kappa) d\kappa + \bar{u}\,(1-G(b-\bar{u}))\,, \end{aligned}$$

where the arguments of $b(r;\lambda)$ and $\bar{u}(\lambda)$ are suppressed for ease of exposition. Defining $h(\kappa) \equiv b-\kappa$ and using integration by parts, we obtain

$$\begin{aligned} e(r;\lambda) &= h(\kappa)G(\kappa)|_0^{b-\bar{u}} - \int_0^{b-\bar{u}} h'(\kappa)G(\kappa)d\kappa + \bar{u}\,(1-G(b-\bar{u})) \\ &= h(b-\bar{u})G(b-\bar{u}) - h(0)G(0) + \int_0^{b-\bar{u}} G(\kappa)d\kappa + \bar{u}\,(1-G(b-\bar{u})) \\ &= \bar{u}G(b-\bar{u}) + \int_0^{b-\bar{u}} G(\kappa)d\kappa + \bar{u}\,(1-G(b-\bar{u})) \\ &= \int_0^{b-\bar{u}} G(\kappa)d\kappa + \bar{u} \gtrless 0. \end{aligned}$$

Using Leibniz's rule, the following properties hold:

$$e_r(r;\lambda) = G(b-\bar{u})b_r \geq 0 \tag{A.1}$$

$$e_{r\lambda}(r;\lambda) = G(b-\bar{u})b_{r\lambda} + g(b-\bar{u})\left(b_\lambda - \bar{u}'\right) b_r \geq 0, \tag{A.2}$$

where these inequalities follow from Assumption 1 and the properties of G. Finally, the impact of a higher λ on $e(r;\lambda)$ is ambiguous as $e_\lambda(r;\lambda) = G(b-\bar{u})\,(b_\lambda - \bar{u}') + \bar{u}'$ is the sum of a positive and a negative term. □

Proof of Proposition 1. Because

$$\left.\frac{\partial\pi(r,p;\lambda)}{\partial r}\right|_{r=0} = -c'(0)[1-F(p-\bar{u}(\lambda))] \leq 0$$

as $c'(0) \geq 0$, the profit-maximizing index of recyclability is given by $\hat{r} = 0$. The profit-maximizing price $\hat{p}$ satisfies the first-order condition

$$\frac{\partial\pi(r,p;\lambda)}{\partial p} = 1-F(p-\bar{u}(\lambda)) - [p-c(r)]f(p-\bar{u}(\lambda)) = 0 \tag{A.3}$$

and can be derived as $\hat{p} = c(0) + \frac{1-F(\hat{p}-\bar{u}(\lambda))}{f(\hat{p}-\bar{u}(\lambda))}$. The waste footprint follows by substitution from (4) and is equal to demand.

The impact of stronger concerns about recyclability λ on the profit-maximizing price $\hat{p}$ is obtained by applying the implicit function theorem to the first-order condition for the price in (A.3), which results in

$$\frac{d\hat{p}}{d\lambda} = \frac{(f+[\hat{p}-c(0)]f')\bar{u}'(\lambda)}{2f+[\hat{p}-c(0)]f'}, \tag{A.4}$$

where the arguments of F and its derivatives are suppressed for convenience. Using that $\hat{p}-c(0) = \frac{1-F}{f}$, (A.4) can be written as

$$\frac{d\hat{p}}{d\lambda} = \frac{[f^2+(1-F)f']\bar{u}'(\lambda)}{2f^2+(1-F)f'}. \tag{A.5}$$

If $\bar{u}'(\lambda) = 0$, then $\frac{d\hat{p}}{d\lambda} = 0$, whereas if $\bar{u}'(\lambda) < 0$, then $\frac{d\hat{p}}{d\lambda} < 0$ by log-concavity of demand in Assumption 2.[14] The profit impact of a higher λ follows from the envelope theorem:

$$\frac{d\pi(0,\hat{p};\lambda)}{d\lambda} = [\hat{p}-c(0)]f\bar{u}'(\lambda),$$

which is negative if $\bar{u}'(\lambda) < 0$ and zero otherwise. Finally, to see the impact of stronger concerns about recyclability λ on the waste footprint, note that

$$\begin{aligned}\frac{d\Phi(\hat{p};\lambda)}{d\lambda} &= -f\left[\frac{d\hat{p}}{d\lambda} - \bar{u}'(\lambda)\right] \\ &= \frac{f^3\bar{u}'(\lambda)}{2f^2+(1-F)f'} \leq 0,\end{aligned}$$

where the last equality follows from substituting $\frac{d\hat{p}}{d\lambda}$ in (A.5). □

[14]Note that $\log(D) = \log(1-F)$, and thus that $\frac{d\log(D)}{dp} = -\frac{f}{1-F}$ and $\frac{d^2\log(D)}{dp^2} = -\frac{f'(1-F)+f^2}{(1-F)^2}$. Demand is therefore log-concave if and only if $f'(1-F)+f^2 > 0$.

Proof of Lemma 2. Recall that $z(0;\lambda,\omega) = c(0) \geq 0$ by our assumptions on the unit cost function. Suppressing the arguments of the benefit function, differentiating $z(r;\lambda,\omega)$ and imposing that $c(r)$ is sufficiently convex in r yields

$$\begin{aligned} z_r(r;\lambda,\omega) &= c'(r) - \omega[\phi_r(r;\lambda)r + \phi(r;\lambda)] \\ &= c'(r) - \omega[g(b-\bar{u})b_r r + G(b-\bar{u})] \geq 0 \end{aligned} \tag{A.6}$$

and

$$\begin{aligned} z_{rr}(r;\lambda,\omega) &= c''(r) - \omega[\phi_{rr}(r;\lambda)r + 2\phi_r(r;\lambda)] \\ &= c''(r) - \omega[(g'(b-\bar{u})b_r^2 + g(b-\bar{u})b_{rr})r + 2g(b-\bar{u})b_r] \geq 0, \end{aligned} \tag{A.7}$$

where the properties of the benefit function are given in Assumption 1 and the properties of $\phi(r;\lambda)$ are derived from (3). Also, because $z(0;\lambda,\omega) \geq 0$ and $z_r(r;\lambda,\omega) \geq 0$, the net unit cost function satisfies $z(r;\lambda,\omega) \geq 0$ for admissible values of (λ,ω). Further,

$$\begin{aligned} z_\lambda(r;\lambda,\omega) &= -\phi_\lambda(r;\lambda)\omega r \\ &= -g(b-\bar{u})(b_\lambda - \bar{u}')\omega r \leq 0, \end{aligned} \tag{A.8}$$

and the impact of a higher λ on the marginal net unit cost $z_r(r;\lambda,\omega)$ is given by

$$\begin{aligned} z_{r\lambda}(r;\lambda,\omega) &= -\omega[\phi_{r\lambda}(r;\lambda)r + \phi_\lambda(r;\lambda)] \\ &= -\omega[(g'(\cdot)(b_\lambda - \bar{u}')b_r + g(\cdot)b_{r\lambda})r + g(\cdot)(b_\lambda - \bar{u}')] \leq 0, \end{aligned} \tag{A.9}$$

where the inequality holds if and only if $\frac{d\log g(\kappa)}{d\kappa} = \frac{g'(\kappa)}{g(\kappa)}$ is not too negative, that is, if

$$\frac{g'(\cdot)}{g(\cdot)} \geq -\frac{1}{b_r}\left(\frac{b_{r\lambda}}{b_\lambda - \bar{u}'} + \frac{1}{r}\right).$$

Finally,

$$z_\omega(r;\lambda,\omega) = -G(b-\bar{u})r \leq 0 \tag{A.10}$$

and

$$z_{r\omega}(r;\lambda,\omega) = -[g(b-\bar{u})b_r r + G(b-\bar{u})] \leq 0, \tag{A.11}$$

as $b_r \geq 0$ from Assumption 1. □

Proof of Proposition 2. Substituting (11) into (10) yields

$$-z_r(r^*;\lambda,\omega)+e_r(r^*;\lambda)+\frac{\mu_1-\mu_2}{1-F(\cdot)}=0, \tag{A.12}$$

where $e_r(r;\lambda)$ and $z_r(r;\lambda,\omega)$ are stated in model primitives in (A.1) and (A.6), respectively. If $-z_r(0;\lambda,\omega)+e_r(0;\lambda)\leq 0$, then there is a corner solution with $r^*=0$. Instead, if $-z_r(1;\lambda,\omega)+e_r(1;\lambda)\geq 0$, then there is a corner solution with $r^*=1$. At an interior solution, $\mu_1=\mu_2=0$, and r^* is implicitly defined by the condition

$$-z_r(r^*;\lambda,\omega)+e_r(r^*;\lambda)=0. \tag{A.13}$$

Solving (11), the optimal price p^* is given by

$$p^*=z(r^*;\lambda,\omega)+\frac{1-F(p^*-e(r^*;\lambda))}{f(p^*-e(r^*;\lambda))}, \tag{A.14}$$

the quality-adjusted inverse-elasticity pricing rule. □

Proof of Proposition 3. The profit function $\pi(r,p)$ is strictly concave in (r,p) if and only if $\pi_{rr}<0$, $\pi_{pp}<0$ and $\pi_{rr}\pi_{pp}-(\pi_{pr})^2>0$. These partial derivatives can be derived as

$$\begin{aligned}
\pi_{rr} &= -z_{rr}[1-F(\cdot)]-2z_r f(\cdot)e_r-[p-z(r)][f'(\cdot)e_r^2-f(\cdot)e_{rr}]\\
\pi_{pp} &= -2f(\cdot)-[p-z(r)]f'(\cdot)\\
\pi_{pr} &= \pi_{rp}=f(\cdot)z_r+f(\cdot)e_r+[p-z(r)]f'(\cdot)e_r.
\end{aligned}$$

For later reference, we now evaluate these derivatives at the interior optimizer (r^*,p^*). First, π_{rr} can be written as

$$\begin{aligned}
\pi_{rr} &= -z_{rr}[1-F(\cdot)]-2z_r f(\cdot)e_r-[p^*-z(r^*)][f'(\cdot)e_r^2-f(\cdot)e_{rr}]\\
&= -z_{rr}[1-F(\cdot)]-2z_r f(\cdot)e_r-\frac{1-F(\cdot)}{f(\cdot)}[f'(\cdot)e_r^2-f(\cdot)e_{rr}]\\
&= -(z_{rr}-e_{rr})[1-F(\cdot)]-\frac{1}{f(\cdot)}[2[f(\cdot)]^2+[1-F(\cdot)]f'(\cdot)]e_r^2\\
&= -(z_{rr}-e_{rr})[1-F(\cdot)]+\pi_{pp}e_r^2.
\end{aligned}$$

Second, π_{pp} reduces to

$$\begin{aligned}\pi_{pp} &= -2f(\cdot) - \frac{1-F(\cdot)}{f(\cdot)} f'(\cdot) \\ &= -\frac{1}{f(\cdot)}(2[f(\cdot)]^2 + [1-F(\cdot)]f'),\end{aligned}$$

whereas π_{pr} boils down to

$$\begin{aligned}\pi_{pr} &= f(\cdot)z_r + f(\cdot)e_r + [p^* - z(r^*)]f'(\cdot)e_r \\ &= [2f(\cdot) + [p^* - z(r^*)]f'(\cdot)]e_r \\ &= \frac{1}{f(\cdot)}[2[f(\cdot)]^2 + [1-F(\cdot)]f'(\cdot)]e_r \\ &= -\pi_{pp}e_r. \end{aligned} \tag{A.15}$$

Finally, the determinant of the Hessian matrix can be calculated as

$$\begin{aligned}\pi_{pp}\pi_{rr} - (\pi_{pr})^2 &= \pi_{pp}(-(z_{rr} - e_{rr})[1-F(\cdot)] + \pi_{pp}e_r^2) - (-\pi_{pp}e_r)^2 \\ &= -\pi_{pp}(z_{rr} - e_{rr})[1-F(\cdot)], \end{aligned} \tag{A.16}$$

which requires that $z_{rr} - e_{rr} > 0$ at (r^*, p^*).

To derive the comparative statics results, we rewrite (10) and (11) in reduced form as

$$\begin{aligned}\pi_r(r^*(x), p^*(x), x) &= 0 \\ \pi_p(r^*(x), p^*(x), x) &= 0,\end{aligned}$$

where $x \in \{\lambda, \omega\}$. Implicit differentiation of the first-order conditions with respect to x yields the system

$$\begin{bmatrix} \pi_{rr} & \pi_{pr} \\ \pi_{pr} & \pi_{pp} \end{bmatrix} \begin{bmatrix} \frac{dr^*(x)}{dx} \\ \frac{dp^*(x)}{dx} \end{bmatrix} = - \begin{bmatrix} \pi_{rx} \\ \pi_{px} \end{bmatrix},$$

which can be solved using Cramer's rule:

$$\begin{aligned}\frac{dr^*}{dx} &= -\frac{\pi_{rx}\pi_{pp} - \pi_{pr}\pi_{px}}{\pi_{pp}\pi_{rr} - (\pi_{pr})^2} \\ \frac{dp^*}{dx} &= -\frac{\pi_{rr}\pi_{px} - \pi_{rx}\pi_{pr}}{\pi_{pp}\pi_{rr} - (\pi_{pr})^2}.\end{aligned}$$

Using the previous results, these expressions boil down to

$$\begin{aligned}\frac{dr^*}{dx} &= -\frac{\pi_{rx}\pi_{pp}-\pi_{pr}\pi_{px}}{\pi_{pp}\pi_{rr}-(\pi_{pr})^2}\\ &= \frac{\pi_{rx}+e_r\pi_{px}}{(z_{rr}-e_{rr})[1-F(\cdot)]}\end{aligned} \tag{A.17}$$

and

$$\begin{aligned}\frac{dp^*}{dx} &= -\frac{\pi_{rr}\pi_{px}-\pi_{rx}\pi_{pr}}{\pi_{pp}\pi_{rr}-(\pi_{pr})^2}\\ &= \frac{[-(z_{rr}-e_{rr})[1-F(\cdot)]+\pi_{pp}e_r^2]\pi_{px}+\pi_{rx}\pi_{pp}e_r}{\pi_{pp}(z_{rr}-e_{rr})[1-F(\cdot)]}\\ &= -\frac{\pi_{px}}{\pi_{pp}}+z_r\frac{e_r\pi_{px}+\pi_{rx}}{(z_{rr}-e_{rr})[1-F(\cdot)]}\\ &= -\frac{\pi_{px}}{\pi_{pp}}+z_r\frac{dr^*}{dx}.\end{aligned} \tag{A.18}$$

The impact of a higher x on demand $D^* = D(p^*, r^*)$ is given by

$$\begin{aligned}\frac{dD^*}{dx} &= -f(\cdot)\left[\frac{dp^*}{dx}-e_r\frac{dr^*}{dx}-e_\lambda\mathbf{1}_{\{x=\lambda\}}\right]\\ &= -f(\cdot)\left[-\frac{\pi_{px}}{\pi_{pp}}+z_r\frac{dr^*}{dx}-e_r\frac{dr^*}{dx}-e_\lambda\mathbf{1}_{\{x=\lambda\}}\right]\\ &= -f(\cdot)\left[-\frac{\pi_{px}}{\pi_{pp}}-e_\lambda\mathbf{1}_{\{x=\lambda\}}\right]\end{aligned} \tag{A.19}$$

where the last equality uses (A.13). Finally, to calculate these comparative statics effects, it is useful to note that

$$\begin{aligned}\pi_{r\lambda} &= -z_{r\lambda}[1-F(\cdot)]-z_rf(\cdot)e_\lambda-z_\lambda f(\cdot)e_r\\ &+ [p-z(r)][f'(\cdot)(-e_\lambda)e_r+f(\cdot)e_{r\lambda}]\end{aligned} \tag{A.20}$$

$$\pi_{p\lambda} = f(\cdot)e_\lambda+z_\lambda f(\cdot)+[p-z(r)]f'(\cdot)e_\lambda. \tag{A.21}$$

Similarly, it is straightforward to show that

$$\pi_{r\omega} = -z_{r\omega}[1-F(\cdot)]-z_\omega f(\cdot)e_r \tag{A.22}$$

$$\pi_{p\omega} = z_\omega f(\cdot). \tag{A.23}$$

Impact on recyclability. Using (A.17),

$$\frac{dr^*}{d\lambda} = \frac{\pi_{r\lambda} + e_r\pi_{p\lambda}}{(z_{rr} - e_{rr})[1 - F(\cdot)]}$$
$$= \frac{e_{r\lambda} - z_{r\lambda}}{z_{rr} - e_{rr}}, \tag{A.24}$$

where the second equality uses that, at the optimum, $\pi_{r\lambda} + e_r\pi_{p\lambda} = (e_{r\lambda} - z_{r\lambda})[1 - F(\cdot)]$ from (A.20) and (A.21). By concavity, the denominator of (A.24) is strictly positive, and $e_{r\lambda} \geq 0$ and $z_{r\lambda} \leq 0$ by (A.2) and (A.9), respectively, which implies that $\frac{dr^*}{d\lambda} \geq 0$. Similarly, it follows from (A.22) and (A.23) that

$$\frac{dr^*}{d\omega} = \frac{\pi_{r\omega} + e_r\pi_{p\omega}}{(z_{rr} - e_{rr})[1 - F(\cdot)]}$$
$$= -\frac{z_{r\omega}}{z_{rr} - e_{rr}} \geq 0, \tag{A.25}$$

as $z_{r\omega}(r;\lambda,\omega) \leq 0$ by Lemma 2.

Impact on price. Using (A.18) and suppressing the arguments of F and its derivatives for convenience,

$$\frac{dp^*}{d\lambda} = -\frac{\pi_{p\lambda}}{\pi_{pp}} + z_r\frac{dr^*(\lambda)}{d\lambda}$$
$$= \frac{[f^2 + (1-F)f']e_\lambda + f^2 z_\lambda}{2f^2 + [1-F]f'} + z_r\frac{dr^*}{d\lambda},$$

where the second equality follows by substitution. Because the sign of e_λ is ambiguous and $z_\lambda(r;\lambda,\omega) \leq 0$, the impact of stronger concerns about recyclability λ on p^* is ambiguous. Similarly, because $\pi_{p\omega} = z_\omega f \leq 0$ at an interior solution for r,

$$\frac{dp^*}{d\omega} = -\frac{\pi_{p\omega}}{\pi_{pp}} + z_r\frac{dr^*}{d\omega},$$

the overall impact of a higher ω on p^* is ambiguous.

Impact on demand. Using (A.19),

$$\frac{dD(p^*,r^*)}{d\lambda} = -f\left[-\frac{\pi_{p\lambda}}{\pi_{pp}} - e_\lambda\right]$$
$$= -f\left[\frac{[f^2 + (1-F)f']e_\lambda + f^2 z_\lambda}{2f^2 + [1-F]f'} - e_\lambda\right]$$
$$= f^3\left[\frac{e_\lambda - z_\lambda}{2f^2 + [1-F]f'}\right],$$

which is negative if $e_\lambda < z_\lambda$ and positive if the inequality is reversed. Next,

$$\begin{aligned}\frac{dD^*}{d\omega} &= -f\left[-\frac{\pi_{p\omega}}{\pi_{pp}}\right] \\ &= f^2\left[\frac{z_\omega}{\pi_{pp}}\right] \geq 0.\end{aligned}$$

Impact on profit. Applying the envelope theorem to the optimized profit function $\pi^* = \pi(p^*, r^*)$ yields

$$\begin{aligned}\frac{d\pi^*}{d\lambda} &= -z_\lambda[1-F] + [p-z](-f)(-e_\lambda) \\ &= -z_\lambda[1-F] + \frac{1-F}{f} f e_\lambda \\ &= (e_\lambda - z_\lambda)[1-F],\end{aligned}$$

which is negative if $e_\lambda < z_\lambda$ and positive if the inequality is reversed. Finally,

$$\frac{d\pi^*}{d\omega} = -z_\omega[1-F] \geq 0.$$

□

Proof of Proposition 4. The impact of a higher x on the effective waste footprint per unit of product $1 - \phi r^*$ is

$$\frac{d}{dx}[1-\phi r^*] = -\left[(\phi_r \frac{dr^*}{dx} + \phi_x) r^* + \phi \frac{dr^*}{dx}\right] \leq 0,$$

whereas the impact on the waste footprint of the firm as a whole is

$$\begin{aligned}\frac{d\Phi^*}{dx} &= -[(\phi_r \frac{dr^*}{dx} + \phi_x) r^* + \phi \frac{dr^*}{dx}] D^* + [1-\phi r^*]\frac{dD^*}{dx} \\ &= -[(\phi_r r^* + \phi)\frac{dr^*}{dx} + \phi_x r^*] D^* + [1-\phi r^*]\frac{dD^*}{dx}. \qquad \text{(A.26)}\end{aligned}$$

By substitution,

$$\frac{d\Phi^*}{d\lambda} = -\left[[\phi_r r^* + \phi]\frac{dr^*}{d\lambda} + \phi_\lambda r^*\right] D^* + [1-\phi r^*]\frac{dD^*}{d\lambda}.$$

Using the results from Proposition 3, the sign of $\frac{d\Phi^*}{d\lambda}$ is generally ambiguous. However, if $\frac{dD^*}{d\lambda} < 0$, then $\frac{d\Phi^*}{d\lambda} < 0$. Similarly, the impact of ω on Φ^* is ambiguous as

$$\frac{d\Phi^*}{d\omega} = -[\phi_r r^* + \phi]\frac{dr^*}{d\omega} D^* + [1-\phi r^*]\frac{dD^*}{d\omega}.$$

□

Proof of Proposition 5. (i) We know from Propositions 1 and 2 that $(r^*, p^*) = (0, \hat{p})$ whenever $-z_r(0;\lambda,\omega) + e_r(0;\lambda) \leq 0$. Hence, $\pi(0,\hat{p};\lambda,\omega,K) - \pi(0,\hat{p};\lambda) < 0$ for any $K > 0$. (ii) We know from Proposition 2 that $r^* > \hat{r} = 0$ if $-z_r(0;\lambda,\omega) + e_r(0;\lambda) > 0$. Because the profit-maximizing price $p^*(r)$ defined in (11) is a smooth function of the recyclability index r, the change in prices across business models is given by

$$p^* - \hat{p} = \int_0^{r^*} \left[\frac{dp^*(r)}{dr}\right] dr > 0,$$

where

$$\begin{aligned}\frac{dp^*(r)}{dr} &= -\frac{\pi_{rp}(p^*(r),r)}{\pi_{pp}(p^*(r),r)} \\ &= \frac{f(\cdot)z_r + [f(\cdot) + (p^* - z(r))f'(\cdot)]e_r}{2f(\cdot) + [p^* - z(r)]f'(\cdot)} > 0\end{aligned}$$

by invoking log-concavity of demand in Assumption 2, with $p^*(r^*) = p^*$ and $p^*(0) = \hat{p}$. For the profit comparison, note that $\pi(r^*,p^*;\lambda,\omega,K) - \pi(0,\hat{p};\lambda)$ can be decomposed as

$$\pi(r^*,p^*;\lambda,\omega,K) - \pi(0,\hat{p};\lambda) = \pi(r^*,p^*;\lambda,\omega,0) - \pi(0,\hat{p};\lambda) - K.$$

Going circular is therefore profitable if the extra profit resulting from the change in product design exceeds the cost of building the reverse supply chain. □

Proof of Proposition 6. Using (12), the change in welfare from going circular can be decomposed into changes in profit, standard consumer surplus, and the firm's waste footprint:

$$\begin{aligned}W(r^*,p^*;\lambda,\omega,K) - W(0,\hat{p};\lambda) &= [\pi(r^*,p^*;\lambda,\omega,K) - \pi(0,\hat{p};\lambda)] \\ &\quad + [S(r^*,p^*;\lambda) - S(0,\hat{p};\lambda)] \\ &\quad - [\Phi(r^*,p^*;\lambda) - \Phi(0,\hat{p};\lambda)].\end{aligned}$$

(i) We know from Propositions 1 and 2 that $(r^*,p^*) = (0,\hat{p})$ whenever $-z_r(0;\lambda,\omega) + e_r(0;\lambda) \leq 0$. Then, $S(r^*,p^*;\lambda) = S(0,\hat{p};\lambda)$ and $\Phi(r^*,p^*;\lambda) = \Phi(0,\hat{p};\lambda)$, and thus

$$W(r^*,p^*;\lambda,\omega,K) - W(0,\hat{p};\lambda) = \pi(0,\hat{p};\lambda,\omega,K) - \pi(0,\hat{p};\lambda).$$

As a result, the profit-maximizing choice of the business model is optimal from a welfare perspective. (ii) We know from Proposition 2 that $r^* > \hat{r} = 0$ whenever $-z_r(0;\lambda,\omega) + e_r(0;\lambda) > 0$. Therefore, going circular is socially desirable if and only if $K < \bar{K}$, where $\bar{K}$ is defined by the condition $W(r^*, p^*; \lambda, \omega, \bar{K}) - W(0, \hat{p}; \lambda) = 0$.

□

Proof of Proposition 7. For ease of exposition, the arguments of some functions are suppressed. The end-of-life utility is given by

$$e^D(r,d;\lambda) = \int_0^{b(r;\lambda)+d-\bar{u}(\lambda)} G(\kappa)d\kappa + \bar{u}(\lambda),$$

with $e_r^D = G(b+d-\bar{u})b_r \geq 0$ and $e_d^D = G(b+d-\bar{u}) \geq 0$. The return probability therefore is $\phi^D(r,d;\lambda) = G(b+d-\bar{u})$, with $\phi_d^D = g(b+d-\bar{u}) \geq 0$. Consequently, $e_d^D = \phi^D$, a result that we will use below. Further, note that the net unit cost $z^D(r,d;\lambda,\omega)$ depends on d through its impact on ϕ^D. Specifically, $z_d^D = -\phi_d^D \omega r$.

To simplify exposition, let $m^D \equiv p - z^D(r,d;\lambda,\omega) + (1-\phi^D(r,d;\lambda))d$ denote the margin. The derivative of the profit function with respect to the deposit refund d is

$$\frac{\partial \pi^D}{\partial d} = [-z_d^D + (1-\phi^D) - \phi_d^D d][1-F] - m^D f(1-e_d^D).$$

At an interior solution for p, we know that the margin is given by $m^D = \frac{1-F}{f}$, which implies that

$$\begin{aligned}\frac{\partial \pi^D}{\partial d} &= [-z_d^D + (1-\phi^D) - \phi_d^D d - 1 + e_d^D][1-F] \\ &= [-z_d^D - \phi_d^D d][1-F] \\ &= \phi_d^D[\omega r - d][1-F],\end{aligned}$$

where the second equality exploits that $e_d^D = \phi^D$ and the third equality makes use of the fact that $z_d^D = -\phi_d^D \omega r$. Thus, the profit-maximizing advanced deposit fee satisfies $d = \omega r$, which corresponds to the value of a recovered product to the firm.

Using a similar approach, partially differentiating π^D with respect to r yields

$$\frac{\partial \pi^D}{\partial r} = [-z_r^D - \phi_r^D d + e_r^D][1-F]. \tag{A.27}$$

At an interior solution, making the substitution $d = \omega r$, the profit-maximizing recyclability index r^D is characterized by the condition $z_r^D + \phi_r^D \omega r = e_r^D$, which equates the marginal increase in net unit cost plus the increase in the expected refund with the marginal increase in the end-of-life utility. Further using that

$$\begin{aligned} z_r^D + \phi_r^D \omega r &= c'(r) - \omega(\phi_r^D r + \phi^D) + \phi_r^D \omega r \\ &= c'(r) - \omega[\phi_r r + \phi] + \omega[\phi_r r + \phi] - \omega \phi^D \\ &= z_r - \omega(\phi^D - \phi) + \omega \phi_r r, \end{aligned}$$

evaluating (A.27) at $r = r^*$ yields

$$\begin{aligned} \left.\frac{\partial \pi^D}{\partial r}\right|_{r=r^*} &= [-z_r + \omega(\phi^D - \phi) - \omega \phi_r r^* + e_r^D][1-F] \\ &= [-z_r + e_r + \omega(\phi^D - \phi) + (e_r^D - e_r) - \omega \phi_r r^*][1-F], \end{aligned}$$

where $-z_r + e_r = 0$ by Proposition 2. Hence, from the first-order condition, $r^D > r^*$ only if $\omega(\phi^D - \phi) + (e_r^D - e_r) > \omega \phi_r r^*$, that is, if the additional benefit from marginally raising recyclability (a higher value of the recovered resource and a higher marginal end-of-life utility) exceeds the additional cost (a higher expected refund). Using that $\phi^D - \phi = \int_{b-\bar{u}}^{b+d-\bar{u}} g(\kappa) d\kappa$ and $e_r^D - e_r = b_r \int_{b-\bar{u}}^{b+d-\bar{u}} g(\kappa) d\kappa$, the condition under which $r^D > r^*$ can be written as

$$\frac{\int_{b-\bar{u}}^{b+d-\bar{u}} g(\kappa) d\kappa}{g(b-\bar{u})} > \frac{\omega r^* b_r}{\omega + b_r},$$

where $\phi_r = g(b-\bar{u}) b_r$. Intuitively, this condition holds if introducing a deposit-refund system induces a sufficiently large number of additional consumers to recycle the product.

Finally, because the firm has an additional instrument and can always choose to set $d = 0$, introducing a deposit-refund system cannot reduce profit compared to the standard circular business model. □

Proof of Proposition 8. Letting $\hat{p} = p + d$, the profit function in (13) can be written as

$$\pi^D = [\hat{p} - z^D(r, d; \lambda, \omega) - \phi^D(r, d; \lambda) d][1 - F(\hat{p} - e^D(r, d; \lambda))],$$

which is equivalent to (14). Hence the outcome under a buyback strategy is equivalent to the outcome under a deposit-refund system with $r^B = r^D$ and $p^B = p^D + d^D$.

□

Proof of Proposition 9. Let $m^O \equiv p - z^O(r;\omega)$ denote the margin under RPO. From the first-order condition for the price p, we know that $m^O = \frac{1-F}{f}$. The derivative of the profit function with respect to the index of recyclability index r is

$$\frac{\partial \pi^O}{\partial r} = [-z_r^O + e_r^O][1-F].$$

Hence, the firm offers a nonrecyclable product if $b_r(0;\lambda) \leq c'(0) - \omega$, a fully recyclable product if $b_r(1;\lambda) \geq c'(1) - \omega$, and a partially recyclable product with r^O being characterized by the condition $b_r(r^O;\lambda) = c'(r^O) - \omega$ otherwise.

Compared to the circular model without any boosting mechanism, because $\phi = 1$, the marginal net unit cost is lower (because $z^O(r;\omega) \leq z(r;\lambda,\omega)$ for any r) and the marginal end-of-life benefit is higher for any r. As a result, $r^O \geq r^*$. Because the firm can recover all products at $p = p^*$, profit cannot decrease when the firm adjusts price under RPO. □