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Leveraging consumers' recycling incentives in a Circular Economy*

Valeria Forlin, Eva-Maria Scholz

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Abstract. We study firms' incentives for supporting the transition to a Circular Economy via the choice of their business model, accounting for consumers' recycling preferences and policy makers' Extended Producer Responsibility (EPR) initiatives. Our analysis focuses on take-back programs (TBPs) that reward consumers for dropping off previous purchases at collection points. Results suggest that the uptake of TBPs is primarily driven by the revenue opportunities of firms' collecting and recycling activities and the EPR policy design. Recycling subsidies provide firms with greater incentives than disposal fees or take-back requirements; stricter policies may increase firms' incentives only under take-back requirements or recycling subsidies. From an environmental and consumer welfare perspective, the introduction of TBPs should be encouraged in most cases; regarding producer welfare and the costs of policy makers' initiatives, the result varies with the EPR policy design. In this context, we also identify the trade-offs policy makers face when designing their initiatives.

Keywords Circular Economy, Extended Producer Responsibility, Optimal Policy Design, Recycling, Take-back Programs, Waste Reduction.

1 Introduction

Over the past years, the concept of a Circular Economy has become a central environmental policy objective. Its aim is to *close the loop*, meaning to decouple economic growth from resource consumption by moving from a linear economy to a circular one that is based on reuse, remanufacturing and recycling. Clearly, for this new paradigm to become successful, all actors of society – consumers, businesses and policy makers – need to embrace it (CIRAIG (2015), Kok et al. (2013)): consumers' recycling decisions determine whether goods, at the end of their lifetime, go to landfills or are re-inserted into the production cycle; businesses need to adopt *circular business models* centered on recycling, remanufacturing and reuse;[1] finally, policy makers are crucial in supporting

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[1] The Ellen MacArthur Foundation's *ReSOLVE* framework (regenerate, share, optimise, loop, virtualise, exchange) classifies different circular business opportunities in six categories; "*all increase the utilisation of physical assets, prolong their life, and shift resource use from finite to renewable sources*" (Ellen MacArthur Foundation (2012, p. 9).

the transition, for instance, by providing an appropriate legislative framework.[2]

Take-back programs (TBPs) are one example of such circular business models. To illustrate the concept, let us focus on the retail-clothing company H&M and their global Garment Collecting initiative. Under this initiative, consumers can drop off clothes or other textiles, whatever the brand, in H&M stores and receive a coupon for their next purchase. Depending on the quality of the returned items, H&M, in cooperation with the collection and recycling company I:CO, either resells, reuses or recycles the products.[3] H&M derives revenues from its take-back scheme by selling the collected items to I:CO and/or by reusing part of the recycled cotton yarn in its production (in September 2015, H&M launched its *Denim Re-Born* collection whose pieces contain 20% recycled denim fibers).

The revenue opportunities of TBPs may extend to compliance with regulatory requirements such as the ones imposed by Extended Producer Responsibility (EPR) schemes. EPR holds producers financially and/or physically responsible for the treatment of their products at the end of their lifetime (Atasu and van Wassenhove (2010)). The concept is a key element among policy makers' environmental initiatives; its aim is to motivate producers to include environmental considerations in their operations and by this to increase the extent and degree of product recovery.[4] For EPR policies to be effective, consumer participation is essential: unless consumers drop off items at collection points, instead of disposing them in curbside collection systems, firms are unable to comply with take-back or recycling targets (EPR as *shared responsibility systems* between firms and consumers (Wagner et. al (2013), OECD (2001))). Since consumers associate recycling with important mental and physical efforts (Knussen and Yule (2008), Wagner (2011), Wagner (2013), Wagner et al. (2013)) TBPs, and similar incentive schemes, are thus instrumental to the effectiveness of EPR initiatives.

This paper studies firms' incentives for supporting the transition to a Circular Economy via the choice of their business model, explicitly accounting for consumers' recycling preferences and policy makers' EPR initiatives. In particular, we clarify what factors drive the uptake of TBPs and evaluate the desirability of such programs from a welfare perspective. We further contrast different EPR policy designs in terms of their capacity to stimulate the introduction of TBPs and their welfare implications.

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[2] Policy makers' support is not restricted to the design of a suitable legislative framework. In their *Toolkit for Policy Makers* the Ellen MacArthur Foundation identifies six areas of policy intervention, ranging from the adoption of awareness-raising measures over the implementation of business support schemes to the design of appropriate regulatory and/or fiscal frameworks (Ellen MacArthur Foundation (2015)). A concrete example is the *Circular Economy Package*, adopted by the European Union in 2015. The package consists of i) an EU Action Plan for the Circular Economy and ii) a revised legislative proposal on waste. The Action plan targets the entire cycle: "*from production to consumption, repair and remanufacturing, waste management, and secondary raw materials*" (European Commission (2015)). The revised legislative proposals on waste define targets for waste reduction and a long-term strategy for waste management and recycling.

[3] Similarly, Dell's Trade-In program offers consumers who bring back a computer, monitor or gaming console a rebate on their next purchase. Returned items are either refurbished and resold or recycled. Many other business cases like these exist. See Esposito et al. (2016) or Tse et al. (2016) for a recent overview of examples whereby producers launch these types of initiatives, driven partly by the intrinsic economic value of the recovered products, and partly by the opportunity to cater to their customers' environmental awareness.

[4] In practice, different countries implement the concept of EPR in different ways. Following OECD (2014), EPR policy instruments can be classified in four categories: take-back requirements (e.g., recycling and/or collection targets), economic- and market-based instruments (e.g., (advanced) disposal fees, taxes, subsidies, deposit-refund schemes), regulation and performance standards (e.g., minimum recycled content) and information-based instruments (e.g., reporting and/or information standards).

Our analysis takes a partial equilibrium approach: we focus on the interaction between firms and consumers via the TBPs; other parts of the model such as the recycling sector or the EPR policy design are taken as given. This choice is motivated by the observation that consumers' recycling activities form the basis for the effectiveness of EPR policies and for any revenue opportunities from collection and recycling schemes. We develop our analysis in a two-period Hotelling model in which consumers are differentiated according to their recycling, or environmental, preferences (for a schematic representation of the modeling framework, see Figure 1). There are two firms that compete in prices and produce non-durable products with a lifetime of one period.[5] In the second period, firms may introduce a TBP and offer a reward to each of their second-period customers who drops off a previously purchased item at a collection point. The reward reduces the price of a second-period purchase from the firm and receiving it is not conditional on being a previous customer.[6,7] These rewards play an important role in motivating consumers to participate in a

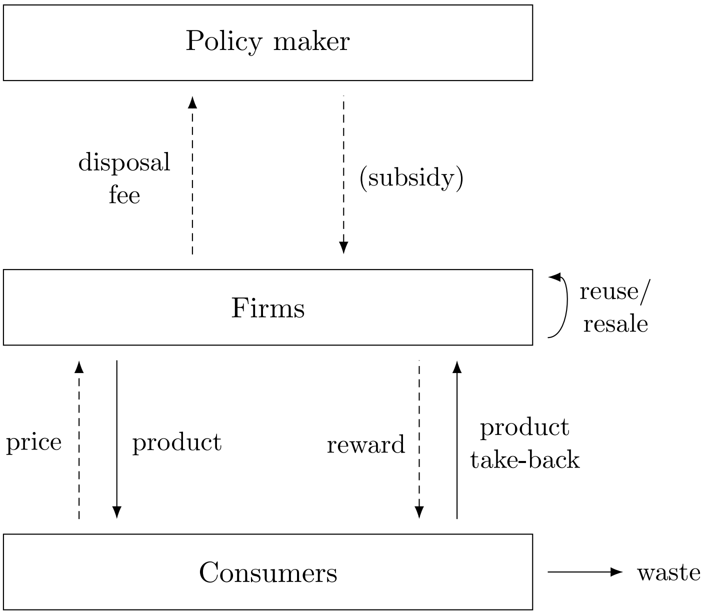

Figure 1: The model: main actors and their interaction.

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[5] Assuming non-durable goods allows us to ignore the case in which firms introduce TBPs in order to decrease competition from the second-hand market (see, for instance, Heese et al. (2005)). Here, durability has to be understood not only in terms of a product's physical life but also in terms of its fashionable life. Especially in the context of the previously introduced example of the retail fashion industry the assumption of non-durable products appears reasonable.

[6] Several reasons for why firms opt for unconditional rewards come to mind. First, distinguishing collected items on the basis of their brand may be impossible or prohibitively costly (especially when taking into account the value of the collected item). This line of reasoning appears to be in line with the example of the retail fashion industry and fits the assumption of our modelling framework (products in a Hotelling model are homogeneous). Second, firms may have an interest to maximize the amount of product collection as this allows them to realize additional revenues from i) the consumers who participate in their TBPs (these consumers spend time in a firm's store, which increases the likelihood of a purchase; moreover, rewards typically take the form of coupons, rebates or in-store credit and as such have to be spend with the firm that offers the TBP) and ii) the collected items themselves (via their recycling, resale or reuse). Note also that a greater amount of product collection may give rise to economies of scale in the collection and/or recycling process.

[7] Two important consequences follow from this assumption: first, consumers in our model do not face switching costs when purchasing from different firms in different periods (for a concise summary of the effects of switching costs on product market competition see Villas-Boas (2015)); second, firms have no basis for behavior-based price discrimination as they are unable to tell whether or not a consumers is a repeat customer (this applies to product prices and the rewards).

TBP, because consumers associate recycling with important mental and physical efforts. Here, we assume that consumers do not give equal importance to these efforts: they are heterogeneous in their environmental preferences and therefore perceive recycling as more or less cumbersome. As a corollary, for a given reward, consumers with strong environmental preferences are more likely to participate in a TBP (and vice versa). We further assume that collected units, via their recycling, remanufacturing or reuse, have an intrinsic value for firms. For instance, firms may recover raw materials, or other components, from collected items and use them in their own production processes or sell them to other industry sectors. To keep our framework simple, we impose that firms recycle all units they collect under their TBPs. The final element is the legislative framework, here modeled as an EPR policy. In this paper, we focus on three different policy designs: a pure disposal fee, a disposal fee combined with a take-back requirement or a disposal fee combined with a recycling subsidy. The policies differ in the costs they inflict on firms. Under a pure disposal fee, firms pay a tax on the total of their first-period production. Under take-back requirements or recycling subsidies, firms continue to pay the disposal fee, but receive a tax-reduction, or subsidy, either for each unit of their first-period production that is collected, up to the take-back target (take-back requirements), or for each unit collected/recycled (recycling subsidies).

Our analysis shows that particularly the revenue opportunities of firms' collecting and recycling activities as well as the type and, potentially, strictness of EPR policy, play a role in explaining the uptake of TBPs. Intuitively, firms find the introduction of a TBP to be worthwhile, only if revenue opportunities from collected products, or their components, are large enough. Conversely, for only small revenue opportunities, none or only one of the two firms may introduce a TBP.[8] Regarding the type of the policy maker's EPR initiative, recycling subsidies maximize firms' incentives for introducing TBPs, while the ranking of pure disposal fees and take-back requirements is ambiguous. A stricter EPR legislation may stimulate the uptake of TBPs only in the case of either take-back requirements or recycling subsidies; under pure disposal fees, policy makers are unable to influence the uptake of TBPs via the strictness of their policies.

In this context, it is important to clarify whether a higher uptake of TBPs is desirable from a welfare perspective and to assess the welfare implications of the different EPR policies. Our analysis makes clear that, from an environmental and consumer welfare perspective, a higher uptake of TBPs should be encouraged in most cases. In terms of aggregate industry profits the result is ambiguous and depends strongly on the type of EPR policy in place: the scenario in which no firm adopts a TBP is equivalent to that with full adoption under pure disposal fees or recycling subsidies; it is also likely to emerge as the best scenario under take-back requirements. The budgetary costs of policy makers' EPR initiatives – in total and per-unit recycled – either do not depend on the uptake of TBPs (for pure disposal fees) or are minimized when no firm introduces such a program (for take-back requirements and recycling subsidies). When analyzing the welfare performance of the different EPR policies we focus on the scenario in which all firms adopt a TBP. This is the only scenario characterized by a strictly positive uptake of TBPs to emerge under all EPR policies considered. We find that the extent of waste reduction is independent of the EPR policy

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[8] The existence of an asymmetric equilibrium (only one of the two firms adopts a TBP) is also shown by Singh et al. (2008) via a numerical analysis. The authors study a two-period Hotelling duopoly in which firms may introduce a loyalty program that rewards consumers for a repeat purchase (the reward is a percentage discount on the second-period market price).

design,[9] but may be influenced by other instruments like those aimed at increasing consumers' recycling incentives or the uptake of TBPs. To conclude, our analysis identifies trade-offs that policy makers may face when designing their EPR initiatives: take-back requirements maximize consumer welfare, but minimize producer welfare; pure disposal fees are the least costly initiative and maximize producer welfare, but yield the highest prices and may further minimize firms' incentives for introducing TBPs.

In an extension, we briefly discuss the implications of a *collection intermediary* on market and welfare outcomes. Our analysis focuses on the case in which both firms introduce a TBP. We show that the presence of an intermediary increases the extent of waste reduction but may also raise the total costs of policy makers' EPR initiatives. The effect on consumer and producer welfare is ambiguous.

Our paper is structured as follows. In Section 2 we outline the modeling framework. Next, in Section 3 and 4, we respectively focus on the analysis of the second and first period and derive their market outcomes. Section 5 derives the conditions under which firms introduce TBPs and discusses their welfare consequences. In Section 6 we study the potential of EPR policies, and other initiatives, to stimulate the uptake of TBPs and clarify their impact on welfare outcomes. In Section 7 we briefly discuss the implications of an intermediary for market and welfare outcomes. Section 8 concludes.

2 The model

We develop our analysis using a two-period Hotelling duopoly with heterogeneous consumers and an active policy maker. In particular, the policy maker, in the beginning of the first period, introduces an Extended Producer Responsibility (EPR) policy. Firms observe the policy and decide whether or not to introduce a take-back program (TBP) in the second period. In making this decision, firms trade off the costs of TBPs (reward to each second-period customer who drops off a first-period purchase at a collection point) and their benefits (additional revenues from the resale/reuse of collected products, and, potentially, compliance with the EPR policy).

We now look at the building blocks of the model – consumers, firms, EPR policy – in more detail.

Consumers. Consumers are uniformly distributed over a unitary Hotelling line, with two firms located at its respective ends. The location, or preference, of a consumer, is denoted by x. In each period, consumers purchase one unit from either of the two firms and have a willingness to pay of v. We assume that v is sufficiently large such that the market is covered. Consumers have *transportation costs* of 1 and therefore total costs of x (resp. of $1 - x$) when buying from the firm that is located at 0 (resp. at 1).

Consumers are not only characterized by their preferences over product characteristics (as captured by their position on the Hotelling line) but also by their environmental preferences. In particular, consumers in our model associate recycling with important mental and physical efforts. Depending on their inclination for an environmentally-friendly behavior, consumers give different importance to these efforts. In other words, consumers are heterogeneous in their disutility of

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[9] This result is likely linked to our choice of modeling framework (fixed total demand in the Hotelling model) and may not be generalizable to alternative settings.

recycling θ, with $\theta \sim U[0,1]$. Low values of θ imply that recycling efforts are perceived as relatively less important, and therefore reflect a high level of environmental consciousness (and vice versa). As a consequence, for a given reward, consumers with strong environmental preferences (i.e., with low θ) are more likely to participate in a TBP.[10]

Firms. As mentioned above, there are two firms, $i \in \{A, B\}$, that are located at the ends of a unitary Hotelling line. Without loss of generality, we assume that firm A is located at zero and firm B at one. Firms compete in two periods by setting prices. Prices are denoted by p_{it} where i is the firm- and t the period-specific subscript. For simplicity, we assume that firms have zero marginal production cost and a discount factor of one.

In the first period, firms decide whether or not to introduce a TBP in the second period. Via the TBP, firm i offers a reward r to its second-period consumers who drop off their previous, first-period, purchases at a collection point. Similar to a coupon, the reward lowers a consumer's second-period price when purchasing from the firm to $p_{i2} - r$. In this context, two elements are worth pointing out. First, receiving the reward is not conditional on being a previous customer of firm i. This distinguishes our approach from loyalty programs that reward consumers for a repeat purchase. Second, the level of the reward is taken as exogenous; we focus on a firm's choice of whether or not to implement a TBP.[11] Taken together, this implies that a firm that adopts a TBP occurs a cost of r for each of its second-period customers who participates in the TBP.

Finally, for each unit collected, firms not only incur costs in the form of the reward but also derive revenues through the resale or reuse of collected products or their components. In particular, we assume that firms realize a net benefit of λ for each unit that is collected.

Extended producer responsibility. We discuss three types of EPR policies: i) a pure disposal fee, ii) a disposal fee combined with a take-back requirement and iii) a disposal fee combined with a recycling subsidy. As will become clear in the following, the policy designs differ in the costs they impose on firms in the second period.

Under a pure disposal fee, firms pay in the second period a disposal fee ϕ on the total of their first-period production $\hat{x}_{i1}$. The EPR policy consequently inflicts second-period costs of $\phi \hat{x}_{i1}$ on firms.

In the case of take-back requirements, firms are obliged to collect a certain share of their first-period production and pay a disposal fee on all units that fall short of the required quota.[12,13] To facilitate the analysis, we set the take-back target to 1, i.e., to 100% of a firm's first-period production.[14] In the second period, firms therefore pay the disposal fee ϕ only on the share of their first-period production that is not collected in the second period, i.e., on $\hat{x}_{i1}(1 - \hat{x}^{\theta}_{i2})$ (where

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[10] Note that θ is independent of the product that is recycled (products are equivalent in terms of their environmental attributes).

[11] This choice is primarily motivated by the complexity of our framework; for instance, depending on the type of EPR policy, firms' profit functions may be fourth-degree equations in r.

[12] Practical examples of such take-back targets are, for instance, the e-waste laws in several US states where producers are required to recover a certain share of their previous-year sales; on all units that fall short of this quota, producers have to pay a disposal fee, typically ranging between \$0.30 and \$0.50 per pound (see Nash and Bosso (2013) or Özdemir et al. (2012)).

[13] A collection target complemented by a tax on the fraction of non-collected waste is also analyzed in Dubois (2012). The policy design is shown to achieve the first-best outcome in a decentralized market.

[14] Setting a target lower than 100% is equivalent to decreasing the unitary disposal fee ϕ and does not add new insights to our analysis.

$\hat{x}_{i2}^{\theta}$ represents total units collected by firm i in the second period).[15] Total second-period costs related to the EPR policy consequently are $\phi \hat{x}_{i1}(1 - \hat{x}_{i2}^{\theta})$: a disposal fee on the total of a firm's first-period production, $\phi \hat{x}_{i1}$, less a tax-reduction/subsidy on all units of $\hat{x}_{i1}$ that are collected in the second-period, up to the take-back target, $\phi \hat{x}_{i1} \hat{x}_{i2}^{\theta}$.

Finally, in the case of recycling subsidies, firms pay the disposal fee ϕ on the total of their first-period production $\hat{x}_{i1}$ and receive a subsidy ϕ for each unit that is recycled $\hat{x}_{i2}^{\theta}$.[16] This type of EPR policy thus imposes second-period costs of $\phi(\hat{x}_{i1} - \hat{x}_{i2}^{\theta})$ on firms.

To summarize, the EPR policy implies second-period costs of

$$\phi \hat{x}_{i1} - \phi \beta \hat{x}_{i2}^{\theta} \tag{1}$$

for firms where $\beta \in \{0, \hat{x}_{i1}, 1\}$, depending on whether the policy maker introduces a pure disposal fee ($\beta = 0$) or combines the latter with a take-back requirement ($\beta = \hat{x}_{i1}$) or a recycling subsidy ($\beta = 1$).

It follows that a firm's first- and second-period profits, π_{i1} and π_{i2}, are given by

$$\begin{aligned} \pi_{i1} &= \underbrace{p_{i1}\hat{x}_{i1}}_{\text{revenues}}, \\ \pi_{i2} &= \underbrace{p_{i2}\hat{x}_{i2}}_{\text{revenues}} - \underbrace{\phi(\hat{x}_{i1} - \beta \hat{x}_{i2}^{\theta})}_{\text{EPR policy}} + \underbrace{\lambda \hat{x}_{i2}^{\theta}}_{\text{collection benefits}} - \underbrace{r \hat{x}_{i2}^{\theta}}_{\text{costs TBP}}, \\ &= \underbrace{p_{i2}\hat{x}_{i2}}_{\text{revenues}} - \underbrace{\left[\phi \hat{x}_{i1} - (\phi\beta + \lambda - r)\hat{x}_{i2}^{\theta}\right]}_{\text{total costs}}, \end{aligned} \tag{2}$$

with $\beta \in \{0, \hat{x}_{i1}, 1\}$.

Timing. In the first period, the policy maker announces the EPR policy. Firms observe β and ϕ and decide whether or not to introduce a TBP in the second period, i.e., whether or not to offer a reward r to each of their second-period customers who drops off a first-period purchase. Firms then set their first-period prices p_{i1}. Consumers observe p_{i1} and take their purchasing decisions. In the second period, firms set second-period prices p_{i2}. Next, consumers, based on p_{i2}, r and θ take their recycling and purchasing decision.

Parameter restrictions. Throughout our analysis we adopt the following parameter restrictions:

$$\phi \in [0,1], \; r \in [0,1], \; \lambda \in [0,1). \tag{3}$$

The first constraint, $\phi \in [0,1]$, ensures that firms realize non-negative profits if they both do not introduce a TBP (benchmark case). Under the second constraint, $r \in [0,1]$, the share of consumers that finds participating in a firm's TBP worthwhile is allowed to vary with the size of the reward (for $r > 1$ all consumers recycle, irrespective of the size of the reward). Finally, $\lambda \in [0,1)$ guarantees that prices and market shares are well-behaved (i.e., non-negative and between zero and one).[17]

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[15] In our framework (Hotelling model) products are identical across firms; it is hence impossible to distinguish collected items on the basis of their brand. It follows that the total units which firm i collects of its own first-period production are $\hat{x}_{i1}\hat{x}_{i2}^{\theta}$: total units collected by firm i, $\hat{x}_{i2}^{\theta}$, multiplied by its first-period market share, $\hat{x}_{i1}$.

[16] Most articles in the related literature show that this policy design is welfare-maximizing (see, for instance, Calcott and Walls (2005), Fullerton and Wolverton (1999) or Palmer and Walls (1997)).

[17] Prices and market shares are well-behaved, irrespective of the type of EPR policy design, whenever $\lambda < r + 1/r - \phi$.

In the following, we proceed by backward induction and analyze the second and first period of the model (respectively Section 3 and Section 4). We do this for three cases: a benchmark case in which neither of the firms introduces a TBP, an asymmetric case in which one of the firms introduces a TBP and a symmetric case in which both firms introduce identical TBPs.

3 Analysis: Second period

In the second period, consumers face two decisions: a purchasing decision (whether to buy from A or B) and a recycling decision (whether or not to participate in a TBP). When deciding about whether or not to participate in a TBP, consumers trade off the reward r and the disutility of recycling θ. There are consequently two types of consumers, recycling and non-recycling ones (see Figure 2). Recycling consumers are characterized by sufficiently low values of θ such that they derive a net benefit from recycling, i.e., by $\theta < \hat{\theta} = r$. Non-recycling consumers, in contrast, have $\theta \geq \hat{\theta}$ and thus do not participate in the TBP. As a corollary, in the absence of TBPs, i.e., for $r = 0$, no consumer finds it worthwhile to participate in a TBP (whereas all consumers participate if $r \geq 1$).

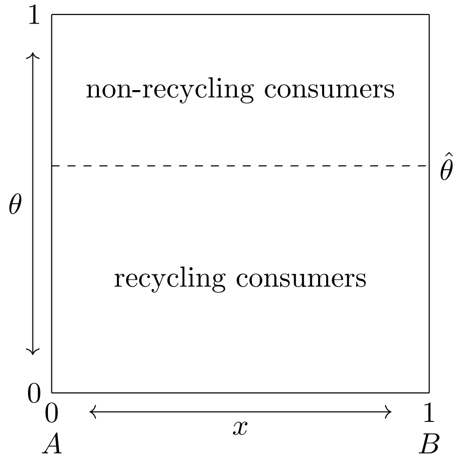

Figure 2: Consumers' recycling decisions.

It follows that a consumer who purchases from firm A (i.e., the firm located at zero) in the second period has the following utility, depending on their recycling decision:[18]

$$U_{A2} = \begin{cases} v - p_{A2} - x + r - \theta & \theta < \hat{\theta}, \\ v - p_{A2} - x & \theta \geq \hat{\theta}, \end{cases} \tag{4}$$

with $\hat{\theta} = r$. U_{B2} is derived by replacing p_{A2} and x with respectively p_{B2} and $1 - x$.

With these results in mind we now solve firms' optimization problems in the benchmark, asymmetric and symmetric case (Section 3.1 through Section 3.3); a comparative analysis of equilibrium

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For this expression to be satisfied $\forall \phi \in [0, 1]$ and $\forall r \in [0, 1]$, $\lambda < 1$ needs to hold.

[18] In terms of consumers' utility, our model is related to the literature that studies vertical quality differences in the context of a Hotelling model such as, among others, Brekke et al. (2006), Garella (2006) or Ma and Burgess (1993). The closest related are Ma and Burgess (1993), who clarify the interaction between firms' quality and pricing strategies in a one-period Hotelling model with linear transportation costs. A main difference to our framework is related to firms' cost functions (see footnote 19 for further details).

prices is provided in Section 3.4.

3.1 Benchmark case

In the benchmark case, none of the two firms introduces a TBP and, as a consequence, there is no recycling. It follows that firm i's market share is given by

$$\hat{x}_{i2} = \frac{1}{2} + \frac{p_{j2} - p_{i2}}{2} \tag{5}$$

where $i, j \in \{A, B\}$ and $j \neq i$.

Maximizing firm i's second-period profits, $\pi_{i2} = p_{i2}\hat{x}_{i2} - \phi\hat{x}_{i1}$, with $\hat{x}_{i2}$ given by (5) yields

$$p_{i2}^{b} = 1. \tag{6}$$

Result 1 *In the absence of TBPs, EPR policies do not affect second-period prices.*

3.2 Asymmetric case

In the asymmetric case, only one firm, say firm A, introduces a TBP and offers a reward r to each of its second-period customers who participates in the program. Consumers, based on their location on the Hotelling line and firms' prices, thus have to decide whether to purchase from firm A or B, taking into account that they can only claim a reward when purchasing from firm A. In the asymmetric case, the possibility to participate in a TBP thus directly influences consumers' second-period purchasing decisions (depending on their environmental preferences).

This also shows itself in firms' second-period market shares:

$$\begin{aligned} \hat{x}_{A2} &= \frac{1}{2} + \frac{p_{B2} - p_{A2}}{2} + \frac{\hat{\theta}(2r - \hat{\theta})}{4}, \\ \hat{x}_{B2} &= \frac{1}{2} + \frac{p_{A2} - p_{B2}}{2} - \frac{\hat{\theta}(2r - \hat{\theta})}{4}. \end{aligned} \tag{7}$$

In the asymmetric case, market shares not only depend on the price gap between the two firms but also on a second component, namely $\hat{\theta}(2r - \hat{\theta})/4$. We refer to this element as the *reward effect*. It reflects that firm A's TBP introduces a positive opportunity cost of buying from firm B for recycling consumers. These consumers derive a net benefit from participating in the TBP and therefore have stronger incentives to purchase from firm A.

In Figure 3, firms' market shares are represented graphically. Here, the shaded area corresponds to firm A's market share $\hat{x}_{A2}$. Area ① and ②+③ respectively refer to units sold to non-recycling and recycling consumers. Notice that ③ represents the part of the market that purchases from firm A only due to the TBP (i.e., to the reward effect).

Firms set their second-period prices p_{i2} to maximize their profits

$$\begin{aligned} \pi_{A2} &= p_{A2}\hat{x}_{A2} - \left[\phi\hat{x}_{A1} - (\phi\beta + \lambda - r)\hat{x}_{A2}^{\theta}\right], \\ \pi_{B2} &= p_{B2}\hat{x}_{B2} - \phi\hat{x}_{B1}, \end{aligned} \tag{8}$$

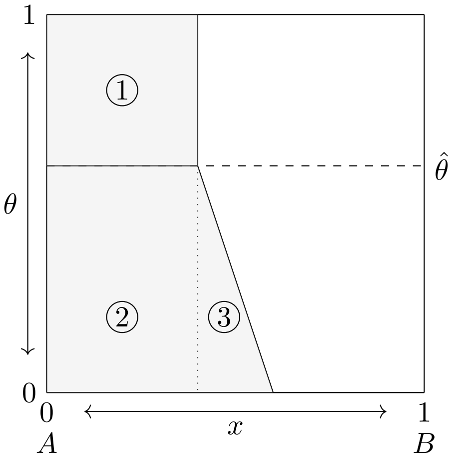

Figure 3: Firms' market shares: asymmetric case.

with $\hat{x}_{A2}$ and $\hat{x}_{B2}$ given by (7) and $\hat{x}^{\theta}_{A2} = \hat{\theta}\big[1 + p_{B2} - p_{A2} + (2r - \hat{\theta})/2\big]/2$. From the corresponding first-order conditions we compute the best response functions as

$$\begin{aligned} p_{A2}(p_{B2}) &= \frac{1+p_{B2}}{2} + \frac{\hat{\theta}(2r-\hat{\theta})}{4} - \frac{\hat{\theta}(\phi\beta+\lambda-r)}{2}, \\ p_{B2}(p_{A2}) &= \frac{1+p_{A2}}{2} - \frac{\hat{\theta}(2r-\hat{\theta})}{4}. \end{aligned} \tag{9}$$

We observe that two components drive firms' second-period pricing decisions: the previously identified reward effect, $\hat{\theta}(2r - \hat{\theta})/4$, and a *recycling effect*, $\hat{\theta}(\phi\beta + \lambda - r)/2$.[19]

The reward effect reflects recycling consumers' opportunity costs of purchasing from firm B. It consequently provides firm A with incentives to increase its price since a part of its consumers is less price-sensitive. In contrast, it forces firm B to lower its price: for a given price of firm A, firm B has to offer a more attractive price in order to convince recycling consumers to purchase from it and by this to forego any benefits of participating in firm A's TBP.

The recycling effect derives from the previously identified net benefit of a TBP. In particular, it reflects the costs and (monetary) benefits of introducing a TBP (and thus only affects firm A directly): firm A has to pay a reward r to all of its recycling customers, but may either avoid the payment of the disposal fee ϕ on the part of its previous sales $\hat{x}_{A1}$ that is collected (take-back requirement) or receive a recycling subsidy ϕ for each unit recycled (recycling subsidy). The firm also makes some revenue λ on each of the collected units. Whenever $\phi\beta + \lambda - r > 0$, the recycling effect is positive and introducing a TBP allows firm A to reduce its costs. In this case, the TBP intensifies competition as firm A prices more aggressively.

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[19] In Ma and Burgess (1993), the reward and recycling effect correspond to the *price undercutting* and *increased marginal cost effect*. The authors show that the low quality firm tries to compensate for its quality disadvantage by reducing its price in order to gain market share (price undercutting effect). Moreover, in their model, quality investment goes hand in hand with an increase in marginal production costs. The high quality firm is thus at a disadvantage in terms of its marginal production costs and is forced to increase its price. As a corollary, the need of the low quality firm to lower its price is reduced (increased marginal cost effect). A main difference of our framework to the one in Ma and Burgess (1993) is hence that the increased marginal cost effect may be negative: a high quality firm (i.e., a TBP-firm) is not necessarily at a disadvantage in terms of its marginal production costs.

From the firms' best response functions we obtain their second-period prices

$$\begin{aligned} p^a_{A2} &= 1 - \frac{2}{3}\big(2RC - RW\big), \\ p^a_{B2} &= 1 - \frac{2}{3}\big(RC + RW\big), \end{aligned} \tag{10}$$

where $RW \equiv \hat{\theta}(2r - \hat{\theta})/4$ (reward effect) and $RC \equiv \hat{\theta}(\phi\beta + \lambda - r)/2$ (recycling effect). Note that the recycling effect decreases both prices, but more so the price of firm A (it only represents an indirect effect for firm B). The reward effect, in contrast, affects both prices by the same magnitude, although in opposite directions.

Result 2 *In the asymmetric case (only firm A implements a TBP), TBPs feature a reward and a recycling effect that influence firms' pricing strategies. The reward effect reflects the opportunity costs of recycling consumers when purchasing from firm B: everything else being equal, it allows firm A to increase its price and forces firm B to lower its price. The recycling effect reflects the costs and benefits of the TBP in terms of the reward as well as potential net benefits from collected/recycled units and EPR policy compliance: whenever it is positive, introducing a TBP allows firm A to price more aggressively (the same applies to firm B via the strategic complementarity of prices).*

3.3 Symmetric case

In the symmetric case, both firms introduce (identical) TBPs and, as a result, realize each a market share of

$$\hat{x}_{i2} = \frac{1}{2} + \frac{p_{j2} - p_{i2}}{2} \tag{11}$$

where $i, j \in \{A, B\}$ and $j \neq i$. In contrast to the asymmetric case, the reward effect is absent from firms' demand functions. The reason is that both firms introduce identical TBPs. As a result, consumers no longer face opportunity costs of purchasing from a firm without a TBP and recycle at their preferred point of purchase (determined by their horizontal preferences).

Maximizing second-period profits

$$\pi_{i2} = p_{i2}\hat{x}_{i2} - \phi\hat{x}_{i1} + (\phi\beta + \lambda - r)\hat{x}^{\theta}_{i2} \tag{12}$$

with $\hat{x}_{i2}$ given by (11) and $\hat{x}^{\theta}_{i2} = \hat{\theta}(1 + p_{j2} - p_{i2})/2$ yields

$$p^s_{i2} = 1 - \frac{2}{3}\big(2RC_i + RC_j\big) \tag{13}$$

where $RC_i = \hat{\theta}(\phi\beta + \lambda - r)/2$ and $\beta = \{0, \hat{x}_{i1}, 1\}$. Due to the absence of the reward effect, firms' pricing decisions in the symmetric case are only driven by the recycling effect which puts a downward pressure on prices.

Result 3 *In the symmetric case (both firms introduce identical TBPs), TBPs only feature a recycling effect which puts a downward pressure on second-period prices.*

3.4 Comparison of prices across different levels of TBP uptake

For the further analysis it is instructive to compare second-period prices across the different cases (benchmark, asymmetric and symmetric case).[20] We observe that whenever the recycling effect is sufficiently strong, firms with TBPs are able to undercut firms without TBPs thanks to the additional revenues from EPR compliance and/or the resale or reuse of the collected products; whenever the recycling effect is only weak, or even negative, firms without TBPs set the most competitive prices instead. This is also illustrated in Figure 4. In its top-left part, the recycling effect is very strong relative to the reward effect and firms with TPBs set the lowest prices. In its bottom part, the recycling effect is negative and firms without TBPs set the most competitive prices.

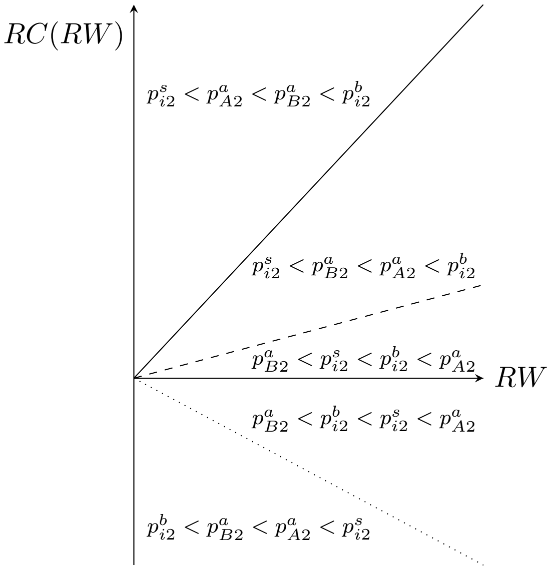

Figure 4: Comparison of prices across different levels of TBP uptake.

Lemma 1 *Firms with TBPs set the lowest second-period prices whenever the recycling effect is sufficiently strong relative to the reward effect (and vice versa).*

4 Analysis: First period

In the first period, firms set their prices to maximize total profits over the two periods. In the benchmark case, when none of the firms introduces a TBP, total profits of each firm $i \in \{A, B\}$ are

$$\pi_i = p_{i1}\hat{x}_{i1} + \frac{1}{2} - \phi\hat{x}_{i1} \tag{14}$$

with $\hat{x}_{i1} = (1 + p_{j1} - p_{i1})/2$ and $j \in \{A, B\}$, $j \neq i$. Straightforward computations yield

$$p_{i1} = 1 + \phi. \tag{15}$$

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[20] In the analysis $\hat{x}_{i1}$ is taken as given and assumed to be equal across firms (as a result, $RC_i = RC_j$ in the symmetric case). This allows us to single out the direct effects of TBPs on firms' second-period strategies, abstracting, for the moment, from any indirect effects of TBPs via firms' first-period market shares.

As to be expected in the context of a Hotelling model, firms increase their first-period prices by ϕ and pass on the disposal fee to consumers.

For $\beta \in \{0,1\}$ this result carries over to the asymmetric and symmetric case. Indeed, under these types of EPR policies, the uptake of TBPs does not affect first-period prices. The reason is that, in the given context, subsidies from policy compliance do not influence firms' first-period strategies either because firms do not receive any ($\beta = 0$) or because they are not linked to firms' first-period market shares ($\beta = 1$).

Result 4 *When the policy maker introduces a disposal fee, either on its own or in combination with a recycling subsidy, the first-period outcome is equivalent to the one in the benchmark case, irrespective of the number of firms that introduces a TBP. In particular, firms fully pass on the disposal fee to consumers by increasing their first period prices by* ϕ.

Under take-back requirements things are different. The reason is that for $\beta = \hat{x}_{i1}$ the EPR policy introduces a link between the two periods which affects firms' first-period price-setting behavior. Recall that under take-back requirements firms pay the disposal fee only on the part of their past production that is not collected. Put differently, firms pay a disposal fee on all units of their first-period production (as they do for $\beta \in \{0,1\}$), and, in addition, receive a subsidy on all units of their first-period production that are collected in the second period. That is, under take-back requirements firms receive subsidies from policy compliance (in contrast to pure disposal fees) and those subsidies depend positively on their first period production (in contrast to recycling subsidies). As a result, the anticipation of these second-period subsidies (hereafter *anticipation effect*) directly affects firms' strategic first-period behavior and provides them with incentives to lower their first-period prices relative to the benchmark case.

In particular, for $\beta = \hat{x}_{i1}$ first-period prices in the asymmetric and symmetric case are

$$\begin{aligned}
p^a_{A1} &= 1 + \phi\Big\{1 - \frac{\hat{\theta}}{3} - \frac{\hat{\theta}}{27 - \hat{\theta}^2\phi^2}\Big\{\Big[\Big(\frac{1-\hat{\theta}}{2\hat{\theta}}\Big)(36 - \hat{\theta}^2\phi^2) + 2\Big]RW + \hat{\theta}\big(\frac{\phi}{2} + \lambda - r\big)\Big\}\Big\},\\
p^a_{B1} &= 1 + \phi\Big\{1 - \frac{\hat{\theta}}{3} - \frac{\hat{\theta}}{27 - \hat{\theta}^2\phi^2}\Big\{\Big[\Big(\frac{1-\hat{\theta}}{2\hat{\theta}}\Big)(18 - \hat{\theta}^2\phi^2) - 2\Big]RW - \hat{\theta}\big(\frac{\phi}{2} + \lambda - r\big)\Big\}\Big\}, \qquad (16)\\
p^s_{i1} &= 1 + \phi\Big(1 - \frac{2\hat{\theta}}{3}\Big).
\end{aligned}$$

A comparison of p^a_{A1}, p^a_{B1} and p^s_{i1} shows that firms have stronger incentives to lower their first-period prices in the symmetric than the asymmetric case. The reason is that in the symmetric case both firms have a direct and an indirect (via the strategic complementarity of prices) incentive to lower their prices; in the asymmetric case the firm with (without) a TBP only has a direct (indirect) incentive to do so. Therefore, it always holds that $p^s_{i1} < p^a_{A1} < p^a_{B1}$.

Lemma 2 *Under take-back requirements, first-period prices are lower than in the benchmark case (anticipation effect) and further decrease in the uptake of TBPs, i.e., are minimized (maximized) in the symmetric (benchmark) case.*

5 Uptake of TBPs

In the following, we derive the conditions under which firms introduce TBPs (Section 5.1) and clarify whether their introduction is desirable from a welfare perspective (Section 5.2).

5.1 Equilibrium conditions

We assume that firms decide whether or not to introduce a TBP in the first period of the game, based on total profits across the two periods. Our analysis shows that particularly the revenue opportunities of firms' collecting and recycling activities, as well as the type and, potentially, strictness of EPR policy, play a role in explaining the uptake of TBPs. In the present section, we focus on the former driver, i.e., on firms' recycling revenues; Section 6.1 studies how policy makers may influence the introduction of TBPs via the design of their EPR policies.

Intuitively, firms find the introduction of a TBP to be worthwhile, only if collected products, or their components, yield sufficiently important revenue opportunities. In particular, none of the firms introduces a TBP when the resale or reuse of the collected items only yields small revenue opportunities, whereas both firms adopt a TBP for large benefits. For intermediate revenues, either a situation with multiple equilibria (in which the benchmark and the symmetric case apply) or an asymmetric equilibrium (in which one of the firms adopts a TBP) emerges; which of these two equilibrium situations applies depends on the type and strictness of the EPR policy as well as the size of the reward (we provide further details below).

Proposition 1 summarizes the results of the equilibrium analysis (analytical details are relegated to Section 9.2).

Proposition 1 *Depending on the revenues from the resale or reuse of collected items λ we distinguish three equilibrium situations: i) for small λ, the unique equilibrium is the benchmark case; ii) for intermediate λ, there is either a unique asymmetric equilibrium (for sufficiently strict take-back requirements and either small or large rewards) or a situation with multiple equilibria in which either the symmetric or the benchmark case emerges; iii) for large λ the unique equilibrium is the symmetric case.*

For small or large recycling benefits the result is clear-cut and intuitive: respectively none or both firms introduce a TBP. For intermediate benefits, however, either a unique asymmetric equilibrium or a situation with multiple equilibria (benchmark and symmetric case) arises. Let us now have a closer look at this parameter range for λ and clarify under which conditions these two equilibrium situations emerge.

We observe that only one firm, say firm A, introduces a TBP (meaning the asymmetric equilibrium emerges) whenever the policy maker introduces a sufficiently strict take-back requirement ($\beta = \hat{x}_{i1}$ and $\phi > \bar{\phi}(r)$) and rewards are either sufficiently small or large ($r \leq 0.1693$ or $r > 0.7578$) (see also Figure 8 in Section 9.2). The reason is that for those parameter values, firm A has strong incentives to introduce a TBP as the EPR policy is sufficiently strict[21] and the TBP either inexpensive (low r) or motivates a sufficiently large share of consumers to recycle (high r). As a consequence, only intermediate values of λ are required to encourage the firm to implement a TBP

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[21] A firm's incentives to introduce a TBP, relative to the benchmark case, not only increase in λ but also in ϕ (substituting role of λ and ϕ; see Section 9.2 in the Appendix for further details).

relative to the benchmark case. For intermediate values of λ, firm A only has a minor competitive advantage over its competitor, here, firm B. It follows that firm B is better off not introducing a TBP, thereby avoiding the tough price competition of the symmetric case.[22]

In contrast, under pure disposal fees ($\beta = 0$) or recycling subsidies ($\beta = 1$) an asymmetric equilibrium never emerges. For $\beta = 0$, firm A receives no subsidies for complying with the EPR policy and hence requires large recycling benefits to find the adoption of a TBP worthwhile. For $\beta = 1$, subsidies are very important and provide firm A with strong incentives to introduce a TBP, even for only minor recycling benefits. In both cases, firm A is, therefore, a strong competitor whenever it finds the introduction of a TBP worthwhile, making firm B better off in the symmetric case.

5.2 Welfare outcomes

It remains to clarify whether a higher uptake of TBPs is desirable from a welfare perspective. To do so, we focus on four indicators – total units collected, consumer surplus (CS), producer surplus (PS) and policy costs – and compare them across the different levels of TBP adoption, separately for the different EPR policy designs. Our analysis makes clear that from an environmental and consumer welfare perspective a higher uptake of TBPs should, most likely, be encouraged; in terms of aggregate industry profits, the result is ambiguous and depends strongly on the type of EPR policy in place (for a graphical illustration see Figure 9 and 10 in Section 9.6). The budgetary costs of policy makers' EPR initiatives – in total and per-unit recycled – are likely to be minimized when no firm introduces a TBP. Analytical details are provided in Sections 9.3, 9.4 and 9.5.

Take-back outcomes. Intuitively, the symmetric case is the best case scenario in terms of product collection: irrespective of the EPR policy in place, total units collected are maximized in the symmetric case. This result follows from two observations. First, in the benchmark case, no firm introduces a TBP and total units collected are therefore zero. Second, in the asymmetric case, consumers not only have to have incentives to recycle but also to purchase from the firm with the TBP.

Consumer Surplus. Also in terms of CS, the symmetric case is likely to emerge as the best case scenario unless the adopted TBPs feature a sufficiently negative recycling effect.

Result 5 *For $\beta \in \{0, 1\}$, the symmetric case maximizes CS except for a sufficiently negative recycling effect ($RC < -RW$). For $\beta = \hat{x}_{i1}$, the symmetric case yields a larger CS than the benchmark case whenever $RC \geq -RW - \hat{\theta}\phi/3$; for $RC \approx -RW - \hat{\theta}\phi/3$, the asymmetric case may maximize CS.*

The intuition behind this result goes along the following lines. Note first that the comparison of CS across different levels of TBP uptake primarily depends on how prices and the rewards that

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[22] In the symmetric case, both firms introduce a TPB and thus compete on equal footing, capturing a market share of 1/2 each. Competition between the firms is consequently intense, so much so that firms always realize (weakly) lower total profits than in the benchmark case. In the asymmetric case, the TBP-firm has a competitive advantage which increases in λ. Higher net benefits from collected products allow the firm to lower its price and to capture a larger share of the market. In contrast, for low values of λ, the firm only has a relatively small advantage over its competitor. In that case, not introducing a TBP in the asymmetric case (and thus avoiding the tough competition of the symmetric case) might be a more profitable strategy.

are collected by recycling consumers compare across the different cases.[23]

For $\beta \in \{0,1\}$ first-period prices are equivalent across all levels of TBP uptake; which case maximizes CS hence primarily depends on second-period prices and consumers' recycling rewards. We observe that second-period prices in the symmetric case are lower than in the benchmark case whenever the recycling effect is positive (Lemma 1). Moreover, in the symmetric case recycling consumers benefit from their collected rewards. This makes clear that for a positive recycling effect consumers are unambiguously better off in the symmetric case; whenever it is negative, the symmetric case maximizes CS if and only if the positive impact of aggregate recycling rewards outweighs the negative impact of higher second-period prices. This is the case whenever $RC \geq -RW$.

Most of this reasoning also applies for $\beta = \hat{x}_{i1}$. However, under this type of EPR policy also first-period prices play a role in explaining variations in consumer welfare across different levels of TBP uptake. In particular, due to the fact that the symmetric case always yields the lowest first-period prices, the condition for CS to be higher in the symmetric than the benchmark case is relaxed and given by $RC \geq -RW - \hat{\theta}\phi/3$. In the given context, also the asymmetric case may maximize CS. The reason is that for $\beta = \hat{x}_{i1}$ the asymmetric case may not only be superior to the benchmark case (due to recycling consumers' aggregate rewards and lower first-period prices) but also to the symmetric case (the weighted average of second-period prices is lower). This is the case for $RC \approx -RW - \hat{\theta}\phi/3$.

Producer Surplus. Which level of TBP uptake is desirable in terms of producer welfare is ambiguous and strongly depends on the type of EPR policy design, as explained in Result 6.

Result 6 *For $\beta \in \{0,1\}$, PS in the symmetric case is equivalent to the one in the benchmark case and may be dominated by PS in the asymmetric case. For $\beta = \hat{x}_{i1}$, PS in the symmetric case is always lower than in the benchmark case; the asymmetric case maximizes PS only in rare occasions.*

For $\beta \in \{0,1\}$, PS in the benchmark and symmetric case are equivalent,[24] i.e., $PS^b = PS^s = 2$, and may be dominated by PS in the asymmetric case, PS^a. Intuitively, $PS^a \geq PS^b = PS^s$ whenever either of the firms realizes a sufficiently large advantage in the asymmetric, relative to the benchmark or symmetric case. Under both EPR policies, this is the case for either sufficiently large recycling benefits or for sufficiently small recycling benefits together with large rewards.[25] Note that the strictness of the EPR policy only plays a role for $\beta = 1$. Under this policy, ϕ increases the likelihood that $PS^a \geq PS^b = PS^s$ (in particular, for $\beta = 1$ and $\phi \geq 0.675$ the asymmetric case always maximizes PS).

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[23] Also other factors such as consumers' transportation costs may vary with the uptake of TBPs and by this explain differences in CS. While we take these factors into account in our analysis (Section 9.4), we exclude them from the following discussion as they are not a main driver of our results.

[24] In the second period, firms pass on all costs (savings) from the TBP to their consumers and realize the same profits as in the benchmark case, i.e., $\pi_2^s = \pi_2^b$ (standard feature of the Hotelling model). Moreover, for $\beta \in \{0,1\}$ firms' first-period strategies are equivalent, irrespective of the uptake of TBPs (see Section 4).

[25] For sufficiently large λ, a TBP-firm enjoys a sufficiently strong competitive advantage in the asymmetric, relative to the benchmark/symmetric case: $PS^a \geq PS^b = PS^s$. For sufficiently small λ and large r, TBPs yield only a small cost advantage (if any) and thus only give a minor competitive advantage to a firm; as a corollary, the firm without a TBP is better off in the asymmetric than in the symmetric case and this goes to a sufficient extent such that $PS^a \geq PS^b = PS^s$ (in the asymmetric case, the firm without a TBP faces only a relatively weak competitor, but avoids the tough competition of the symmetric case).

For $\beta = \hat{x}_{i1}$, subsidies from complying with the EPR policy affect firms' first-period pricing strategies (i.e., the anticipation effect is present). In terms of PS, this has two important implications. First, we observe that $PS^s < PS^b$ (*prisoners' dilemma* configuration). That is, collectively, firms are better off not introducing a TBP. The reason is that the anticipation effect yields lower first-period prices in the symmetric than the benchmark case (recall that for $\beta \in \{0, 1\}$ first-period prices are equivalent). As a result, firms realize lower first-period profits than in the benchmark case, whereas their second-period profits are equivalent across both cases. Second, as for $\beta \in \{0, 1\}$, PS may be maximized in the asymmetric case. For $\beta = \hat{x}_{i1}$ this is, however, unlikely to be the case. This result is again driven by the presence of the anticipation effect, which ultimately leads to lower first-period profits in the asymmetric than the benchmark case.

Policy costs.[26] Which level of TBP uptake minimizes the budgetary costs of policy makers' EPR initiatives depends on the type of policy in place. Pure disposal fees do not offer any subsidies to firms. As a result, this type of policy does not inflict any costs on policy makers, irrespective of the uptake of TBPs. Take-back requirements or recycling subsidies instead do offer subsides for product collection. For these types of EPR initiatives, policy makers' costs – in total and per-unit recycled – are consequently minimized when none of the firms introduces a TBP, i.e., in the benchmark case.

6 Policy discussion

We now clarify how policy makers can encourage the uptake of TBPs (Section 6.1) and evaluate the welfare performance of their interventions (Section 6.2).

6.1 Incentivizing the adoption of TBPs

Policy makers can stimulate the uptake of TBPs via three main channels: i) the type of EPR policy β, ii) the strictness of the EPR policy ϕ and ii) the net benefits from recycling λ.

Let us start with the type of EPR policy, β. Among the three policy designs considered, recycling subsidies maximize firms' incentives to introduce TBPs. The reason is that under this type of EPR policy firms receive the largest subsidies for complying with the policy and further realize larger first-period profits due to the absence of the anticipation effect. Comparing take-back requirements and disposal fees, we observe that either policy may provide firms with greater adoption incentives: pure disposal fees do not feature an anticipation effect but also do not give any subsidies to firms (and vice versa for take-back requirements). Which of the two policies provides firms with greater incentives thus depends on the relative strength of both effects.

Also the strictness of the EPR policy, ϕ, plays a role in terms of firms' incentives to implement TBPs under recycling subsidies and take-back requirements; under pure disposal fees, the policy maker is unable to encourage the uptake of TBPs via the strictness of the policy. The former point follows from two observations. First, the minimal amount of recycling benefits necessary to motivate the introduction of a TBP by one firm decreases in ϕ. In the case of recycling subsidies or take-back requirements, stricter EPR policies thus make it more likely that at least one firm

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[26] In our framework policy makers also have revenues of $\phi(\hat{x}_{A1} + \hat{x}_{B1}) = \phi$. As these revenues do neither depend on the type of policy, nor on the uptake of TBPs, we focus on the costs of policy makers' interventions.

introduces a TBP (under recycling subsidies and for ϕ sufficiently large the critical threshold on λ may even be negative; in this case the introduction of an EPR policy always stimulates the uptake of TBPs by at least one firm). Second, under recycling subsidies, a similar statement applies to the minimal amount of recycling revenues necessary to encourage the uptake of TBPs by two firms (again, the critical threshold on λ may be negative for a sufficiently strict policy).

As a final point, we discuss the potential net benefits firms derive from the reuse or resale of collected units, λ. It is clear from the preceding analysis that λ has a positive impact on firms incentives to introduce TBPs. In particular, for sufficiently large parameter values, a symmetric equilibrium emerges in which both firms introduce TBPs. This raises the question of how the policy maker may influence λ. Note that the parameter may be interpreted as $\lambda = p^\theta s^\theta$ where p^θ denotes the revenue a firm receives per unit recycled and s^θ the share of collected units that is recycled. The policy maker may thus encourage the uptake of TBPs by positively influencing p^θ and/or s^θ. In our eyes, the main channel for the policy maker is s^θ which primarily depends on factors such as the quality and type of the collected items and their general recyclability (particularly if the value is in a product's components). Also the efficiency of the recycling process plays a role. It follows that policy makers may increase s^θ by introducing policies that aim at encouraging firms to design their products with their later recyclability in mind (*design for the environment*) and/or to invest in recycling processes and technology.

6.2 Welfare outcomes

It is important to evaluate the different EPR policies not only in terms of their effectiveness (i.e., their ability to stimulate the uptake of TPBs) but also with respect to their welfare performance. We do this on the basis of four indicators – total units collected, consumer surplus, producer surplus and policy costs – and focus on the symmetric equilibrium. This choice is motivated by the fact that the symmetric equilibrium is the only type of equilibrium that may emerge under all three EPR policies and is further characterized by a strictly positive uptake of TBPs. Our analysis reveals that the extent of waste reduction is independent of the EPR policy design, but may be influenced by other instruments like those aimed at increasing consumers' recycling incentives or the uptake of TBPs. Policy makers may further face trade-offs in terms of the optimal EPR policy: take-back requirements maximize consumer welfare, but minimize producer welfare; pure disposal fees are the least costly EPR initiatives and maximize producer welfare, but yield the highest prices and may further minimize firms' incentives for introducing TBPs. Analytical details are provided in Sections 9.3, 9.4 and 9.5.

Take-back outcomes. Total units collected in the symmetric case only depend on consumers' recycling incentives, i.e., on $\hat{\theta} = r$, and are independent of the type or strictness of the EPR policy.[27] For the policy maker, the main channels for increasing take-back outcomes are thus i) increasing consumers' recycling incentives (e.g., via information-based instruments that either reduce the private costs of recycling, θ, or increase its benefits for consumers (*warm glow*)) or ii) encouraging the adoption of TBPs so that the symmetric case emerges as equilibrium (see the discussion in the previous section).

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[27] Note that this result is likely to be driven by our choice of modeling framework (fixed total demand in the Hotelling model) and may not extend to alternative settings.

Consumer Surplus. From a consumer welfare perspective, take-back requirements are optimal. To see this, note that there are generally two reasons for why CS may vary with the type of EPR policy: policy-dependent differences in aggregate rewards to consumers and/or prices. Given the symmetric case, consumers receive the same aggregate rewards, irrespective of the policy design. Variations in CS across different EPR policies are therefore entirely driven by policy-dependent price differences.

In the first period, take-back requirements, due to their anticipation effect, yield the lowest prices and by this the highest CS ($p^s_{i1} = 1 + \phi$ for $\beta \in \{0, 1\}$ vs $p^s_{i1} = 1 + \phi(1 - \frac{2\hat{\theta}}{3})$ for $\beta = \hat{x}_{i1}$). In the second period, take-back requirements continue to be superior to pure disposal fees but are dominated by recycling subsidies which feature the strongest recycling effect ($p^s_{i2} = 1 - \hat{\theta}(\lambda - r)$ for $\beta = 0$, $p^s_{i2} = 1 - \hat{\theta}(\frac{\phi}{2} + \lambda - r)$ for $\beta = \hat{x}_{i1}$, $p^s_{i2} = 1 - \hat{\theta}(\phi + \lambda - r)$ for $\beta = 1$). Nevertheless, taken together, take-back requirements yield the lowest aggregate prices across the two periods and thus maximize CS.

Producer Surplus. In terms of producer surplus, either pure disposal fees or recycling subsidies are optimal. This follows from two observations: first, in the symmetric case firms realize equivalent second-period profits irrespective of the EPR policy design ($\pi^s_{i2} = \frac{1}{2}(1 - \phi)\ \forall \beta$); second, firms' first-period profits are minimized for $\beta = \hat{x}_{i1}$ due to the presence of the anticipation effect ($\pi^s_{i1} = \frac{1}{2}(1 - \phi)$ for $\beta \in \{0, 1\}$ vs $\pi^s_{i1} = \frac{1}{2}\big[1 + \phi(1 - \frac{2\hat{\theta}}{3})\big]$ for $\beta = \hat{x}_{i1}$). It is then immediate that pure disposal fees and recycling subsidies maximize aggregate producer surplus across periods.

Policy costs. Not surprisingly, the budgetary costs of policy makers' EPR initiatives are the lowest under pure disposal fees. This type of policy does not offer any subsidies to firms and therefore does not inflict any costs on policy makers. This result not only applies in terms of policy makers' aggregate costs but extends to costs per-unit recycled (in particular, depending on the type of EPR policy design, costs per-unit recycled are zero (for $\beta = 0$), $\phi/2$ (for $\beta = \hat{x}_{i1}$) or ϕ (for $\beta = 1$)). This implies that unless policy makers factor in other components in their decision process, pure disposal fees are their optimal choice. While this type of policy is the best choice in terms of producer welfare, it also yields the highest prices and may minimize firms' incentives for introducing TBPs.

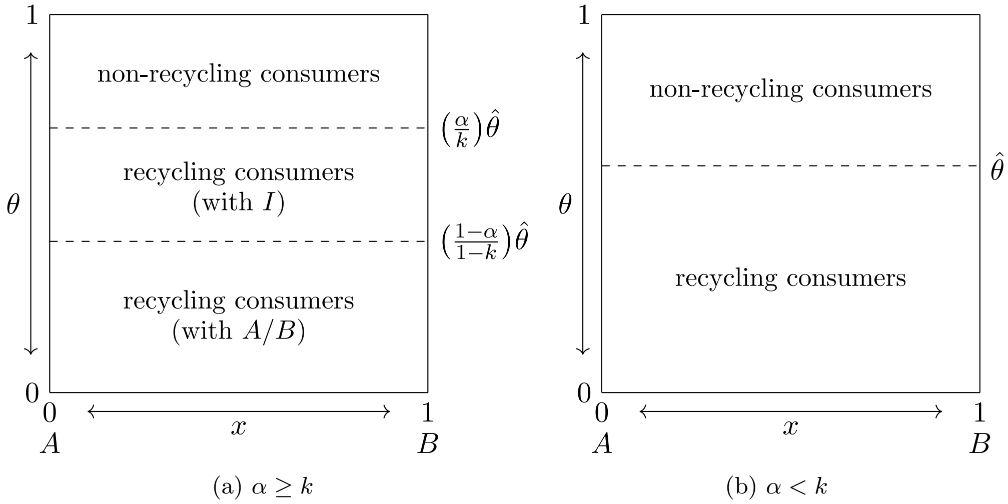
7 An intermediary

Assume that there is an intermediary, I, who collects consumers' first-period purchases and recycles the collected products with a TBP-firm. Note that in order to benefit from acting as an intermediary, I has to be a consumer (in our setting, rewards are modeled as a coupon/voucher, i.e., they reduce the price of a second-period purchase with a TBP-firm).

When recycling with I, consumers receive a reward of αr with $\alpha \in [0, 1]$, the remaining $(1 - \alpha)r$ go to I. We further assume recycling with I to be more convenient than participating in a TBP. This may be due to the fact that there is more or better information on I's collection program. Moreover, I might offer more collection/drop-off points or at more convenient locations. In particular, consumers face a disutility of $k\theta$ with $k \in [0, 1]$ when recycling with I.

It is clear that consumers now have three recycling options: recycling with I (payoff: $\alpha r - k\theta$), recycling with a firm (payoff: $r - \theta$) or no recycling (payoff: 0). Comparing these payoffs it follows that for $\alpha \geq k$ consumers with $\theta \in \big(0, (\frac{1-\alpha}{1-k})r\big]$ recycle with a firm, consumers with

$\theta \in \big((\frac{1-\alpha}{1-k})r, (\frac{\alpha}{k})r\big]$ recycle with I and consumers with $\theta \in \big((\frac{\alpha}{k})r, 1\big]$ do not recycle. For $\alpha < k$ consumers only recycle with a firm. Figure 8 represents consumers' recycling decisions graphically (for comparability with our main modeling framework, all relevant thresholds are expressed in terms of $\hat{\theta} = r$).



(a) $\alpha \geq k$

(b) $\alpha < k$

Figure 5: Consumers' recycling decisions in the presence of an intermediary.

In the following, we discuss the implications of an intermediary for market and welfare outcomes. For simplicity, our analysis focuses on the symmetric case in which both firms adopt identical TBPs.

As we mention before, in order to benefit from acting as an intermediary, I is required to be a consumer (rewards reduce the price of a second-period purchase from a TBP-firm). Assume that I is characterized by $(x_I, \theta_I) \in \big\{\big[0, \frac{1+p_{B2}-p_{A2}}{2}\big], \big[0, \big(\frac{1-\alpha}{1-k}\big)\hat{\theta}\big]\big\}$. That is, I has incentives to purchase from A and to participate in the firm's TBP. It follows that in the second period, I purchases one unit from A and recycles with it its own first-period purchase as well as the items it collects from consumers with $\theta \in \big(\big(\frac{1-\alpha}{1-k}\big)\hat{\theta}, \big(\frac{\alpha}{k}\big)\hat{\theta}\big]$. Note that this assumption implies that firms are unable to attract I via their pricing strategies.

A first immediate consequence of I is that less consumers recycle directly with the firms: when an intermediary is present, only consumers with $\theta \in \big[0, \big(\frac{1-\alpha}{1-k}\big)\hat{\theta}\big]$, where $\frac{1-\alpha}{1-k} \leq 1$, have incentives to participate in a firm's TBP (compared to the previous $\theta \in [0, \hat{\theta}]$). This implies that of a firm's second-period market share, $\big(\frac{1+p_{j2}-p_{i2}}{2}\big)$, a share $\big(\frac{1-\alpha}{1-k}\big)\hat{\theta}$ participates in the firm's TBP. Moreover, the firm that is selected by I collects an additional $\big[\frac{\alpha}{k} - (\frac{1-\alpha}{1-k})\big]\hat{\theta} = \big(\frac{\alpha-k}{k(1-k)}\big)\hat{\theta}$ units. This follows from the fact that one of this firm's recycling customers does not drop off one unit but an additional $\big(\frac{\alpha-k}{k(1-k)}\big)\hat{\theta}$ units. Note that these additional units do not depend on prices; irrespective of firms' first- or second-period prices, I collects the same number of units.[28]

---

[28] If I was not a consumer but, e.g., a recycling intermediary, these units would not go to a TBP-firm but directly to the recycling sector.

In the given scenario, firms consequently collect

$$\begin{aligned} \hat{x}^{\theta}_{A2} &= \Big(\frac{1-\alpha}{1-k}\Big)\hat{\theta}\Big(\frac{1+p_{B2}-p_{A2}}{2}\Big) + \Big(\frac{\alpha-k}{k(1-k)}\Big)\hat{\theta}, \\ \hat{x}^{\theta}_{B2} &= \Big(\frac{1-\alpha}{1-k}\Big)\hat{\theta}\Big(\frac{1+p_{A2}-p_{B2}}{2}\Big), \end{aligned} \tag{17}$$

units via their TBPs.

As less consumers recycle directly with the firms, the presence of I results in a weaker recycling effect[29] and for $\beta = \hat{x}_{i1}$ also in a lower anticipation effect (recall that the anticipation effect exists only for $\beta = \hat{x}_{i1}$). As a result, first-period prices (for $\beta = \hat{x}_{i1}$) and second-period prices ($\forall\beta$) increase. Market shares are unaffected and firms continue to split the market equally in both periods.

It follows that B is not impacted negatively by the presence of I (for $\beta \in \{0,1\}$) and may even benefit from it (for $\beta = \hat{x}_{i1}$).[30] In the case of A, note that the firm realizes additional profits or losses via the $\big(\frac{\alpha-k}{k(1-k)}\big)\hat{\theta}$ units that are recycled by I. These profits/losses correspond to $(\phi\beta+\lambda-r)\big(\frac{\alpha-k}{k(1-k)}\big)\hat{\theta}$ where $\beta \in \{0, \hat{x}_{i1}, 1\}$. Taken together, this implies that A may be impacted positively or negatively by the presence of I. It is then clear that also aggregate industry profits may in- or decrease relative to a scenario without an intermediary.[31]

Similar to firms, consumers may be impacted negatively or positively by the presence of I. On the one hand, consumers pay higher prices (at least in the second period). On the other hand, more consumers recycle and thus receive an extra utility of $\alpha r - k\theta \geq 0$. Moreover, those consumers who recycle with I instead of A or B enjoy, by definition, a greater net-utility compared to recycling with one of the firms (for those consumers, $\alpha r - k\theta \geq r - \theta$). Whether I has a positive or negative impact on consumer welfare thus depends on the relative strength of the two effects.

In terms of waste reduction, notice that although less consumers recycle directly with the firms, the presence of I increases the overall extent of product collection and is, therefore, desirable from an environmental perspective.

Finally, for $\beta \in \{\hat{x}_{i1}, 1\}$, policy makers' EPR initiatives are more costly in the presence of an intermediary; costs per-unit recycled are unchanged ($\forall\beta$).

Result 7 *In the symmetric case, the presence of an intermediary increases the extent of waste reduction, while raising the total costs of policy makers' EPR initiatives (for $\beta \in \{\hat{x}_{i1}, 1\}$); a priori, the effect on consumer and producer welfare is ambiguous.*

---

[29] Recall that the recycling effect (RC) derives from the units that a firm recycles. In the second period, each firm maximizes its profits, $\pi_{i2} = p_{i2}\hat{x}_{i2} + (\phi\beta+\lambda-r)\hat{x}^{\theta}_{i2}$, with respect to p_{i2}. This yields $p_{i2} = 1/2 - RC$ where $1/2$ and RC respectively derive from maximizing $p_{i2}\hat{x}_{i2}$ and $(\phi\beta+\lambda-r)\hat{x}^{\theta}_{i2}$. As we mention before, firms are unable to attract I via their pricing strategies. As a result, the additional $(\frac{\alpha-k}{k(1-k)})\hat{\theta}$ units that firm A collects via I do not depend on firms' prices and thus do not affect the recycling effect. It follows that the presence of I results in a lower recycling effect for both firms, despite the fact that firm A collects more units than its competitor.

[30] Recall that in the second period, firms pass on all costs (savings) from the TBP to their consumers and realize the same profits as in the benchmark case ($\forall\beta$). For $\beta = \hat{x}_{i1}$ first-period profits are lower due to the anticipation effect, which is reduced by the presence of I; for $\beta \in \{0,1\}$ first-period profits again correspond to the ones in the benchmark case.

[31] In particular, A benefits from the presence of I if $\phi\beta+\lambda-r \geq 0$ (for $\beta \in \{0,1\}$) or if $\phi\big(\frac{2k+3}{6}\big)+\lambda-r \geq 0$ (for $\beta = \hat{x}_{i1}$). It follows that PS is larger with an intermediary if $\phi\beta+\lambda-r \geq 0$ (for $\beta \in \{0,1\}$) or if $\phi\big(\frac{4k+3}{6}\big)+\lambda-r \geq 0$ (for $\beta = \hat{x}_{i1}$).

8 Conclusion

The successful transition to a Circular Economy depends on its adoption by all actors of society: consumers, businesses and policy makers. Consumers play a particularly important critical role. Their recycling decisions determine whether goods, at the end of their lifetime, go to landfills or are re-inserted into the production cycle. As such, they form the basis for firms' recycling and collection initiatives as well as for the effectiveness of environmental policies such as Extended Producer Responsibility (EPR). Research, however, shows that consumers associate recycling with important efforts and may require additional incentives to participate in a Circular Economy. Against this background, we study firms' incentives for supporting the transition to a Circular Economy via the choice of their business model, explicitly accounting for consumers' recycling preferences and policy makers' initiatives. In our analysis, we focus on take-back programs (TBPs). These are recycling schemes that reward consumers who drop off previously purchased items at collection points. Our research objective is two-fold: first, to clarify what factors drive the uptake of TBPs and to evaluate the desirability of such take-back schemes from a welfare perspective; second, to contrast different EPR policies (pure disposal fees, take-back requirements, recycling subsidies) in their capacity to stimulate the introduction of TBPs and to assess their welfare implications.

We find that the uptake of TBPs primarily depends on the revenue opportunities of firms' collecting and recycling activities as well as on the type and, potentially, strictness of EPR initiative. Depending on the EPR policy design, none or only one of the two firms may introduce a TBP when the resale or reuse of the collected items yields only small benefits; for sufficiently important recycling revenues, both firms adopt a take-back scheme. Recycling subsidies maximize firms' adoption incentives, as compared to pure disposal fees or take-back requirements; a stricter EPR legislation may stimulate the uptake of TBPs only for take-back requirements or recycling subsidies.

From an environmental and consumer welfare perspective a higher uptake of TPBs should be encouraged in most cases; in terms of producer welfare the result is ambiguous and depends strongly on the type of EPR policy in place. The budgetary costs of policy makers' EPR initiatives – in total and per-unit recycled – either do not depend on the uptake of TPBs (for pure disposal fees) or are minimized when no firm introduces such a program (for take-back requirements and recycling subsidies). The extent of waste reduction is independent of the policy design; nevertheless, it may be influenced by other instruments like those aimed at increasing consumers' recycling incentives or the uptake of TBPs. Policy makers further face trade-offs: take-back requirements maximize consumer welfare, but minimize producer welfare; pure disposal fees are the least costly measure and maximize producer welfare but also yield the highest prices and may minimize firms' incentives for introducing TBPs.

There are a number of potential extensions to our modeling framework. First, we consider that collected items, via their recycling, remanufacturing or reuse, have an intrinsic value for firms. As a consequence, firms may derive revenues from collected items by recovering raw materials, or other components, and then using them in their own production processes or selling them to other industry sectors. In our analysis, we take this intrinsic value as given. It would be interesting to endogenize it, for instance, by introducing firms' product design decisions (*design for the environment*) and/or explicitly modeling the recycling sector. Second, our analysis takes the size of the reward as given. As in the case of firms' recycling revenues, it would be interesting to endogenize this parameter. Finally, this paper focuses on unconditional rewards: consumers, by participating in a firm's TBP, can claim a reward, irrespective of their first-period purchasing decision. In reality, depending on the industry sector, such unconditional reward schemes co-exist with conditional ones that offer rewards only to returning customers. In our eyes, it would be interesting to study conditional rewards and compare the results to the ones obtained in this paper as well as to the literature on loyalty programs.

9 Appendix

9.1 Prices and market shares

In the benchmark case,

$$\begin{aligned} p_{i1}^b &= 1+\phi, \\ p_{i2}^b &= 1, \\ \hat{x}_{i1}^b &= \hat{x}_{i2}^b = \frac{1}{2}. \end{aligned} \tag{18}$$

In the asymmetric case,

$$\begin{aligned} p_{i1}^a &= 1+\phi && \beta\in\{0,1\}, \\ p_{A1}^a &= 1+\phi\Big\{1-\frac{\hat{\theta}}{3}-\frac{\hat{\theta}}{27-\hat{\theta}^2\phi^2}\Big\{\Big[\Big(\frac{1-\hat{\theta}}{2\hat{\theta}}\Big)(36-\hat{\theta}^2\phi^2)+2\Big]RW+\hat{\theta}(\frac{\phi}{2}+\lambda-r)\Big\}\Big\} && \beta=\hat{x}_{i1}, \\ p_{B1}^a &= 1+\phi\Big\{1-\frac{\hat{\theta}}{3}-\frac{\hat{\theta}}{27-\hat{\theta}^2\phi^2}\Big\{\Big[\Big(\frac{1-\hat{\theta}}{2\hat{\theta}}\Big)(18-\hat{\theta}^2\phi^2)-2\Big]RW-\hat{\theta}(\frac{\phi}{2}+\lambda-r)\Big\}\Big\} && \beta=\hat{x}_{i1}, \\ p_{A2}^a &= 1-\frac{2}{3}\big(2RC-RW\big), \\ p_{B2}^a &= 1-\frac{2}{3}\big(RC+RW\big), \\ \hat{x}_{i1}^a &= \frac{1}{2} && \beta\in\{0,1\}, \\ \hat{x}_{A1}^a &= 1-\hat{x}_{B1}^a=\frac{1}{2}+\frac{\hat{\theta}\phi}{2(27-\hat{\theta}^2\phi^2)}\Big\{RW\Big[9\Big(\frac{1-\hat{\theta}}{\hat{\theta}}\Big)+4\Big]+\hat{\theta}(\frac{\phi}{2}+\lambda-r)\Big\} && \beta=\hat{x}_{i1}, \\ \hat{x}_{A2}^a &= 1-\hat{x}_{B2}^a=\frac{1}{2}+\frac{1}{3}(RW+RC). \end{aligned} \tag{19}$$

In the symmetric case,

$$\begin{aligned} p_{i1}^s &= \begin{cases} 1+\phi & \beta=\{0,1\}, \\ 1+\phi\big(1-\frac{2\hat{\theta}}{3}\big) & \beta=\hat{x}_{i1}, \end{cases} \\ p_{i2}^s &= 1-\hat{\theta}(\phi\beta+\lambda-r), \\ \hat{x}_{i1}^s &= \hat{x}_{i2}^s = \frac{1}{2}. \end{aligned} \tag{20}$$

9.2 Uptake of TBPs

Firms decide whether or not to introduce a TBP in the first period of the game, based on their total profits across the two periods. Let π^b, π^a_{TBP}, π^a_N and π^s denote these profits for the benchmark, asymmetric and symmetric case. Which case emerges in equilibrium depends on two inequalities: $\pi^a_{TBP} - \pi^b$ and $\pi^a_N - \pi^s$. The Nash Equilibrium corresponds to the benchmark case whenever $\pi^b - \pi^a_{TBP} > 0$ (no firm introduces a TBP), while the symmetric case emerges for $\pi^s - \pi^a_N > 0$ (two firms introduce a TBP). When $\pi^a_{TBP} - \pi^b \geq 0$ and $\pi^a_N - \pi^s \geq 0$ hold simultaneously, an asymmetric equilibrium arises (one firm introduces a TBP).

Figure 6 illustrates $\pi^a_{TBP} - \pi^b$ and $\pi^a_N - \pi^s$ as functions of λ; Lemma 3 and Lemma 4 summarize some of their properties.

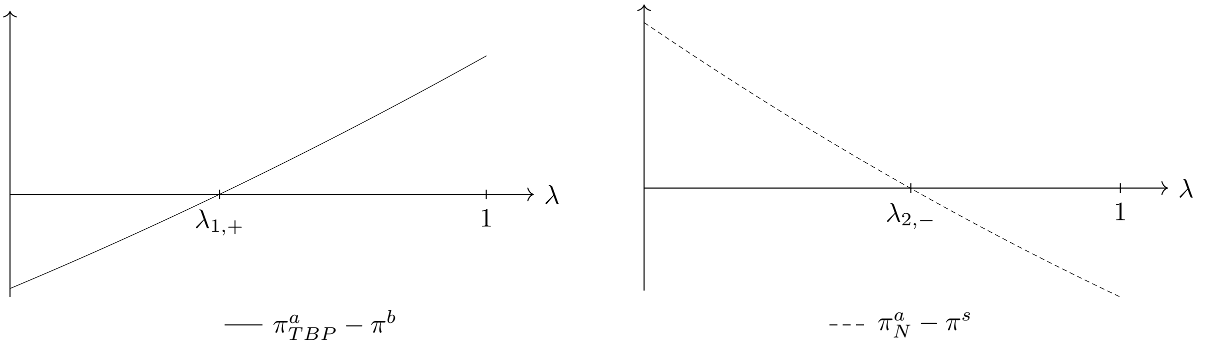


Figure 6: Graphical representation of $\pi^a_{TBP} - \pi^b$ and $\pi^a_N - \pi^s$ as a function of λ.

Lemma 3 *A firm's incentives for introducing a TBP relative to the benchmark case* ($\pi^a_{TBP} - \pi^b$) *are positive whenever recycling yields sufficiently large net benefits, that is, for any* $\lambda \in [\lambda_{1,+}, \lambda_{max})$. *Moreover, the larger these net benefits* ($\forall \beta$) *and/or the stricter the EPR policy (for* $\beta \in \{\hat{x}_{i1}, 1\}$*), the larger the incentives to adopt a TBP relative to the benchmark case.*

Proof The function $\pi^a_{TBP} - \pi^b$ is a second degree equation in λ which i) is U-shaped, ii) has two real roots (denoted by $\lambda_{1,-}$ and $\lambda_{1,+}$, with $\lambda_{1,-} < \lambda_{1,+}$) and iii) reaches its minimum at a value of λ that is strictly negative.

Note that $\pi^a_{TBP} - \pi^b \geq 0$ if and only if $\lambda \leq \lambda_{1,-}$ or $\lambda \geq \lambda_{1,+}$. We now evaluate the feasibility of these intervals given our parameter restrictions (particularly given $\lambda \in [0, \lambda_{max})$ with $\lambda_{max} = r + \frac{1}{r} - \theta$). First, we observe that $\lambda_{1,-} < 0$ so that we exclude $\lambda \leq \lambda_{1,-}$. Second, $\lambda_{1,+} \leq 0$ or $\lambda_{1,+} > 0$ depending on β, ϕ and r. For $\beta \in \{0, \hat{x}_{i1}\}$, $\lambda_{1,+} > 0$; for $\beta = 1$, $\lambda_{1,+} \leq 0$ or $\lambda_{1,+} > 0$, depending on r and ϕ. Notice also that $\lambda_{1,+} < \lambda_{max}$.

It follows that $\pi^a_{TBP} \geq \pi^b$ if and only if $\lambda \in [\max\{0, \lambda_{1,+}\}, \lambda_{max})$. $\square$

Lemma 4 *A firm's incentives for not introducing a TBP although its competitor does* ($\pi^a_N - \pi^s$) *are positive whenever recycling yields sufficiently small net benefits, that is, for any* $\lambda \in (0, \lambda_{2,-}]$. *Moreover, the larger these net benefits* ($\forall \beta$) *and/or the stricter the EPR policy (for* $\beta = 1$*; for* $\beta = \hat{x}_{i1}$ *the result is ambiguous), the higher the likelihood that both firms introduce a TBP.*

Proof Similar to the previous proof, $\pi^a_N - \pi^s$ is a second degree equation in λ which i) is U-shaped, ii) has two real roots and iii) reaches its minimum at a value of λ that is strictly positive.

Note that $\pi_N^a - \pi^s \geq 0$ if and only if $\lambda \leq \lambda_{2,-}$ or $\lambda \geq \lambda_{2,+}$. We now evaluate the feasibility of these intervals given the parameter restrictions. First, $\lambda_{2,+} > \lambda_{max}$ so that we exclude the $\lambda \geq \lambda_{2,+}$ range. Second, $\lambda_{2,-} \leq 0$ or $\lambda_{2,-} > 0$, depending on β, ϕ and r. For $\beta \in \{0, \hat{x}_{i1}\}$, $\lambda_{2,-} > 0$; for $\beta = 1$, $\lambda_{2,-} > 0$ or $\lambda_{2,-} \leq 0$. Notice also that $\lambda_{2,-} < \lambda_{max}$.

Therefore, $\pi_N^a \geq \pi^s$ if and only if $\lambda \in [0, \lambda_{2,-})$. □

From Lemma 3 and Lemma 4 it is clear that whenever $\lambda \in [0, \lambda_{1,+})$ or $\lambda > \lambda_{2,-}$ respectively none or both firms adopt a TBP in equilibrium (i.e., the benchmark or the symmetric equilibrium arise). For $\lambda \in [\lambda_{1,+}, \lambda_{2,-})$, the equilibrium is asymmetric, meaning only one of the two firms implements a TBP in equilibrium. However, the ranking of $\lambda_{1,+}$ and $\lambda_{2,-}$ is not clear cut. Depending on r and ϕ, either $\lambda_{1,+} > \lambda_{2,-}$ (Case 1) or $\lambda_{1,+} \leq \lambda_{2,-}$ (Case 2) (this is also illustrated in Figure 7).

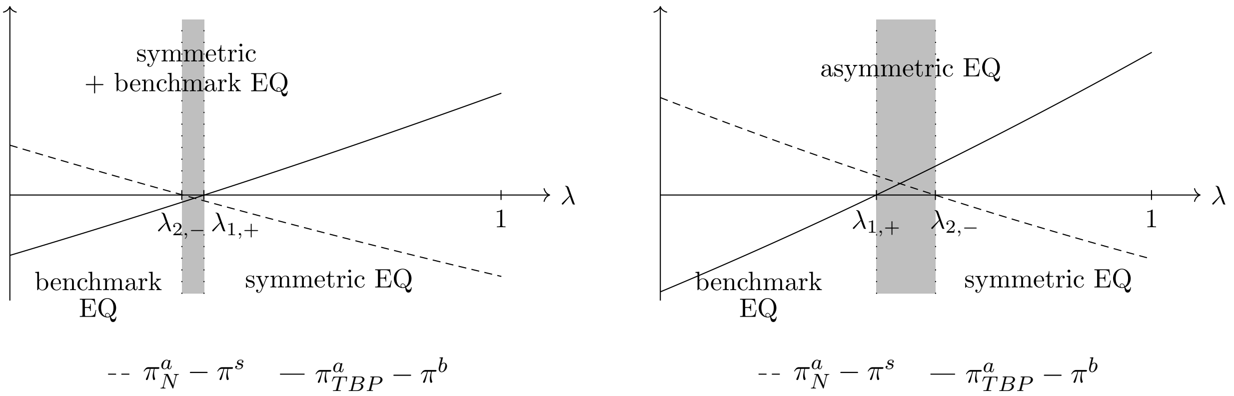


Figure 7: Equilibrium conditions: Case 1 and Case 2.

Case 1: $\lambda_{1,+} > \lambda_{2,-}$. For $\lambda_{1,+} > \lambda_{2,-}$, three equilibrium situations may arise, depending on the value of λ. For small ($\lambda < \lambda_{2,-}$) or large ($\lambda > \lambda_{1,+}$) parameter values, the benchmark case or the symmetric case emerge respectively as the unique equilibria. For intermediate parameter values ($\lambda \in [\lambda_{2,-}, \lambda_{1,+})$), both the benchmark case and the symmetric case arise as an equilibrium.

Case 2: $\lambda_{1,+} \leq \lambda_{2,-}$. For $\lambda_{1,+} \leq \lambda_{2,-}$, three equilibrium situations may arise. The benchmark case, the asymmetric case or the symmetric case represent the unique equilibria for respectively small ($\lambda < \lambda_{1,+}$), intermediate ($\lambda \in [\lambda_{1,+}, \lambda_{2,-})$) or large ($\lambda > \lambda_{2,-}$) parameter values.

For small and large λ we obtain a clear cut, and intuitive, result: either no firm or both firms introduce a TBP. We now have a closer look at intermediate values of λ, meaning at $\lambda \in [\min\{\lambda_{1,+}, \lambda_{2,-}\}, \max\{\lambda_{1,+}, \lambda_{2,-}\})$. For those parameter values either no, one or two firms introduce a TBP in equilibrium: for $\min\{\lambda_{1,+}, \lambda_{2,-}\} = \lambda_{2,-}$ a situation with multiple equilibria may arise in which either the benchmark or the symmetric case applies; for $\min\{\lambda_{1,+}, \lambda_{2,-}\} = \lambda_{1,+}$ the equilibrium may be asymmetric. Result 8 clarifies the value of $\min\{\lambda_{1,+}, \lambda_{2,-}\}$ and its relation to r and ϕ (see also Figure 8).

Result 8 *For* $\beta \in \{0, 1\}$, $\min\{\lambda_{1,+}, \lambda_{2,-}\} = \lambda_{2,-}$. *For* $\beta = \hat{x}_{i1}$, *either* $\min\{\lambda_{1,+}, \lambda_{2,-}\} = \lambda_{2,-}$ *or* $\min\{\lambda_{1,+}, \lambda_{2,-}\} = \lambda_{1,+}$*: for* $\phi \leq \bar{\phi}(r)$ *or* $\phi > \bar{\phi}(r)$ *together with* $r \in (0.1693, 0.7538]$, $\min\{\lambda_{1,+}, \lambda_{2,-}\} = \lambda_{2,-}$*; for* $\phi > \bar{\phi}(r)$ *together with* $r \leq 0.1693$ *or* $r > 0.7538$, $\min\{\lambda_{1,+}, \lambda_{2,-}\} = \lambda_{1,+}$.

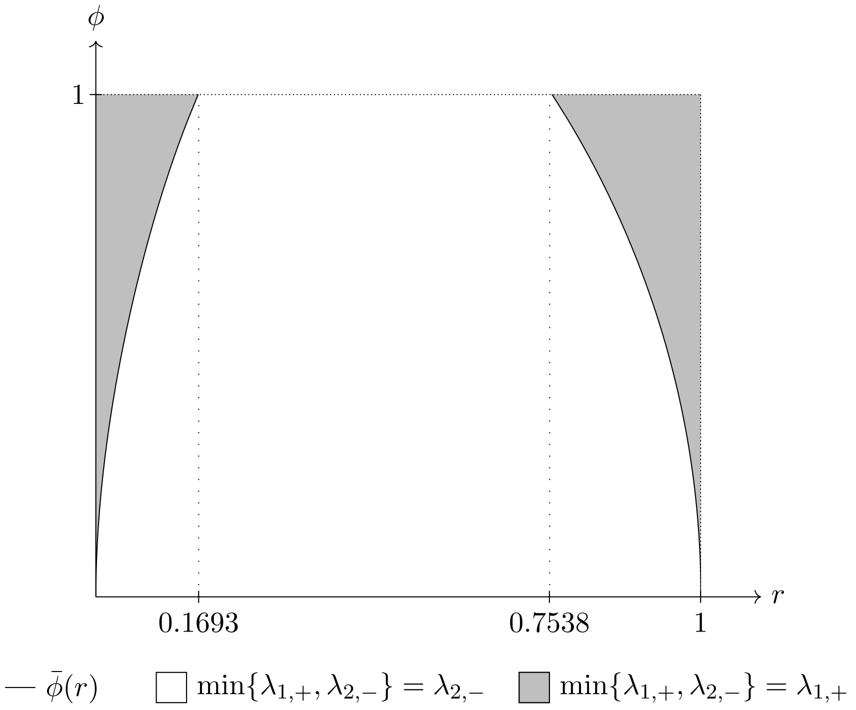


Figure 8: Ranking of $\lambda_{1,+}$ and $\lambda_{2,-}$ for $\beta = \hat{x}_{i1}$.

9.3 Take-back outcomes

Aggregate take-back outcomes ($\hat{x}^{\theta}_{tot}$) correspond to total units collected in the industry

$$\hat{x}^{\theta}_{tot} = \sum_{i \in \{A,B\}} \hat{x}^{\theta}_{i2}. \tag{21}$$

In the benchmark case,

$$\hat{x}^{\theta}_{A2} = \hat{x}^{\theta}_{B2} = 0. \tag{22}$$

In the asymmetric case,

$$\begin{aligned} \hat{x}^{\theta}_{A2} &= \hat{\theta}\Big[\frac{1}{2} + \frac{1}{3}\Big(RC + \Big(\frac{3 - 2\hat{\theta}}{\hat{\theta}}\Big)RW\Big)\Big], \\ \hat{x}^{\theta}_{B2} &= 0, \\ \hat{x}^{\theta}_{tot} &= \hat{x}^{\theta}_{A2}. \end{aligned} \tag{23}$$

In the symmetric case,

$$\begin{aligned} \hat{x}^{\theta}_{A2} &= \hat{x}^{\theta}_{B2} = \frac{\hat{\theta}}{2}, \\ \hat{x}^{\theta}_{tot} &= \hat{\theta}. \end{aligned} \tag{24}$$

9.4 Consumer surplus

Aggregate consumer surplus (CS) corresponds to consumer surplus across the two periods

$$CS = \sum_{t=1}^{2} CS_t. \tag{25}$$

Here,

$$CS_1 = \int_0^{\hat{x}_{A1}} (v - p_{A1} - x)dx + \int_{\hat{x}_{A1}}^{1} \big[v - p_{B1} - (1-x)\big]dx,$$

$$CS_2 = \begin{cases} \int_0^{\hat{x}_{A2}} (v - p_{A2} - x)dx + \int_{\hat{x}_{A2}}^{1} \big[v - p_{B2} - (1-x)\big]dx & (b), \\ \int_0^{\hat{x}_{A2}} \big[v - p_{A2} - x + \int_0^{\hat{\theta}} (r-\theta)d\theta\big]dx + \int_{\hat{x}_{A2}}^{1} \big[v - p_{B2} - (1-x)\big]dx & (a), \\ \int_0^{\hat{x}_{A2}} \big[v - p_{A2} - x + \int_0^{\hat{\theta}} (r-\theta)d\theta\big]dx + \int_{\hat{x}_{A2}}^{1} \big[v - p_{B2} - (1-x) + \int_0^{\hat{\theta}} (r-\theta)d\theta\big]dx & (s), \end{cases} \tag{26}$$

where (b) benchmark case, (a) asymmetric case, (s) symmetric case.

In the benchmark case,

$$\begin{aligned} CS_1^b &= v - (1+\phi) - \frac{1}{4}, \\ CS_2^b &= v - 1 - \frac{1}{4}, \\ CS^b &= 2v - (1+\phi) - \frac{1}{2}. \end{aligned} \tag{27}$$

In the asymmetric case,

$$\begin{aligned} CS_1^a &= v - \sum_{i\in\{A,B\}} \hat{x}_{i1}^a p_{i1}^a - \sum_{i\in\{A,B\}} \hat{x}_{i1}^a \Big(\frac{\hat{x}_{i1}^a}{2}\Big), \\ CS_2^a &= v - \sum_{i\in\{A,B\}} \hat{x}_{i2}^a p_{i2}^a - \sum_{i\in\{A,B\}} \hat{x}_{i2}^a \Big(\frac{\hat{x}_{i2}^a}{2}\Big) + \hat{x}_{A2}^a \hat{\theta}\Big(r - \frac{\hat{\theta}}{2}\Big), \\ CS^a &= 2v - \sum_{t=1}^{2} \sum_{i\in\{A,B\}} \hat{x}_{it}^a p_{it}^a - \sum_{t=1}^{2} \sum_{i\in\{A,B\}} \hat{x}_{it}^a \Big(\frac{\hat{x}_{it}^a}{2}\Big) + \hat{x}_{A2}^a \hat{\theta}\Big(r - \frac{\hat{\theta}}{2}\Big), \end{aligned} \tag{28}$$

with p_{it}^a and $\hat{x}_{it}^a$ given in Section 9.1.

In the symmetric case,

$$
\begin{aligned}
CS_1^s &= \begin{cases} v-(1+\phi)-\frac{1}{4} & \beta\in\{0,1\}, \\ v-\big[1+\phi(1-\frac{2\hat{\theta}}{3})\big]-\frac{1}{4} & \beta=\hat{x}_{i1}, \end{cases} \\
CS_2^s &= v-\big[1-\hat{\theta}(\theta\beta+\lambda-r)\big]-\frac{1}{4}+\hat{\theta}\Big(r-\frac{\hat{\theta}}{2}\Big), \\
CS^s &= \begin{cases} 2v-[2+\phi-\hat{\theta}(\lambda-r)]-\frac{1}{2}+\hat{\theta}\big(r-\frac{\hat{\theta}}{2}\big) & \beta=0, \\ 2v-[2+\phi-\hat{\theta}(\frac{7}{6}\phi+\lambda-r)]-\frac{1}{2}+\hat{\theta}\big(r-\frac{\hat{\theta}}{2}\big) & \beta=\hat{x}_{i1}, \\ 2v-[2+\phi-\hat{\theta}(\phi+\lambda-r)]-\frac{1}{2}+\hat{\theta}\big(r-\frac{\hat{\theta}}{2}\big) & \beta=1. \end{cases}
\end{aligned} \tag{29}
$$

9.5 Producer surplus

Aggregate producer surplus (PS) corresponds to industry profits across the two periods

$$
PS=\sum_{t=1}^{2}\sum_{i\in\{A,B\}}\pi_{it}. \tag{30}
$$

In the benchmark case,

$$
\begin{aligned}
\pi_{i1}^b &= \frac{1+\phi}{2}, \\
\pi_{i2}^b &= \frac{1-\phi}{2}, \\
PS^b &= 2.
\end{aligned} \tag{31}
$$

In the asymmetric case,

$$
\begin{aligned}
\pi_{i1}^a &= \begin{cases} \frac{1+\phi}{2} & \beta\in\{0,1\}, \\ p_{i1}^a\hat{x}_{i1}^a & \beta=\hat{x}_{i1}, \end{cases} \\
\pi_{A2}^a &= 2\Big[\frac{1}{2}+\frac{2}{3}(RW+RC)\Big]^2-\phi\hat{x}_{A1}^a+2\Big(\frac{1-\hat{\theta}}{\hat{\theta}}\Big)*RW*RC, \\
\pi_{B2}^a &= 2\Big[\frac{1}{2}-\frac{2}{3}(RW+RC)\Big]^2-\phi(1-\hat{x}_{A1}^a), \\
PS^a &= \sum_{t=1}^{2}\sum_{i\in\{A,B\}}\pi_{it}^a,
\end{aligned} \tag{32}
$$

with p_{it}^a and $\hat{x}_{it}^a$ given in Section 9.1.

In the symmetric case,

$$\begin{aligned}
\pi_{i1}^{s} &= \begin{cases} \frac{1+\phi}{2} & \beta \in \{0,1\}, \\ \\ \frac{1}{2}\big[1+\phi(1-\frac{2\hat{\theta}}{3})\big] & \beta = \hat{x}_{i1}, \end{cases} \\
\pi_{i2}^{s} &= \frac{1-\phi}{2}, \\
PS^{s} &= \begin{cases} 2 & \beta \in \{0,1\}, \\ \\ 2\big(1-\frac{\hat{\theta}\phi}{3}\big) & \beta = \hat{x}_{i1}. \end{cases}
\end{aligned} \tag{33}$$

9.6 Numerical simulations

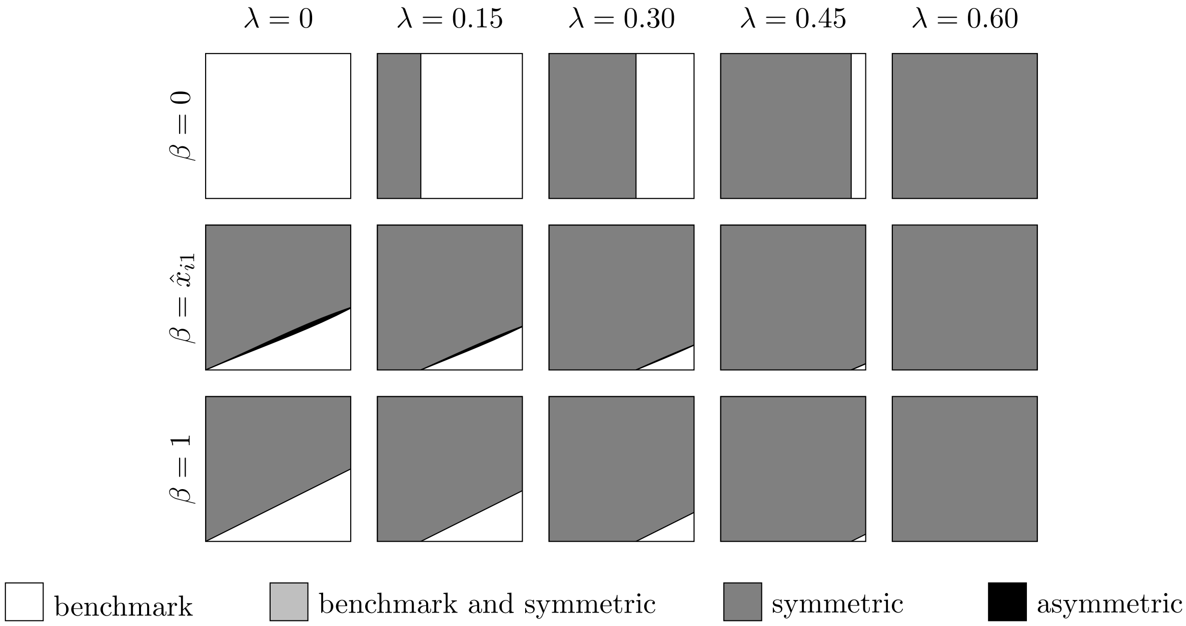


Figure 9: CS maximizing level of TBP uptake (horizontal/vertical axis: $\phi \in [0,1]/r \in [0,1]$).

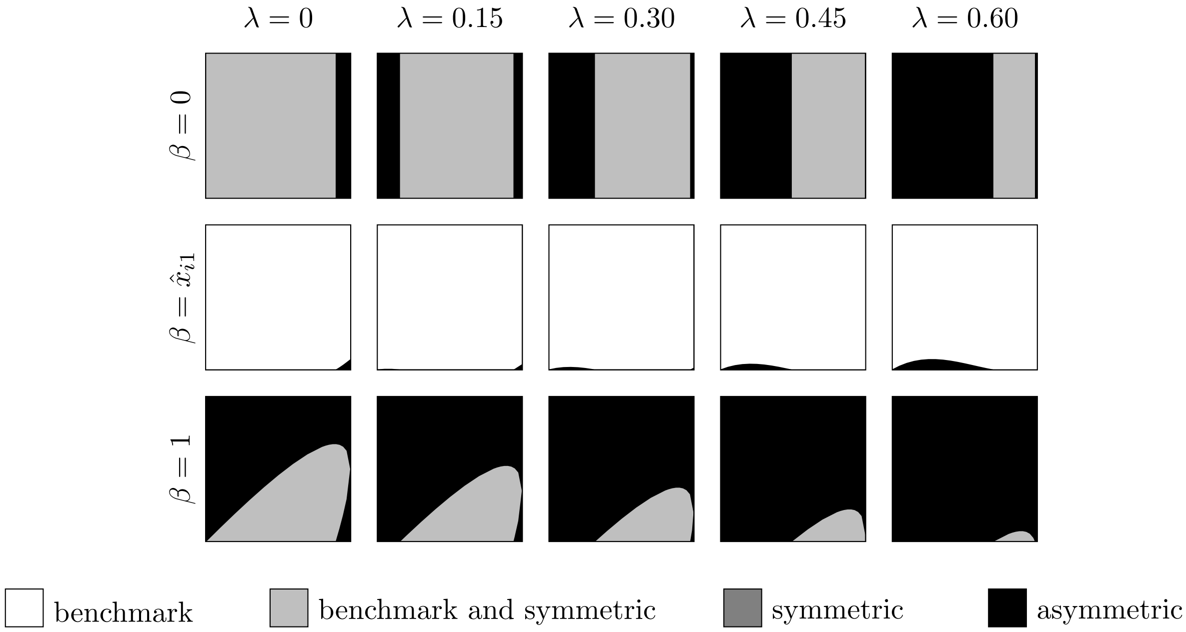


Figure 10: PS maximizing level of TBP uptake (horizontal/vertical axis: $\phi \in [0,1]/r \in [0,1]$).

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