Working Paper

2022/05/TOM

Business Model Choice under Right-to-Repair: Economic and Environmental Consequences

Ece G. Gulserliler,
INSEAD, eceguliz.gulserliler@insead.edu

Atalay Atasu
INSEAD, Atalay.atasu@insead.edu

Luk N. Van Wassenhove
INSEAD, Leena.van-wassenhove@insead.edu

Right-to-Repair (RTR) regulations require producers to design easy-to-repair products and supply necessary information and parts for consumers to independently undertake repairs. While these regulations aim to prolong product lifetimes through repairs, increase secondhand use, and reduce waste; the ease of access to proprietary information and spare parts can have unintended consequences. For example, they may facilitate cloning by third parties. The increased risk of cloning under RTR may, in turn, encourage producers to reconsider their business model choices between ownership and non-ownership models (e.g. leasing). In this paper, we analyze the effect of RTR on business model choice, and the implications for producers, consumers, and the environment. We identify the conditions under which RTR may motivate producers to retain ownership of products and bear responsibility for repairs to avoid competition from secondary markets and third-party clones. We find that RTR regulations may indeed lead to a lower environmental impact for some products. However, for a wide range of product types, these regulations may result in a “lose-lose" situation for producers and the environment, while also decreasing consumer surplus and potentially curtailing producers' incentives to innovate.

Key words: Right to Repair; Circular Economy; Leasing; Selling; Ownership; Circular Business Models

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Ece G. Gülserliler, Atalay Atasu, Luk N. Van Wassenhove
INSEAD Boulevard de Constance, 77300 Fontainebleau, France
{eceguliz.gulserliler@insead.edu, atalay.atasu@insead.edu, luk.van-wassenhove@insead.edu}

Right-to-Repair (RTR) regulations require producers to design easy-to-repair products and supply necessary information and parts for consumers to independently undertake repairs. While these regulations aim to prolong product lifetimes through repairs, increase secondhand use, and reduce waste; the ease of access to proprietary information and spare parts can have unintended consequences. For example, they may facilitate cloning by third parties. The increased risk of cloning under RTR may, in turn, encourage producers to reconsider their business model choices between ownership and non-ownership models (e.g. leasing). In this paper, we analyze the effect of RTR on business model choice, and the implications for producers, consumers, and the environment. We identify the conditions under which RTR may motivate producers to retain ownership of products and bear responsibility for repairs to avoid competition from secondary markets and third-party clones. We find that RTR regulations may indeed lead to a lower environmental impact for some products. However, for a wide range of product types, these regulations may result in a "lose-lose" situation for producers and the environment, while also decreasing consumer surplus and potentially curtailing producers' incentives to innovate.

Key words: right to repair; circular economy; leasing; selling; ownership; circular business models

1. Introduction

The Right-to-Repair (RTR) movement argues consumers should be able to repair the products they own, or use services of any independent repairer they choose (iFixit 2021). Consequently, recent regulations require producers to design easy-to-repair products, make repair information (e.g. manuals, documentation, and schematics), diagnostic tools, and spare parts available to independent repairers and consumers (The Repair Association 2020). In the EU, as of 2021, household appliances are subject to RTR laws, which are expected to be extended to mobile phones and laptop computers (European Commission 2020, Harrabin 2019). In the U.S., to date, 25 states have introduced RTR legislations for digital electronic equipment (Proctor 2021), though none have yet passed. On the federal level, President Biden has issued an order directing the Federal Trade Commission to draft regulations limiting manufacturers' ability to restrict independent repairs (Wiens 2021, Seddon and West 2021).

RTR regulations aim to prolong product lifetimes by facilitating repairs and preventing consumers from discarding products that are still valuable. While some producers oppose the RTR movement arguing it would hurt producers, consumers, and the environment (DIGITALEUROPE 2017), popular opinion is that it will be beneficial to consumers and the environment — consumers will have easier access to repair services and thus will use their products for longer, resulting in lower new production and waste, and hence lower environmental impact. For example, if the useful life of all mobile phones in the U.S. was extended by a year, estimates suggest the resulting decrease in emissions would be equivalent to taking 636,000 cars off the road (Rosa-Aquino 2020).

As a strategy to extend product lifetimes, RTR is considered a key piece of the Circular Economy (CE) paradigm (Ellen MacArthur Foundation 2016, 2018), which aims to ensure products and materials are kept in use for as long as possible, and recovered and regenerated at the end of their service life (Waste and Resources Action Programme 2021). To that aim, proponents of the CE advocate transitioning to "a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products" (European Parliament 2021, Mikolajczak 2020). They contend that a fundamental change in the transaction between producer and consumer is required to establish a CE. Instead of the traditional selling model in which ownership is transferred to the consumer, they promote non-ownership models (e.g. leasing, servicizing) in which the producer retains ownership and consumers only access and pay for use of the product (Ellen MacArthur Foundation 2013).

The notion of product ownership is also central in RTR discussions. RTR advocates argue that upon purchasing, a consumer should be the sole decision maker on the use and repair of a product — they have a *right* to repair (iFixit 2021, Wiens 2021). As stated on the iFixit website: "You bought it. You own it. Once you've paid money for a product, the manufacturer shouldn't be able to dictate how you use it — it's yours. Ownership means you should be able to open, hack, repair, upgrade, or tie bells on it" (iFixit 2021). By this argument, a producer who sells a product also sells the authority to make repair decisions, and under the proposed regulations, must also supply the necessary information and parts for consumers to independently undertake repairs. Conversely, a producer might maintain control over repairs and avoid the regulatory requirements by retaining ownership. Thus, from the producer's perspective, RTR, as an essential step towards CE, may generate a re-examination of non-ownership business models.

Another important consideration in the business model choice under RTR is intellectual property rights (IPR). RTR regulations have generated concerns amongst manufacturers over intellectual property. Some companies argue supplying repair information will give access to a product's proprietary architecture and inadvertently invite imitation by third parties (Wharton Public Policy Initiative 2019, Purdy 2019, Electronic Products Manufacturers Coalitions 2018, DIGITALEUROPE 2017). These manufacturers claim that "unauthorized repairs could infringe patents or trade secrets, expose their intellectual property to theft, and endanger consumers" (Hiltzik 2018). There are also concerns that third parties could create duplicate products out of proprietary spare parts (Grinvald and Tur-Sinai 2019, DIGITALEUROPE 2017). These concerns have some support among legal scholars as well, who note RTR may not be easily reconcilable with intellectual property rights: requiring manufacturers to release repair manuals and employing measures weakening a manufacturer's control of the market for spare parts can conflict with patent exclusivity (Grinvald and Tur-Sinai 2019). Indeed, some argue that certain countries explicitly eliminate IPR as part of their RTR laws. For example, Germany allows third parties to produce any car part used for repair without being subject to IPR limitations (Purdy 2019), and a similar act (The Promoting Automative Repair, Trade and Sales Act) was introduced in the U.S. Congress in 2017 (Grinvald and Tur-Sinai 2019). In France, if a spare part is unavailable from the producer but can be produced with 3D printing, then the producer must make the design available to third parties (French Ministry of Ecological and Inclusive Transition 2020). Producers therefore argue that RTR conflicts with IPR, and losing legal protections would jeopardize their businesses and incentives to innovate (DIGITALEUROPE 2017). They maintain that RTR regulations would lead to a surge in counterfeits, potentially also harming consumers and the environment (DIGITALEUROPE 2017, European Economic and Social Committee 2017, OECD 2007).

Bringing these factors together, in this paper we posit that these intellectual property risks, combined with the push from the CE movement towards non-ownership models, will have producers to reconsider their choice of business model under RTR. Producers can therefore see RTR as "an opportunity to revamp traditional business models" (Okie 2021) and move towards "models [which] represent new offers to customers, [such as] through leasing, device-as-a-service..." (Grice 2020). For example, at the national level, Finland is exploring municipal renting of electronic equipment as part of RTR regulations (Finnish Ministry of the Environment 2018).

Accordingly, we investigate whether and how RTR will affect a producer's perspective towards retaining ownership of their products. In this context, we focus on leasing as an example of a non-ownership model, since it is prevalent in practice and allows us to use well-established models in the literature. While it has been shown that non-ownership models such as leasing (Agrawal et al. 2012) and servicizing (Agrawal and Bellos 2017, Bellos et al. 2017, Avci et al. 2015) are not always greener or more profitable than selling, the question is more challenging under RTR due to the associated intellectual property risks. We therefore examine the impact of RTR on a producer's choice between leasing and selling, and the resulting economic and environmental implications in the context of IPR risks manifesting in the form of competition with clones.

To this end, we model the particular concept we are interested in as a game between a producer of a durable product, a (potential) competitor that can clone the producer's product, and consumers. Our model incorporates two effects of RTR regulations: it increases the availability of products in the secondary market by prolonging product lifetimes, and it inadvertently also increases the risk of cloning. Therefore, under RTR, if the producer chooses selling, she needs to share proprietary information about the product and a competitor can enter the market by cloning the producer's product. Conversely, retaining ownership of products allows the producer to protect against this risk by avoiding the release of information. We characterize the conditions under which the regulations may incentivize a producer to retain or sell ownership of products, and examine the consequences of this choice on producer profits, environmental impact, and consumer surplus.

We find that RTR may indeed achieve its objective of lower new production and higher secondhand use, and lead to lower environmental impact for some products. However, especially for products with low production cost and high secondhand availability without RTR, due to the change in business model, the environmental consequences of RTR may conflict with its goals: it may increase new production, decrease secondhand use, and exacerbate the environmental impact. We show that for a wide range of parameter values, RTR results in a "lose-lose" situation: it compromises producer profits and worsens environmental impact. We also demonstrate, contrary to common assumption, RTR does not necessarily benefit consumers, and may halt producers' incentives to innovate. Our results caution against the intuitive claims on the environmental and economic consequences of RTR, and highlight the importance of understanding the potential strategic response of producers to environmental regulations.

2. Related Literature

We study the economic and environmental consequences of RTR regulations by considering producers' potential strategic response in the form of business model change. We therefore build on the durable goods literature on a producer's business model choice. We also build on and contribute to the sustainable operations literature on the economic and environmental implications of circular business models, and environmental regulations. Since imposing RTR regulations is associated with an increased risk of cloning in the RTR context, our work is also related to the literature on the impact of clones[1] and combating strategies.

RTR regulations apply to durable products whose lifetimes can be extended through repairs. Thus, we adopt an analytical model from the durable goods literature, which examines a firm's decision on business model choice and secondary market intervention (see Waldman 2003, for a review). According to this literature, leasing, as opposed to selling, allows the firm to maintain ownership of products and limit the availability of secondhand products by discarding off-lease products. Therefore, leasing is a strategy to reduce the competition from the secondary market. A stream of papers in this literature identifies the conditions under which leasing is more profitable than selling. For example, leasing can be more profitable under different durability or disposal costs between leasing and selling (e.g., Agrawal et al. 2012, Desai and Purohit 1998), or when complementary product externalities are present (Bhaskaran and Gilbert 2005). We contribute to this literature by investigating the potential of non-ownership business models such as leasing as a strategic response to RTR regulations. In the RTR context, leasing can be a strategy to limit competition from both the secondary market and potential third-party clones, by avoiding sharing proprietary information.

[1] Different terms have been used in the literature for clones, such as copycats or counterfeits. We adopt the term "clone" throughout the paper.

A growing number of papers in the sustainable operations literature examines the economic and environmental implications of non-ownership business models, such as leasing (Lim et al. 2015, Agrawal et al. 2012), servicizing (Agrawal and Bellos 2017, Bellos et al. 2017, Avci et al. 2015), and shared-savings contract services (Corbett et al. 2005, Corbett and DeCroix 2001). See Girotra and Netessine (2013) and Agrawal et al. (2019) for reviews. One important conclusion from these papers is that non-ownership business models are not always more environmentally friendly. For example, Agrawal et al. (2012) study when leasing is both more profitable and greener than selling. They find that leasing can be harmful to the environment even if it leads to full remarketing of products, or it can be greener than selling even if a fraction of off-lease products is prematurely disposed. Similar to our work, several papers in this literature have investigated the interaction of other strategic considerations with the business model choice, such as product design (Agrawal et al. 2018), and the presence of a government subsidy (Agrawal et al. 2021). We also consider the economic and environmental implications of a business model change, however, in our context, this potential change is driven by an environmental regulation which entails intellectual property risks.

The effects of environmental regulations such as the Extended Producer Responsibility has been a popular topic in the sustainable operations literature, some examples are Alev et al. (2019), Atasu and Souza (2013), Plambeck and Wang (2009). We differ from these papers by our focus on the RTR regulations. To our knowledge, the only other paper on the RTR regulations in the operations management literature is Jin et al. (2020), which studies the impact of RTR on the producer's pricing strategy. Jin et al. (2020) find that RTR may trigger a decrease in the cost of independent repairs, but also an eventual increase in new product prices. While Jin et al. (2020) investigate the effect of RTR on pricing, we focus on intellectual property issues and analyze the business model implications. Our analysis of business model choice differentiates our paper from the previous work in the sustainable operations literature: to our knowledge, this paper is the first to study the potential impact of RTR regulations on the producer's business model choice.

Since in our context leasing is a strategy to fight clones, we also need to position our contribution relative to the literature on cloning. Most research on cloning has been descriptive. See Staake and Fleisch (2008) for a review of the frameworks based on case studies to combat clones. Grossman and Shapiro (1986) classify clones into two types: non-deceptive clones that are sold at significantly lower prices and consumers are aware upon purchase that they are not original, and deceptive clones that are often sold by the same retailers at the same price as originals. Our focus in this paper is on non-deceptive clones. Limited prior research in the operations management literature has investigated topics such as inventory management when both originals and deceptive clones are available (Liu et al. 2005), outsourcing decisions where low-cost production brings a higher risk of imitation (Sun et al. 2010), implications of clones on the price and profit of an original producer and fighting strategies (Zhang et al. 2012), the decisions of the competitor, original producer and consumers in the supply chains with clones (Cho et al. 2015). In the marketing literature, Purohit (1994) considers the impact of cloning on the innovation decisions of a durable goods producer, and finds that a manufacturer introducing a new generation product in each period and competing with clones of the previous version should increase the level of innovation to fight clones. Our work differs from this stream of papers by our focus on a regulation. Moreover, in the RTR context, maintaining ownership can be a strategy to fight clones, and we are interested in understanding the environmental as well as the economic consequences of this strategy.

3. Model

In this section, we develop a discrete-time, infinite-horizon, dynamic game to model the decisions of the producer, the (potential) competitor, and consumers. In this model, the legislator announces whether RTR regulations are imposed on the producer. The producer then chooses whether to sell or lease products. Depending on the producer's business model choice, a potential competitor may enter the market. Before formally stating the model, we begin by discussing our assumptions.

3.1. Model Assumptions

In our model, the impact of RTR is twofold: it extends product lifetimes by facilitating repairs, and it inadvertently also facilitates cloning. The RTR movement maintains that the release of repair information under RTR will make the existing repair operations by independent technicians and consumers more efficient, and products will be kept in use for longer (iFixit 2021, Ramirez and Duffy 2021). First, to capture this effect of RTR on product lifetimes, we assume that without RTR, if the producer chooses to sell, some products break down and do not get repaired by consumers due to the unavailability of necessary information and spare parts. In comparison, under RTR, all products can be repaired and resold by consumers. We reflect this in our model by assuming that in the absence of RTR regulation, only a fraction $f \in (0,1)$ of new products are available to be resold in the secondhand market. We call this fraction the secondhand availability of the product without RTR. That is, a product with a relatively large secondhand availability f already achieves a long lifetime through reuse in the market even in the absence of RTR. On the other hand, a small f indicates that a high percentage of products have to be discarded by consumers instead of being repaired and resold, and RTR can be especially beneficial in extending the lifetime of such products.

Second, we aim to understand the potential adverse effects of RTR on inadvertently facilitating cloning, and the role of leasing as a strategy to avoid it. To that aim, we assume that without RTR, the producer is a monopolist; while under RTR, a competitor enters the market by cloning the producer's product. In reality, clones can also exist in the absence of RTR. Our stylized model captures the effect of RTR on easing cloning by examining the extreme case where clones enter the market only under RTR due to the release of proprietary information. Nevertheless, the effect of RTR on facilitating cloning can also be interpreted as an increase in the quality of an existing clone. Our model allows for this interpretation.

Finally, to model the potential role of leasing as a strategy to avoid the risk of cloning, we assume that if the producer chooses leasing, she bears the cost and responsibility of repairs and does not need to share repair information. Therefore, the competitor is not able to access the proprietary information and parts to clone the product. In this case, the producer remains a monopolist who leases new and used products.

3.2. Model Description

We now formalize the model. Periods are indexed by $t \geq 0$. Subscripts l, s denote leasing and selling; n, u denote new and used products; and c stands for the clone that the competitor sells. Superscripts R and NR signify the presence and absence of the regulation, respectively.

The timeline of events is as follows: at $t = 0$, the legislator announces RTR regulations imposed on the producer. Given the regulations, the producer chooses whether to sell or lease. If the producer chooses leasing, in every subsequent period $t > 0$, she determines the quantities $q_{l,n,t}$ (quantity of *n*ew products to *l*ease) and $q_{l,u,t}$ (quantity of *u*sed products to *l*ease). Note that we do not need to differentiate between the quantities to lease under or without RTR, since the imposing of RTR regulations does not impact these quantities if the producer chooses leasing and hence avoids the entry of the competitor.

If the producer chooses selling in the absence of regulations, she remains a monopolist, and in every period $t > 0$, determines the quantity $q_{s,n,t}^{NR}$ (quantity of *n*ew products to *s*ell when the producer is *N*ot subject to *R*TR). Used products are traded in the secondhand market by consumers, and $q_{s,u,t}^{NR}$ similarly denotes the available quantity. Without RTR, only a fraction $f \in (0,1)$ of products are available in the secondhand market, i.e. $q_{s,u,t}^{NR} = f q_{s,n,t}^{NR}$.

On the other hand, if the producer chooses selling under the regulations, a competitor enters the market by cloning the producer's product. In every period $t > 0$, the producer and the competitor simultaneously choose the respective quantities $q_{s,n,t}^{R}$ (quantity of *n*ew products to *s*ell when the producer is subject to *R*TR) and $q_{c,t}^{R}$ (quantity of *c*lones to sell). Due to the imposing of RTR, all original products are available in the secondhand market to be resold, i.e. $q_{s,u,t}^{R} = f q_{s,n,t}^{R}$.

3.3. Product Characteristics

Costs. An original product lasts for two periods. A clone lasts for only one period, therefore cannot be resold in the secondhand market. It costs $c_n > 0$ to produce an original new product and $c_c \leq c_n$ to produce a clone. We normalize $c_c = 0$ for simplicity. Leasing is associated with a higher per-unit disposal cost, as in Agrawal et al. (2012)[2]. Under leasing, the producer bears an additional disposal cost per unit produced, $\gamma > 0$.

Environmental Impact. A product's per-unit environmental impact in each life-cycle phase (production, use, disposal) is found using life-cycle analysis (U.S. Environmental Protection Agency 2008). Consistent with the literature (Agrawal et al. 2018, 2012, White et al. 1999), we represent the total environmental impact of each strategy (leasing, selling without RTR, selling under RTR) by the environmental impact of each phase, multiplied by the number of products in that phase in each period. Let i_p and i_d denote the per-unit environmental impact during the *p*roduction and *d*isposal phases, respectively. Let also i_{u2} and i_{u1} denote the per-unit environmental impact during the first and second *u*se periods,

[2] There are various reasons why a producer may not prefer leasing, such as costs of repair and maintenance, consumer preferences towards leasing (Gülserliler et al. 2021, FinanCE 2016, White et al. 1999), administrative costs (Van Loon et al. 2018), and disposal costs (Agrawal et al. 2012). Here we only integrate disposal costs into the model, but explicitly modeling other reasons would yield similar results.

respectively. We allow for the used items to have higher environmental impact than new items due to depreciation: $i_{u2} \geq i_{u1}$.

Clones may differ from original products in terms of environmental impact. The production of substandard clones and the disposal of seized products can raise environmental problems (OECD 2007). We allow for this by defining i_{pc}, i_{dc}, i_{uc} for the per-unit environmental impact of a *c*lone during the *p*roduction, *d*isposal and *u*se phases, respectively. Note that clones last for only one period, therefore they do not have a second-period use impact.

3.4. Consumer Characteristics

The consumer population is normalized to 1. Consumers are heterogeneous in their valuation of the product, characterized by a finite and time-independent taste parameter $\theta \sim \text{Uniform}[0,1]$. Consumer θ's gross utility from using a *n*ew original product, a *u*sed original product, or a *c*lone are denoted respectively by $U_n(\theta)$, $U_u(\theta)$, and $U_c(\theta)$. Consumers derive zero utility from staying inactive. Ceteris paribus, all consumers prefer a new original product to a used one and a used original product to a clone, and they also prefer consuming any product to staying inactive, i.e. $U_n(\theta) \geq U_u(\theta) \geq U_c(\theta) \geq 0$. As in the literature (Agrawal et al. 2012, Desai and Purohit 1998), we adopt the following specification for the consumer utility: $U_n(\theta) = \theta$, $U_u(\theta) = \delta\theta$ and $U_c(\theta) = \delta_c\theta$, where $\delta \in (0,1)$ and $\delta_c \in (0,\delta)$ are interpreted as the relative consumer willingness to pay for the used product and the clone, respectively, compared to the new product. In this specification, δ represents the decrease in consumer willingness to pay due to performance deterioration (physical decay) of the product after a period of use. For brevity, in the rest of the paper, we refer to δ_c as the clone quality.

Let $p_{n,t}$, $p_{u,t}$ and $p_{c,t}$ denote the selling *p*rice of the *n*ew product, the market-clearing *p*rice of the *u*sed product in the secondhand market, and the selling *p*rice of the *c*lone at time t, respectively. Let also $l_{n,t}$ and $l_{u,t}$ denote the one-period *l*easing fee of a *n*ew and a *u*sed product. We assume that consumers are forward-looking and have rational expectations: without RTR, a consumer who purchases a new product anticipates that it may break down and he will only be able to repair and resell it in the secondhand market with probability f, while under RTR, he expects to be able to resell all products he purchases. We further assume that all information regarding preferences is common knowledge and that all players have a common per-period discount factor, ρ.

3.5. Solution Approach

Given a product with a two-period lifetime, we need to analyze only the consumer strategies for two periods. Consumer utility from selling a product after one period of use and buying another in the secondhand market is the same as keeping the product (See Hendel and Lizzeri (1999) pp. 1099-1100 for an explanation). Consequently, under any business model, there are at most four undominated consumer strategies: i) consume (by leasing or purchasing) new products in every period (N), ii) consume used products in every period (U), iii) (if available) purchase clones in every period (C), and iv) stay inactive (I).

Following the literature (Huang et al. 2019, Agrawal et al. 2018, 2012, Hendel and Lizzeri 1999), in the analysis, we restrict our attention to a "focal point" where all parties make the same decisions and the quantities and prices remain constant. In what follows, we omit the subscript t, i.e. $p_{n,t} \doteq p_n$, $p_{u,t} \doteq p_u$, $p_{c,t} \doteq p_c$, $l_{n,t} \doteq l_n$, $l_{u,t} \doteq l_u$ and $q_{s,n,t} \doteq q_{s,n}$, $q_{s,u,t} \doteq q_{s,u}$, $q_{c,t} \doteq q_c$, $q_{l,n,t} \doteq q_{l,n}$, $q_{l,u,t} \doteq q_{l,u}$. For simplicity and ease of exposition, we take the discount factor, $\rho = 1$. We further assume that, in each strategy, the production and (if applicable) disposal costs are low enough that production is profitable, i.e. $c_n < 1 + f\delta$ for selling without RTR, $c_n < 1 + \delta - \delta_c$ for selling under RTR, $c_n + \gamma < 1 + \delta$ for leasing.

4. Preliminaries

Before we investigate our main research questions on the business model choice under RTR and its implications, in this section, we derive the optimal decisions under each business model: selling without RTR, selling under RTR, and leasing. All proofs are given in Appendix A.

4.1. Selling without RTR

Without RTR, the producer is a monopolist and determines the volume of new products to sell in each period, $q_{s,n}^{NR}$. We solve for the steady-state equilibrium as follows (See Appendix A.1 for details). Consumers who follow strategy N buy new products every period and sell them in the secondhand market at the market-clearing price $p_u^{NR} = \frac{\delta(p_n^{NR} + f p_n^{NR} - f + f\delta)}{1 + f(2+f)\delta}$. We then solve for the inverse demand function: $p_{s,n}^{NR}(q_{s,n}^{NR}) = 1 - q_{s,n}^{NR} + f\delta - 2f\delta q_{s,n}^{NR} - f^2\delta q_{s,n}^{NR}$. Finally, the producer's profit maximization problem is: $\max_{q_{s,n}^{NR}} \Pi_s^{NR} = q_{s,n}^{NR}(p_n^{NR} - c_n)$ s.t. $q_{s,n}^{NR} \geq 0$, and $1 - (1+f)q_{s,n}^{NR} \geq 0$. The constraints ensure that the sizes of all consumer segments are non-negative.

At the steady-state, the producer chooses the profit-maximizing new product quantity $q_{s,n}^{NR*} = \frac{1 - c_n + f\delta}{2(1 + f(2+f)\delta)}$, and the optimal profits are given by $\Pi_s^{NR*} = \frac{(-c_n + 1 + f\delta)^2}{4(1 + f(2+f)\delta)}$.

We now discuss how the optimal profits depend on the secondhand availability without RTR, f. This discussion provides intuition for our results on the consequences of RTR on producer profits, in Sections 5 and 6.1. Producer profits from selling in the absence of RTR increase with f if $c_n > \frac{f(1-\delta)}{1+f}$, and decrease otherwise. An increase in the secondhand availability, f, changes profits in two ways. First, it increases the consumer valuation of new products, hence the new product price, since consumers expect to be able to sell the product in the secondhand market with a higher probability. Second, it results in a higher quantity in the secondhand market, hence a lower new quantity due to cannibalization. Thus, an increase in f boosts producer profits if the producer gains more from the increase in new product price than she is hurt by the decrease in new product quantity. This happens for products with a high production cost, i.e. $c_n > \frac{f(1-\delta)}{1+f}$. On the other hand, for products with a low production cost (i.e. $c_n \leq \frac{f(1-\delta)}{1+f}$), an increase in f decreases profits through the decrease in new production quantity. The effect of RTR on producer profits will depend on its impact on the secondhand availability, which will be further discussed in Sections 5 and 6.1.

Finally, the total steady-state, per-period environmental impact of the selling strategy without RTR is: $E_s^{NR} = (i_p + i_d + i_{u1})q_{s,n}^{NR*} + i_{u2}q_{s,u}^{NR*}$.

4.2. Selling under RTR

When the producer chooses selling under RTR, clones enter the market. The producer chooses the new quantity $q_{s,n}^R$ and the competitor chooses the clone quantity q_c^R.

In this case, consumers following strategy N buy a new product in every period at price $p_n^R(q_{s,n}^R, q_c^R)$. Consumers following strategy U buy a used period in every period at the market-clearing price $p_u^R(q_{s,n}^R, q_c^R)$. Consumers following strategy C buy a clone in every period at price $p_c^R(q_{s,n}^R, q_c^R)$. The rest of the market remains inactive. Note that in this case $q_{s,n}^R = q_{s,u}^R$ since RTR makes all products available in the secondhand market. Solving the inverse demand equations, we determine these prices as follows: $p_n^R(q_{s,n}^R, q_c^R) = -2\delta_c q_c^R - q_{s,n}^R(1+3\delta) + 1 + \delta$, $p_u^R(q_{s,n}^R, q_c^R) = -\delta_c q_c^R - 2\delta q_{s,n}^R + \delta$, and $p_c^R(q_{s,n}^R, q_c^R) = \delta_c(1 - 2q_{s,n}^R - q_c^R)$.

The competitor solves the problem $\max_{q_c^R} \Pi_c^R = p_c^R q_c^R$ subject to the constraints: $q_{s,n}^R \geq 0$, $q_{s,u}^R \geq 0$, $q_c^R \geq 0$, $1 - 2q_{s,n}^R - q_c^R \geq 0$ and $p_u^R \geq 0$. Similarly, the producer solves the problem $\max_{q_{s,n}^R} \Pi_s^R = (p_n^R - c_n)q_n^R$ subject to $q_{s,n}^R \geq 0$, $q_c^R \geq 0$, $1 - 2q_{s,n}^R - q_c^R \geq 0$ and $p_u^R \geq 0$. We solve for the Nash equilibrium (See Appendix A.2 for details).

In equilibrium, all consumer segments are positive and the optimal quantities are $q_{s,n}^{R*} = \frac{-c_n+\delta_c+1+\delta}{2(\delta_c-1-3\delta)}$ and $q_c^{R*} = \frac{-c_n-2\delta}{2(\delta_c-1-3\delta)}$. Optimal profits for the producer and the competitor are $\Pi_s^{R*} = \frac{(-c_n-\delta_c+1+\delta)^2(1+3\delta)}{4(-\delta_c+1+3\delta)^2}$ and $\Pi_c^{R*} = \frac{\delta_c(c_n+2\delta)^2}{4(-\delta_c+1+3\delta)^2}$, respectively.

The total steady-state, per-period environmental impact of the selling strategy under RTR is: $E_s^R = (i_p + i_d + i_{u1})q_{s,n}^{R*} + i_{u2}q_{s,u}^{R*} + (i_{pc} + i_{dc} + i_{uc})q_c^{R*}$

4.3. Leasing

When the producer chooses leasing, she maintains control over the quantity of used products in the market, and chooses the volume of new ($q_{l,n}$) and used ($q_{l,u}$) products to lease in each period. We solve for the steady-state equilibrium under the leasing strategy, the analysis is similar to the leasing model in Agrawal et al. (2012) (See Appendix A.3 for details). Under leasing, there are three undominated consumer strategies: lease new products in every period, lease used products in every period, or stay inactive. Solving the utility maximization problem of these consumer segments, we determine the inverse demand functions for new and used products at one-period lease fees l_n and l_u as $l_n = 1 - q_{l,n} - \delta q_{l,u}$ and $l_u = \delta(1 - q_{l,n} - q_{l,u})$. Then, the producer's profit maximization problem becomes: $\max_{q_{l,n},q_{l,u}} \Pi_l = q_{l,n}(l_n - (c_n + \gamma)) + q_{l,u}l_u$ s.t. $q_{l,u} \geq 0$, $q_{l,n} - q_{l,u} \geq 0$ and $1 - q_{l,n} - q_{l,u} \geq 0$. The constraints ensure that the sizes of all consumer segments are non-negative.

Lemma 1 **(Leasing Strategy)**. *At the steady-state, it is optimal for the producer to follow a partial remarketing strategy i.e.,* $q_{l,n}^* = \frac{1}{2}(1 + \frac{c_n+\gamma}{\delta-1}) > q_{l,u}^* = \frac{c_n+\gamma}{2(1-\delta)}$ *if and only if* $0 \leq c_n + \gamma < (1-\delta)/2$*. Otherwise, if* $1 + \delta > c_n + \gamma \geq (1-\delta)/2$*, the producer follows a full remarketing strategy:* $q_{l,n}^* = q_{l,u}^* = \frac{-c_n-\gamma+1+\delta}{2(1+3\delta)}$*).*

See Appendix A.3 for the proof.

At the steady-state, the producer always leases both new and used products. However, at low levels of production and disposal costs, as also explained in Agrawal et al. (2012), she may prefer to dispose a fraction of the off-lease products instead of leasing them for a second time. Premature disposal of off-lease products allows the producer to reduce cannibalization of new product leases, and increase demand for new products. This is only attractive to the producer if the cost of disposing a product and producing new instead is not too high, that is, at low levels of c_n and γ. Otherwise, the producer chooses to follow a full remarketing strategy and leases all products in both periods of their useful lifetime. Consequently, the firm's per-period optimal profits are given by: $\Pi_l^* = \frac{(c_n+\gamma)^2-2(c_n+\gamma)+2(c_n+\gamma)\delta-\delta+1}{4(1-\delta)}$ when partial remarketing is optimal, and $\Pi_l^* = \frac{(-c_n-\gamma+1+\delta)^2}{4(1+3\delta)}$ when full remarketing is optimal.

The total steady-state, per-period environmental impact under the leasing strategy is: $E_l = (i_p + i_d + i_{u1})q_{l,n}^* + i_{u2}q_{l,u}^*$.

5. Business Model Choice under RTR

To investigate the impact of RTR on the business model choice, in Lemma 2, we first define thresholds for the disposal cost above which selling becomes more profitable than leasing. Then, in Proposition 1, we compare these thresholds under and without RTR to determine the cases under which RTR makes leasing or selling more attractive.

Lemma 2 **(Disposal Cost Thresholds)**. *There exist thresholds $\hat{\gamma}^R, \hat{\gamma}^{NR}$ for the disposal cost such that $\Pi_l^* - \Pi_s^{i*} > 0$ if $\gamma < \hat{\gamma}^i$, where $i \in \{R, NR\}$ respectively denote the cases under and without RTR regulation.*

See Appendix B.1 for the proof.

Proposition 1 **(Business Model Choice)**. *$\exists\, \hat{\gamma}^R, \hat{\gamma}^{NR}$, such that RTR increases producer incentives to lease, i.e $\hat{\gamma}^R > \hat{\gamma}^{NR}$, if:*

1. *The production cost is low, i.e. $c_n < \frac{f(1-\delta)}{1+f}$, or*
2. *The production cost is high, i.e. $c_n > \frac{f(1-\delta)}{1+f}$, and clone quality is high enough as a function of the secondhand availability, i.e. $\delta_c > \hat{\delta}_{c,j}(f)$, where $j \in \{1, 2\}$ denote the cases where partial and full remarketing is optimal under leasing, respectively.*

See Appendix B.2 for the proof.

Proposition 1 characterizes the regions where RTR may increase producer's incentives to lease, depending on the production cost, the secondhand availability without RTR and the quality of clones. Without RTR, when making the business model choice, the producer faces a trade-off between the disposal cost that applies under leasing, and competition with used products in the secondhand market under selling. Under RTR, the trade-off is between the disposal cost (under leasing) and competition with both used products in the secondhand market and clones (under selling). RTR affects producer profits from selling by increasing the secondhand availability (effectively, all products are available in the secondhand market under RTR), and inadvertently allowing clones to enter the market. Therefore, the conditions under which RTR makes leasing more attractive are determined by the secondhand availability without RTR, f, and the clone quality, δ_c.

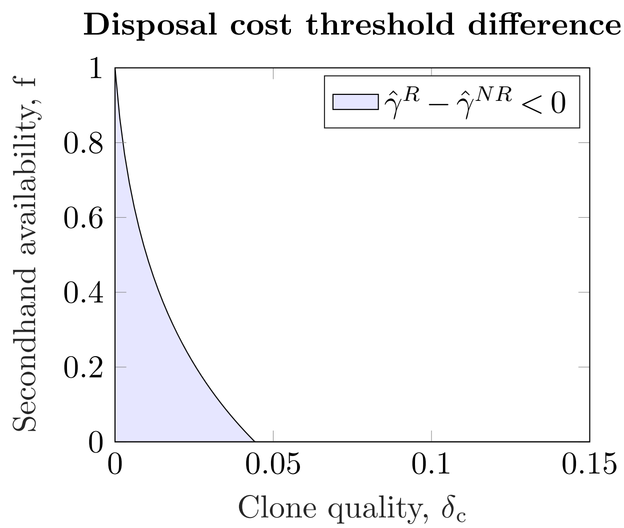


Figure 1 **The impact of RTR on business model choice, with $c_n = 0.3, \delta = 0.5$, such that full remarketing is optimal under leasing. The curve plots $\hat{\delta}_{c,2}(f)$, below which RTR makes selling more attractive (shaded region).**

For products with a low production cost (i.e. when partial remarketing is optimal under leasing), Proposition 1 establishes that RTR makes leasing more attractive. The intuition behind this result comes from how a change in secondhand availability affects producer profits from selling without RTR, as discussed in Section 4.1. For low values of production cost, the producer prefers fewer products in the secondhand market, such that she can avoid cannibalization of new product demand and sell a high volume at a low price. Hence, profits from selling without RTR decrease with secondhand availability. Note also that the intuition here is similar to that in the optimal remarketing strategy under leasing, as discussed in Section 4.3 and in Agrawal et al. (2012), where, at low values of production cost, the producer prefers a low quantity of used products in the market and partially remarkets off-lease products. Therefore, the producer who sells cheap products is hurt by the increase in secondhand quantity as a result of RTR, and prefers leasing more under RTR.

On the other hand, for products with a high production cost (i.e. when full remarketing is optimal under leasing), profits from selling increase with secondhand availability. This is because the producer gains from the increase in consumer valuation of products, and is able to sell a lower volume at a higher price. However, the producer now faces competition with a clone, and may prefer to pay the additional disposal cost under leasing to avoid competition. There exists a threshold on the clone quality as a function of the secondhand availability, above which the RTR regulations make leasing more attractive for the producer. Figure 1 plots this threshold. For a small range of parameter values (the shaded region), RTR makes selling more attractive for the producer, since in this region, the producer enjoys the raise in consumer valuation due to the increase in secondhand availability, more than she is hurt by the competition by the low quality clone.

Proposition 1 illustrates the parallel between our paper and the durable goods literature. For products with a low production cost, the producer prefers leasing to avoid the effect of RTR on increasing product availability in the secondhand market. This is the core argument for leasing in the durable goods literature – leasing is a strategy to avoid cannibalization from the secondhand market (Agrawal et al. 2012, Waldman 2003, Desai and Purohit 1998). For products with a high production cost, and a potential high quality clone, the producer prefers leasing to avoid the effect of RTR on easing cloning. That is, in our context of RTR regulations, leasing is also a strategy to avoid competition from higher quality clones.

6. Economic and Environmental Consequences of RTR

6.1. Producer Profits

Proposition 2 characterized when RTR makes selling or leasing more attractive. However, the business model choice depends on the realized level of the disposal cost (γ) and its comparison with the thresholds that the producer is willing to pay under and without RTR ($\hat{\gamma}^R$ and $\hat{\gamma}^{NR}$, as identified in Lemma 2). In Proposition 2, we characterize the effect of RTR on producer profits for a given level of disposal cost.

PROPOSITION 2 **(Producer Profits)**. 1. *RTR does not lead to a change in producer profits if* $\gamma < \min(\hat{\gamma}^{NR}, \hat{\gamma}^R)$.

2. *RTR results in higher profits for the producer if:*

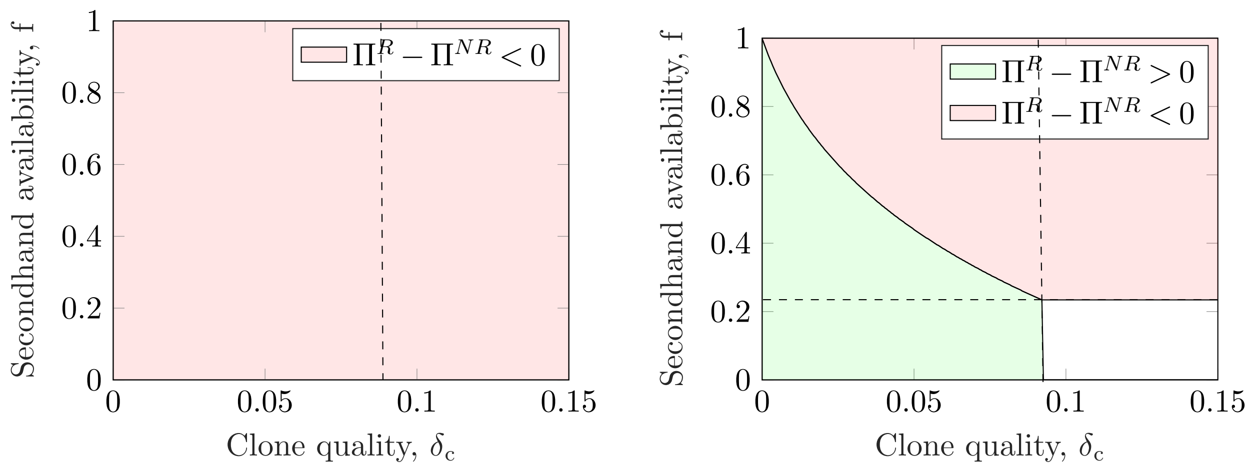
   (a) $\hat{\gamma}^{NR} > \gamma > \hat{\gamma}^R$, *or*

   (b) *If* $\gamma > \max(\hat{\gamma}^{NR}, \hat{\gamma}^R)$, *and the clone quality is lower than a threshold* $\hat{\delta}_c^p(f)$, $\delta_c < \hat{\delta}_c^p(f)$.

3. *RTR results in lower profits for the producer if:*

   (a) $\hat{\gamma}^R > \gamma > \hat{\gamma}^{NR}$, *or if*

   (b) $\gamma > \max(\hat{\gamma}^{NR}, \hat{\gamma}^R)$ *and the clone quality is higher than a threshold* $\hat{\delta}_c^p(f)$, $\delta_c > \hat{\delta}_c^p(f)$.



(a) Partial remarketing is optimal under leasing, $c_n = 0.1$. Under RTR, it is optimal to sell if $\delta_c < 0.078$ and lease otherwise. Without RTR, it is optimal to sell for all $f \in (0, 1)$.

(b) Full remarketing is optimal under leasing, $c_n = 0.3$. Under RTR, it is optimal to sell if $\delta_c < 0.094$ and lease otherwise. Without RTR, it is optimal to lease if $f < 0.235$ and sell otherwise.

Figure 2 Change in producer profits due to RTR, with $\delta = 0.5$ and $\gamma = 0.05$. The dashed lines indicate the underlying business model change.

See Appendix B.3 for the proof.

Figure 2 plots the change in producer profits due to RTR. The effect of RTR on producer profits depend on the underlying business model change, which is determined by the secondhand availability of products without RTR, the clone quality, and the production cost, as discussed in Section 5.

First, note that RTR does not impact the producer profits from leasing. Therefore, when the producer chooses to lease both under and without RTR, there is no difference in profits due to RTR. We observe this case in the empty region in the bottom right corner of Figure 2b.

RTR can increase producer profits when the producer chooses selling under RTR. This happens in two cases: either the producer switches from leasing without RTR to selling under RTR (bottom left corner of Figure 2b), or she prefers to sell both without and under RTR (upper left corner of Figure 2b). This counter-intuitive result that a regulation can increase profits very much hinges on that releasing information is not a major cost burden for the producer and it will improve the system efficiency of the repair market. But it comes with a strong qualifier as it only holds for a small range of parameter values. Specifically, this case is possible only when RTR makes selling more attractive, which, as identified in Proposition 2, only happens for products with a high production cost, when the clone quality is low enough as a function of the secondhand availability. Under these circumstances, RTR boosts profits from selling through the increase in secondhand availability f, and hence the new product price. The clone quality needs to be low enough such that the producer is not hurt too much from the competition by the clone.

On the other hand, if the clone quality is high, the competitive externalities RTR imposes render this presumed benefit on producer profits to quickly disappear, and we observe a decrease in profits due to RTR (the area above the curve in the upper left corner of Figure 2b). RTR leads to a decrease in producer profits also when it causes a switch from selling to leasing. Under high values of clone quality, to avoid the risk of cloning, the producer changes her business model to leasing. However, she is not able to fully mitigate the fall in profits, since now she has to pay the additional disposal cost per product. This case is illustrated in the right hand side of Figures 2a and 2b.

Thus, for a wide range of parameter values, RTR is not good news for the producer: it compromises profits either by inadvertently easing cloning or by driving the producer to choose leasing over selling (hence paying the associated additional cost). While RTR hurts producer profits, it is commonly believed to benefit the environment. The intuition is that RTR increases secondhand availability and reduces waste, and as our results show, it may also incentivize the producer to opt for a (potentially greener) non-ownership business model. We next discuss that this intuition does not always hold – RTR does not necessarily lower the total environmental impact.

6.2. Environmental Impact

Recall that the total environmental impact is determined by the impact in each life-cycle phase and the quantity of products in that phase. To investigate the environmental consequences of RTR, we first identify the change in new and used product quantities due to RTR in Lemma 3. We then compare the total per-period environmental impact under and without RTR in Proposition 3. For simplicity, we assume that clones have the same environmental impact in the production, disposal and first-period use phases as original products, i.e. $i_{pc} = i_p, i_{uc} = i_{u1}, i_{dc} = i_d$.

LEMMA 3 **(Product Quantities)**. 1. *If* $\gamma < \min(\hat{\gamma}^{NR}, \hat{\gamma}^{R})$*, there is no difference in product quantities due to RTR.*

2. *If $\hat{\gamma}^{NR} > \gamma > \hat{\gamma}^{R}$, RTR increases the total production volume, $q_{s,n}^{R*} + q_{c}^{R*} > q_{l,n}^{*}$. There exists a threshold for the disposal cost, $\hat{\delta}_c^q$, such that RTR increases the used product quantity, $q_{s,u}^{R*} > q_{l,u}^{*}$, if $\delta_c < \hat{\delta}_c^q$.*

3. *If $\hat{\gamma}^{R} > \gamma > \hat{\gamma}^{NR}$, there exists a threshold on the secondhand availability without RTR, $\hat{f}$, such that RTR decreases the new quantity, $q_{l,n}^{*} < q_{s,n}^{NR*}$, and increases the used quantity, $q_{l,u}^{*} > q_{s,u}^{NR*}$ if $f < \hat{f}$. On the other hand, if $f > \hat{f}$ and partial remarketing is optimal under leasing, then RTR increases the new quantity $q_{l,n}^{*} > q_{s,n}^{NR*}$ and decreases the used quantity $q_{l,u}^{*} < q_{s,u}^{NR*}$. If $f > \hat{f}$ and full remarketing is optimal, then RTR decreases both new and used quantities, $q_{s,n}^{NR*} > q_{s,u}^{NR*} > q_{l,n}^{*} = q_{l,u}^{*}$.*

4. *If $\gamma > \max(\hat{\gamma}^{NR}, \hat{\gamma}^{R})$, RTR increases the total production volume, $q_{s,n}^{R*} + q_{c}^{R*} > q_{s,n}^{NR*}$. There exists a threshold on the clone quality as a function of the secondhand availability, $\hat{\delta}_c^q(f)$, such that RTR also increases the used product quantity, $q_{s,u}^{R*} > q_{s,u}^{NR*}$, if $\delta_c < \hat{\delta}_c^q(f)$.*

See Appendix B.4 for the proof.

Proposition 3 **(Environmental Impact)**. *Assume $i_{pc} = i_p$, $i_{dc} = i_d$, and $i_{uc} = i_{u1}$.*

1. *If $\gamma < \min(\hat{\gamma}_c^{NR}, \hat{\gamma}_c^{R})$, $\Delta E = E_l - E_l = 0$.*

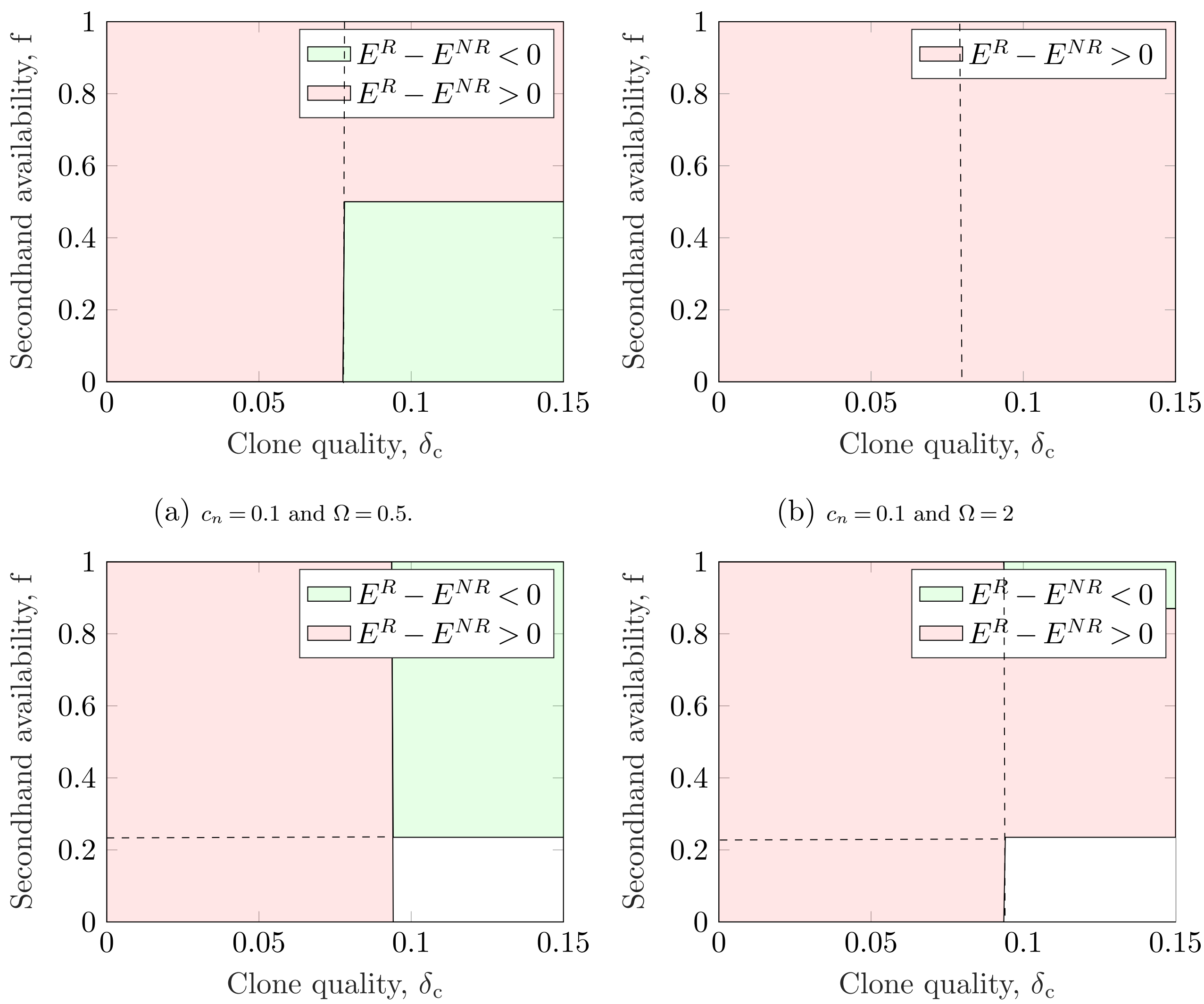
2. *If $\hat{\gamma}^{NR} > \gamma > \hat{\gamma}^{R}$, $\Delta E = E_s^R - E_l > 0$ if $\delta_c < \hat{\delta}_c^q$. If $\delta_c > \hat{\delta}_c^q$, $\Delta E < 0$ for products with $\Omega = i_{u2}/(i_{u1} + i_p + i_d) > \hat{\Omega}_1$ when partial remarketing is optimal, and for products with $\Omega > \hat{\Omega}_2$ when full remarketing is optimal.*

3. *If $\hat{\gamma}^{R} > \gamma > \hat{\gamma}^{NR}$ and $f < \hat{f}$, $\Delta E = E_l - E_s^{NR} < 0$ for products with $\Omega < \hat{\Omega}_3$ if partial remarketing is optimal under leasing, and for products with $\Omega < \hat{\Omega}_4$ if full remarketing is optimal. If $f > \hat{f}$ and partial remarketing is optimal, $\Delta E < 0$ for products with $\Omega > \hat{\Omega}_3$. If $f > \hat{f}$ and full remarketing is optimal, $\Delta E < 0$ for all products.*

4. *If $\gamma > \max(\hat{\gamma}^{R}, \hat{\gamma}^{NR})$, $\Delta E = E_s^R - E_s^{NR} > 0$ if $\delta_c < \hat{\delta}_c^q(f)$. If $\delta_c > \hat{\delta}_c^q(f)$, $\Delta E < 0$ for products with $\Omega > \hat{\Omega}_5$.*

See Appendix B.5 for the proof.

The effect of RTR on the total environmental impact depends on the product type as follows. An increase in the new production quantity (original or clone) increases the steady-state production (i_p) and disposal impacts (i_d), as well as the steady-state use impact of new products (i_{u1}). An increase in the used quantity increases the steady-state use impact of used products (i_{u2}). Therefore, the effect of RTR on the environmental impact is determined by the change in the new and used quantities in the market due to RTR. For



(a) $c_n = 0.1$ and $\Omega = 0.5$.

(b) $c_n = 0.1$ and $\Omega = 2$

(c) $c_n = 0.3$ and $\Omega = 0.5$

(d) $c_n = 0.3$ and $\Omega = 2$

Figure 3 **Change in total environmental impact due to RTR, with $\delta = 0.5$ and $\gamma = 0.05$. The dashed lines indicate the underlying business model change. In panels a and b: $c_n = 0.1$ and partial remarketing is optimal under leasing. Under RTR, it is optimal to sell if $0 < \delta_c < 0.078$ and lease otherwise. Without RTR, it is optimal to sell for all $f \in [0,1]$. In panels c and d: $c_n = 0.3$ and full remarketing is optimal. Under RTR, it is optimal to sell if $0 < \delta_c < 0.094$ and lease otherwise. Without RTR, it is optimal to lease if $0 < f < 0.235$ and sell otherwise.**

example, if RTR causes an increase in the new quantity but a decrease in the used quantity, it results in a lower total environmental impact only for products with a high impact in the second use phase, i_{u2}, i.e., $\Omega = i_{u2}/(i_p + i_d + i_{u1}) > \hat{\Omega}$, such that the increase in i_p, i_d, i_{u1} is dominated by the decrease in i_{u2}. Figure 3 plots the results for different product types. In Section 6.5., we calibrate our model for mobile phones and washing machines.

The change in new and used product quantities due to RTR depends on the underlying business models, which, in turn, is determined by the clone quality under RTR, the secondhand availability without RTR, and the production and disposal costs. We now bring these results together considering the underlying business model change.

If the producer leases both under and without RTR, there is no change in the product quantities or the environmental impact due to RTR. This is observed in the blank regions in Figures 3c and 3d.

If the producer chooses to sell under RTR, clones enter the market, and the total production quantity (clone and original) is higher than the production quantity under leasing or selling without RTR (only original). However, the competition with a high quality clone may limit the quantity of original products, hence the used quantity. If the clone quality is low, RTR leads to an increase in both new production and used quantity, hence a higher environmental impact. This case is exhibited on the left hand side of all panels of Figure 3: clone quality is low and producer chooses selling, resulting in a higher environmental impact. On the other hand, if the clone quality is high enough to limit original production, and therefore the availability of secondhand products, then it benefits the environment for products with high use-phase impact, i.e. a high Ω.

If it is optimal to sell without RTR and lease under RTR, the change in quantities depends on the secondhand availability without RTR. If only a small fraction of products were available in the secondary market without RTR, it may reach its objectives of more used quantity and less new production. While this change in quantities benefits the environment for products with a low use-phase impact (the green region in Figure 3c), it worsens the environmental impact for products with a high use-phase impact (the red region in Figure 3d).

However, if the producer switches from selling to leasing while a high fraction of products were already available without RTR, the consequences of RTR may be contrary to its goals. Under low production and disposal costs, the producer chooses to lease under RTR and prematurely dispose of some products (i.e. partial remarketing), resulting in a lower used quantity and a higher new quantity. The removal of products from the secondary market increases the total environmental impact, as seen in Figures 3a and 3b. This result highlights the importance of understanding the potential strategic response of producers to the proposed regulations. Due to the change in the business model, RTR may lead to higher environmental impact.

In contrast, for products with high production and disposal costs, leasing with full remarketing is optimal under RTR. The switch to leasing decreases both new and used quantities, hence the total environmental impact (upper right corners of Figures 3c and 3d).

6.3. Lose-Lose Region

We now consider the economic and environmental consequences of RTR together. Comparing Figures 2 and 3, one can observe that there is no "win-win" region: the green areas do not coincide. Furthermore, the red areas coincide for a many values of δ_c and f, that is, RTR leads to lower profits for the producer and a higher environmental impact. In Corollary 1, we characterize the values of parameters for which RTR leads to a "lose-lose" situation for the environment and the producer.

COROLLARY 1 **(Lose-Lose Region)**. *Under the following conditions, RTR results in a lose-lose situation for the producer and the environment:*

- *If* $\hat{\gamma}^R > \gamma > \hat{\gamma}^{NR}$ *and* $f < \hat{f}$, $\Delta\Pi < 0$ *and* $\Delta E > 0$ *for products with* $\Omega > \hat{\Omega}_3$ *if partial remarketing is optimal under leasing, and for products with* $\Omega > \hat{\Omega}_4$ *if full remarketing is optimal. If* $f > \hat{f}$ *and partial remarketing is optimal,* $\Delta\Pi < 0$ *and* $\Delta E > 0$ *for products with* $\Omega < \hat{\Omega}_3$.
- *If* $\gamma > \max(\hat{\gamma}^R, \hat{\gamma}^{NR})$, $\Delta\Pi < 0$ *and* $\Delta E > 0$ *if either: (i)* $\hat{\delta}_c^q(f) > \delta_c > \hat{\delta}_c^p(f)$ *or (ii)* $\delta_c > \hat{\delta}_c^q(f)$ *and* $\Omega < \hat{\Omega}_5$.

See Appendix B.6 for the proof.

Corollary 1 follows from Propositions 2 and 3, and shows that for a wide range of parameter values, RTR may result in a "lose-lose" situation for the producer and the environment.

First, consider the products with a low production and disposal cost. Intuition may suggest that the focus of RTR should be on these products, since the producer has an incentive to produce and sell a high quantity at low cost and keep the secondhand availability low by monopolizing the repair market. However, Figures 3a, 3b demonstrate that this intuition is incomplete, since it ignores the potential business model change. At low production costs, the producer partially remarkets products under leasing, and if the secondhand availability was high before RTR, the result is contrary to the intentions of RTR:

higher new production, lower used quantity. This leads to a worse environmental impact, especially for products with a high use-phase impact.

Next, consider the products with a high production and disposal cost. Figure 2b shows that for a small range of values, the producer may be better off under RTR when the clone quality is low. This happens either because of the switch RTR induces from selling to leasing, or, for a producer that continues selling, because of the increase in consumer valuation of products. If the secondhand availability is low without RTR, the producer enjoys the increase in secondhand availability due to RTR, since it boosts consumer valuation and prices. However, when the producer is better-off by RTR, the environment is worse-off (Figures 3c, 3d). On the other hand, in the region where RTR hurts producer profits, it benefits the environment for products with a low use-phase impact (Figure 3c), but this result is reversed for products with a high use-phase impact (Figure 3d).

6.4. Consumer Surplus

While we have established that RTR may lead to a “lose-lose” situation for the producer and the environment, it is commonly believed to benefit consumers by making repairs more convenient and increasing secondhand quantity. Proposition 4 investigates the impact of RTR on consumer surplus[3].

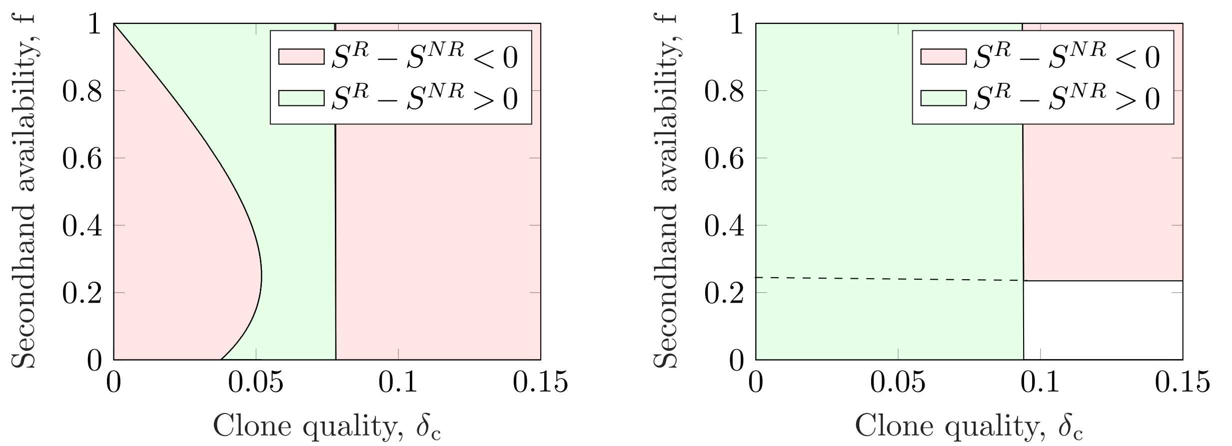
PROPOSITION 4 **(Consumer Surplus)**. *Let S_s^{NR}, S_s^{R}, S_l denote respectively the total consumer surplus when the producer sells in the absence of RTR, when the producer sells under RTR, and when the producer leases.*

1. *If $\gamma < \min(\hat{\gamma}^{NR}, \hat{\gamma}^{R})$, there is no difference in consumer surplus, $\Delta S = S_l - S_l = 0$.*
2. *If $\hat{\gamma}^{NR} > \gamma > \hat{\gamma}^{R}$, RTR increases consumer surplus, $\Delta S = S_s^R - S_l > 0$.*
3. *If $\hat{\gamma}^{R} > \gamma > \hat{\gamma}^{NR}$, there exists a threshold on the secondhand availability, $\hat{f}^{cs}$, such that RTR increases consumer surplus $\Delta S = S_l - S_s^{NR} > 0$ if $f < \hat{f}^{cs}$ and full remarketing is optimal, and decreases otherwise.*
4. *If $\gamma > \max(\hat{\gamma}^{NR}, \hat{\gamma}^{R})$, there exists a threshold on the clone quality as a function of the secondhand availability, $\hat{\delta}_c^{cs}(f)$, such that RTR increases consumer surplus $\Delta S = S_s^R - S_s^{NR} > 0$ if $\delta_c > \hat{\delta}_c^{cs}(f)$.*

See Appendix B.7 for the proof.

Proposition 4 identifies the impact of RTR on consumer surplus and Figure 4 plots the results.

[3] Our analysis in this section focuses solely on the consumer surplus as defined by the prices and quantities of products in the market. The potential impacts of clones on consumer health etc. are outside of the scope of our analysis.



(a) Partial remarketing is optimal under leasing, $c_n = 0.1$. Under RTR, it is optimal to sell if $0 < \delta_c < 0.078$ and lease otherwise. Without RTR, it is optimal to sell for all $f \in [0,1]$.

(b) Full remarketing is optimal under leasing, $c_n = 0.3$. Under RTR, it is optimal to sell if $0 < \delta_c < 0.094$ and lease otherwise. Without RTR, it is optimal to lease if $0 < f < 0.235$ and sell otherwise.

Figure 4 **Change in consumer surplus due to RTR, with $\delta = 0.5$ and $\gamma = 0.05$. The dashed lines indicate the underlying change in business model.**

When the producer leases both without and under RTR, which happens in the blank region on the bottom right of Figure 4b, RTR does not impact consumer surplus.

When the producer leases without RTR and sells under RTR, the change always benefits consumers through an increase in the alternatives available in the market. In the bottom left corner of Figure 4b, this case is presented, where the producer switches from leasing to selling under RTR.

When the producer sells in the absence of RTR and leases under RTR, the results depend on the production and disposal cost. Under low costs such that partial remarketing is optimal, the change results in a decrease in product quantities and an increase in prices, since the producer increases prices to cover the additional disposal cost she pays under leasing. This case is observed to the right of Figure 4a. However, under high costs such that full remarketing is optimal, consumers may benefit from the RTR if it leads to an increase in the secondhand availability. Otherwise, if the secondhand availability was sufficiently high without RTR, it leads to a decrease in consumer surplus due to higher prices. This case is observed to the right of Figure 4b.

Finally, when it is optimal to sell both without and under RTR, and consumers benefit from RTR if the clone quality is high enough such that the competition between the clone and original product is high. This is seen in the green region in Figure 4a.

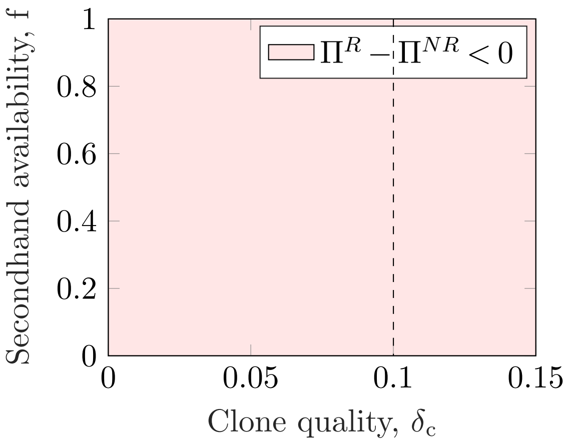
RTR is assumed to benefit consumers by facilitating repairs and ensuring a higher quantity in the secondhand market. However, we find that this is not necessarily the case. Due to the underlying business model change, consumers may be worse-off under RTR, especially if the competition by a high quality clone is threatening and the producer prefers leasing.

6.5. Calibrated Numerical Study

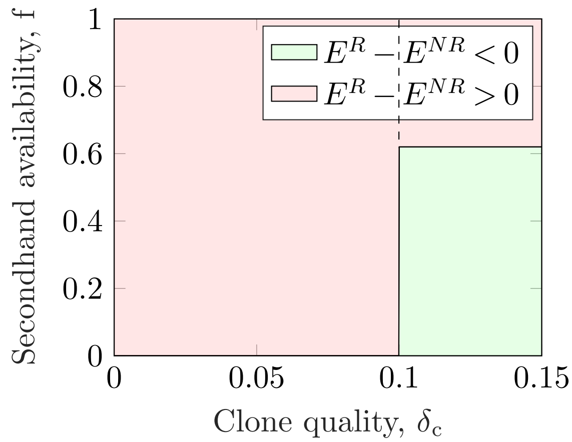
We calibrate our model with data on mobile phones and washing machines, following a similar approach to Agrawal and Bellos (2017). These products were chosen because both consumer electronics and home appliances are at the center of RTR discussions, and they allow us to explore cases with different parameter ranges: mobile phones have a relatively low production cost and use-phase impact, whereas washing machines have a high production cost and use-phase impact. See Appendix C for the details of the parameter estimation. Figure 5 plots the results.

Due to the low production cost, partial remarketing is optimal under leasing for mobile phones. Without RTR, the producer chooses selling, and under RTR, she switches to leasing with partial remarketing if a clone of high quality is present. In Figures 5a and 5b, we observe that both the producer and the environment are worse-off, for a large range of permissible values for the secondhand availability and clone quality. Mobile phones have a large percentage of their environmental impact during the production phase, hence a low Ω. For such products, keeping an item in use for as long as possible is environmentally better than disposing and producing a new item. Therefore, the intuition is that RTR would decrease the total environmental impact by ensuring that products are repaired and reused. However, due to the underlying potential change in the business model, RTR may lead to lower secondhand quantity, hence increasing the total environmental impact, if the secondhand availability was already high without RTR (the upper right corner of Figure 5b). Overlooking the potential implications of RTR on the business model choice, and considering only the type of product (e.g. with low use-phase impact), one might conclude that RTR would be beneficial for the environment by extending the lifetime of mobile phones. Nevertheless, our results demonstrate that RTR may not necessarily reduce the total environmental impact of mobile phones.

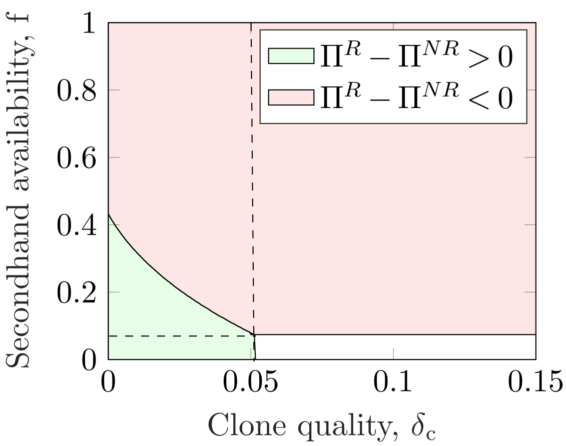
Washing machines have a relatively higher production cost, and full remarketing is optimal under leasing. Without RTR, it is optimal to lease if f is relatively low, and under



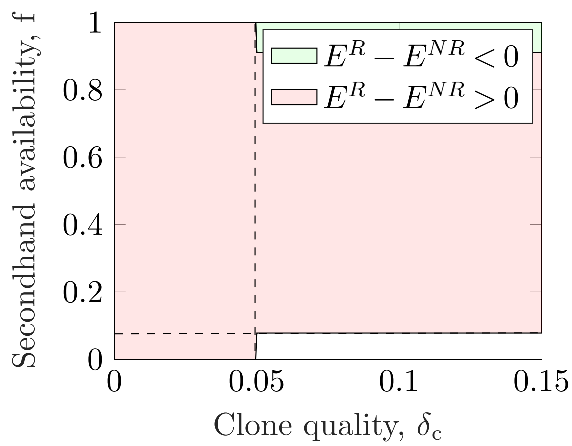
(a) The effect of RTR on producer profits for mobile phones.



(b) The effect of RTR on environmental impact for mobile phones.



(c) The effect of RTR on producer profits for washing machines.



(d) The effect of RTR on environmental impact for washing machines.

Figure 5 **Environmental and economic consequences of RTR for mobile phones and washing machines. The dashed lines signify the change in the business model. For mobile phones, it is always optimal to sell without RTR and optimal to lease (partial remarketing) under RTR if $\delta_c > 0.103$. For washing machines, it is optimal to sell without RTR if $f > 0.078$ and lease (full remarketing) otherwise. Under RTR, it is optimal to lease if $\delta_c > 0.05$ and sell otherwise.**

RTR, it is optimal to lease if δ_c is relatively high. In Figures 5c and 5d, we observe that RTR may result in a lose-lose situation for the producer and the environment, for a wide range of values of δ_c. This is because in this region the producer switches from selling to leasing. This switch leads to lower profits for the producer due to the additional disposal cost under leasing. In this case, since the producer fully remarkets products under RTR, it leads to an increase in secondhand availability. However, means a higher environmental impact for products such as washing machines, which have most of its total environmental impact in the use phase, hence a high Ω.

6.6. Extension: Endogenous Innovation Level

To investigate the potential effects of RTR on innovation, we extend our model to allow the producer to choose the innovation level of products. In each period, the producer introduces a new version of the product. A baseline, generation zero product has quality 1 and innovation enhances the quality by a factor of $\alpha \geq 1$, at a cost per product $c_n = c_0 + c_i \alpha^2$, where c_0 is the baseline production cost and c_i is the cost of innovation. After the first period of use, the product depreciates and becomes an old generation product of quality $\delta \in (0,1)$. Under RTR, we allow the competitor to enter the market by cloning either the new or the old generation, at quality $\delta_c \in (0, \delta/k)$, where $k = 1$ if the old generation is cloned, and $k = \alpha$ if the new generation is cloned. This model is analytically intractable, hence we conducted numerical analyses by keeping c_0, δ and c_i fixed and varying γ, f and δ_c. See Appendix D for details.

When the producer sells both without and under RTR, and the competitor clones the old generation, RTR increases the innovation level. This is in line with the results of Purohit (1994). Under RTR, the new generation product competes with the old generation in the secondary market and clones of the old generation. The increased competition incentivizes the producer to innovate on the new version and differentiate the new original product from clones and secondhand products. From this perspective, the producer claims about the effect of RTR on innovation may seem unfounded. However, if, as producers argue, RTR inadvertently accelerates cloning by providing information on product design and allows competitors to clone the new product quickly after it has been released, it may indeed halt producer incentives to innovate. In this case, innovation is leaked through the releasing of proprietary information, and the competitor also benefits from the innovation efforts of the producer. Therefore, when the producer sells both under and without RTR and new products are cloned, we observe that RTR may hurt innovation.

If RTR results in a switch from selling to leasing, the impact of RTR on innovation depends on the level of the secondhand availability f and the disposal cost γ, which together determine for how long a product will be in use. The intuition is, if the producer does not expect the product to be in use for a long time (by either not getting repaired after the first period of use, i.e. when f is low without RTR, or by being discarded after the first lease term in the case of partial remarketing, i.e. when γ is low), she does not allocate resources on improving the product. Thus, if the disposal cost is low such that partial remarketing is optimal, RTR may decrease innovation. If, on the other hand, the disposal cost is high such that full remarketing is optimal, depending on the level of the secondhand availability, RTR may increase (at low levels of f) or decrease (at high levels of f) producer's incentives to innovate.

7. Conclusions

The RTR movement aims to make repairs more convenient for consumers in order to ensure that products are repaired and reused instead of being discarded before the end of their useful life. As an essential part of a CE, the goal of RTR is to prolong product lifetimes, and reduce new production and waste. To that aim, the repair advocates demand government legislation that requires producers to supply repair information and spare parts to independent repairers and consumers. However, recent regulations in the EU and the U.S. are met with concern from some producers, who maintain that the product information and spare parts they are required to share are proprietary. They contend that making these available would inadvertently facilitate cloning, compromise profits, and decrease incentives to innovate.

Faced with the risks around intellectual property under RTR, and the pressure from the CE advocates for a switch to non-ownership models, producers may consider remaining responsible for repairs by retaining ownership of their products and operating under business models such as leasing. We investigate the economic and environmental consequences of RTR regulations by considering producers' potential strategic response in the form of business model change. We identify the conditions under which RTR may indeed make leasing more attractive for producers who want to prevent the increased risk of imitation, and cannibalization from the increase in used product availability. Our results suggest that producers operating in markets with an expensive product and a risk of a high quality clone may consider switching to a non-ownership model to mitigate the fall in profits due to RTR.

We find that producers can benefit from the increase in the secondhand volume due to RTR, however, this comes with a strong qualifier as it only holds for products with a high production cost and a low secondhand availability, when the clone quality is also sufficiently low. On the other hand, in many cases, RTR understandably hurts producer profits either due to the increased competition with an imitator, or the costs associated with the business model change. Our numerical analyses also suggest that RTR can undermine innovation, especially if, as producers argue, RTR accelerates cloning and a competitor is able to clone a new product shortly after its release.

Contrary conventional wisdom, we demonstrate that RTR does not necessarily benefit consumers or the environment. We find that for a wide range of parameter values, RTR may lead to a situation where both producers and the environment are worse-off. The goal of increasing secondhand use and decreasing new production does not automatically bring about environmental benefits for all types of products. As our calibrated numerical study also demonstrates, for some products, due to the potential business model change, RTR may (fail to) achieve this goal, but still increase (reduce) the total environmental impact. The results depend on product type, production and disposal costs, availability of products in the secondary market in the absence of RTR, and clone quality. We therefore caution against a blanket legislation for all products, as is the current model legislation in the U.S. (The Repair Association 2020), and instead recommend a case-by-case analysis.

We also recommend that the regulations be written considering the potential business model change as a strategic response to RTR. The model legislation in the U.S. defines the owner as "an individual or business who owns or leases digital electronic equipment" (The Repair Association 2020). However, it does not differentiate between financial and operational leases, where in the former the consumer becomes the owner of the product at the end of the lease term, and in the latter the producer retains ownership (Fishbein et al. 2000). The regulations in the EU do not mention business model of producers.

While this paper focuses on the intellectual property risks, RTR also has other implications, e.g., on quality and safety of repairs, repair cost and revenue, and product design. Producers argue that allowing consumers and independent repairers without necessary technical training to carry out repairs would compromise the quality and safety of repairs, damaging brand image (DIGITALEUROPE 2017). Moreover, producers would lose information on breakdowns that is used for designing newer versions of the product (DIGITALEUROPE 2017). Although RTR may make repairs cheaper for consumers (Jin et al.

2020), from the producers' perspective, it would decrease revenues from repairs. Furthermore, we consider leasing as an example of a non-ownership model, and it would be interesting to examine the change to other non-ownership business models such as servicizing (Agrawal et al. 2021).

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Appendix A: Derivation of Optimal Decisions

A.1. Selling without RTR

Under selling without RTR, there are three undominated consumer strategies: (i) buy new products in every period (N), (ii) buy used products in every period (U), and (iii) stay inactive (I), with the following respective net utilities: (i) $V_{s,n}^{NR}(\theta)=\theta-p_{s,n}^{NR}+\rho f p_{s,u}^{NR}$, (ii) $V_{s,u}^{NR}(\theta)=\delta\theta-p_{s,u}^{NR}$, (iii) $V_i^{NR}(\theta)=0$. The differences $V_{s,n}^{NR}(\theta)-V_{s,u}^{NR}(\theta)$, and $V_{s,u}^{NR}(\theta)-V_i^{NR}(\theta)$ are increasing in θ. Hence, there exist $\theta_1^{NR},\theta_2^{NR}\in[0,1]$ such that consumers of type $\theta\in(\theta_1^{NR},1]$ always buy new, $\theta\in(\theta_2^{NR},\theta_1^{NR}]$ always buy old, and others remain inactive. This analysis gives $\theta_1^{NR}=\frac{p_{s,n}^{NR}-(1+f)p_{s,u}^{NR}}{1-\delta}$ and $\theta_2^{NR}=\frac{p_{s,u}^{NR}}{\delta}$.

The market-clearing price $p_{s,u}^{NR}$ is found by solving $1-\theta_1^{NR}=\theta_1^{NR}-\theta_2^{NR}$. Taking $\rho=1$, this gives $p_{s,u}^{NR}=\frac{\delta((1+f)p_{s,n}^{NR}-f+f\delta)}{1+f(2+f)\delta}$. We then solve for the inverse demand function by $1-\theta_1^{NR}=q_{s,n}^{NR}$, and get $p_{s,n}^{NR}(q_{s,n}^{NR})=1-q_{s,n}^{NR}+f\delta-2f\delta q_{s,n}^{NR}-f^2\delta q_{s,n}^{NR}$. Finally, the producer's profit maximization problem is: $\max_{q_{s,n}^{NR}}\Pi_s^{NR}=q_{s,n}^{NR}(p_{s,n}^{NR}-c_n)$ s.t. $q_{s,n}^{NR}\geq 0$, and $1-(1+f)q_{s,n}^{NR}\geq 0$. We further assume that $c_n<1+f\delta$ such that production is profitable.

The Lagrangian function of this maximization problem is $\mathcal{L}=q_{s,n}(1-q_{s,n}^{NR}+f\delta-2f\delta q_{s,n}^{NR}-f^2\delta q_{s,n}^{NR}-c_n)+\lambda_1 q_{s,n}^{NR}+\lambda_2(1-(1+f)q_{s,n}^{NR})$ subject to the constraints: $\frac{\partial\mathcal{L}}{\partial q_{s,n}^{NR}}=0$, $\lambda_1 q_{s,n}^{NR}=0$ and $\lambda_2(1-(1+f)q_{s,n}^{NR})=0$, $\lambda_1\geq 0$, $\lambda_2\geq 0$, $\lambda_3\geq 0$ $q_{s,n}^{NR}\geq 0$, $(1-(1+f)q_{s,n}^{NR})\geq 0$. There is only one valid case: $\left(q_{s,n}^{NR}=\frac{1-c_n+f\delta}{2(1+f(2+f)\delta)},\lambda_1=0,\lambda_2=0\right)$. All consumer segments are positive: $q_{s,n}^{NR}>0$, $q_{s,u}^{NR}=fq_{s,n}^{NR}>0$, $1-(1+f)q_{s,n}^{NR}>0$.

A.2. Selling under RTR

If the producer chooses the selling strategy under RTR, there exists clones and consumers take the same action in every period. Therefore, there are four undominated strategies: (i) buy new products in every period (N), (ii) buy used products in every period (U), (iii) buy clones in every period (C), (iv) stay inactive (I), with the following respective net utilities: (i) $V_{s,n}^R(\theta)=\theta-p_{s,n}^R+\rho p_{s,u}^R$,(ii) $V_{s,u}^R(\theta)=\delta\theta-p_{s,u}^R$, (iii) $V_c^R(\theta)=\delta_c\theta-p_c^R$, (iv) $V_i^R(\theta)=0$. The differences $V_{s,n}^R(\theta)-V_{s,u}^R(\theta)$, $V_{s,u}^R(\theta)-V_c^R(\theta)$, and $V_c^R(\theta)-V_i^R(\theta)$ are increasing in θ. Hence, there exist $\theta_1^R,\theta_2^R,\theta_3^R\in[0,1]$ such that consumers of type $\theta\in(\theta_1^R,1]$ always buy new, $\theta\in(\theta_2^R,\theta_1^R]$ always buy old, $\theta\in(\theta_3^R,\theta_2^R]$ always buy clones, and others remain inactive. This analysis gives $\theta_1^R=\frac{p_{s,n}^R-2p_{s,u}^R}{1-\delta}$, $\theta_2^R=\frac{p_{s,u}^R-p_c^R}{\delta-\delta_c}$ and $\theta_3^R=\frac{p_c^R}{\delta_c}$.

Solving the inverse demand equations, we get these prices as follows: $p_n^R(q_{s,n}^R,q_c^R)=-2\delta_c q_c^R-q_{s,n}^R(1+3\delta)+1+\delta$, $p_{s,u}^R(q_{s,n}^R,q_c^R)=-\delta_c q_c^R-2\delta q_{s,n}^R+\delta$, and $p_c^R(q_{s,n}^R,q_c^R)=\delta_c(1-2q_{s,n}^R-q_c^R)$.

The competitor solves the problem $\max_{q_c^R}\Pi_c^R=p_c^R q_c^R$ subject to the constraints: $1\geq\theta_1^R\geq\theta_2^R\geq\theta_3^R\geq 0$ and $p_{s,u}^R\geq 0$. Similarly, the producer solves the problem $\max_{q_{s,n}^R}\Pi_s^R=(p_{s,n}^R-c_n)q_{s,n}^R$ subject to $1\geq\theta_1^R\geq\theta_2^R\geq\theta_3^R\geq 0$ and $p_{s,n}^R\geq 0$. We assume that $c_n<1+\delta-\delta_c$ such that production is profitable.

It can be shown that the producer's profit function is concave in $q_{s,n}^R$.The Lagrangian function of the producer's problem is $\mathcal{L}=q_{s,n}^{RTR}(-2\delta_c q_c^R+1-q_{s,n}^R+\delta-3q_{s,n}^R\delta)+\lambda_1 q_{s,n}^R+\lambda_2(1-q_c^R-2q_{s,n}^R)$ subject to the constraints $\frac{\partial\mathcal{L}}{\partial q_{s,n}^R}=0$, $\lambda_1 q_{s,n}^R=0$, $\lambda_2(1-q_c^R-2q_{s,n}^R)=0$, $\lambda_1=0$, $\lambda_2=0$, $q_c^R\geq 0$, and $(1-q_c^R-2q_{s,n}^R)\geq 0$. There are two cases:

1. $\left(q_{s,n}^R=\frac{-c_n+1+\delta-q_c^R(\delta_c+\delta)}{2(1+3\delta)},\lambda_1=0,\lambda_2=0\right)$: This case is valid if $0<c_n<1+\delta-2\delta_c$ and $\frac{c_n+2\delta}{-2\delta_c+1+3\delta}<q_c^R<1$.

2. $\left(q^R_{s,n} = \frac{1-q^R_c}{2}, \lambda_1 = 0, \lambda_2 = 1/2(-c_n - 2\delta + q^R_c(-2\delta_c + 1 + 3\delta))\right)$: This case is valid if $(0 < c_n < 1 + \delta - 2\delta_c$ and $q^R_c < \frac{c_n+2\delta}{1+3\delta-2\delta_c})$ or $(c_n > 1 + \delta - 2\delta_c$ and $q^R_c < \frac{1+\delta-c_n}{2\delta_c})$

It can also be shown that the competitor's profit function is concave in q^R_c. The Lagrangian function of the competitor's problem is $\mathcal{L} = q^R_c(-\delta_c(-1 + q^R_c + 2q^R_{s,n})) + \lambda_1 q^R_c + \lambda_2(1 - q^R_c - 2q^R_{s,n})$, subject to the constraints: $\frac{\partial \mathcal{L}}{\partial q^R_c} = 0$, $\lambda_1 q^R_c = 0$, $\lambda_2(1 - q^R_c - 2q^R_{s,n}) = 0$, $\lambda_1 \geq 0$, $\lambda_2 \geq 0$ and $q^R_c \geq 0$. There is only one valid case: $\left(q^R_c = 1/2 - q^R_{s,n}, \lambda_1 = 0, \lambda_2 = 0\right)$.

Combining the optimal strategies of the producer and the competitor, we get the following Nash Equilibrium: $0 < c_n < 1 + \delta - \delta_c$, $q^{R*}_c = \frac{c_n+2\delta}{2(1+3\delta-\delta_c)}$, $q^{R*}_{s,n} = \frac{c_n+\delta_c-1-\delta}{2(\delta_c-1-3\delta)}$, $q^{R*}_i = 1 - 2q^{R*}_{s,n} - q^{R*}_c$.

A.3. Leasing

Under leasing, there are three undominated consumer strategies: (i) lease new products in every period (N), (ii) lease used products in every period (U), (iii) stay inactive (I). These strategies have the following respective net utilities: (i) $V_{l,n}(\theta) = \theta - l_n$,(ii) $V_{l,u}(\theta) = \delta\theta - l_u$, (iii) $V_i(\theta) = 0$. The differences $V_{l,n}(\theta) - V_{l,u}(\theta)$ and $V_{l,u}(\theta) - V_i(\theta)$ are increasing in θ. Then, there exist $\theta_1, \theta_2 \in [0,1]$ such that consumers of type $\theta \in (\theta_1, 1]$ always lease new, $\theta \in (\theta_2, \theta_1]$ always lease old, and others remain inactive. This analysis gives $\theta_1 = \frac{l_n - l_u}{1-\delta}$ and $\theta_2 = \frac{l_u}{\delta}$.

The inverse demand functions are determined by solving $q_{l,n} = 1 - \theta_1$ and $q_{l,u} = \theta_1 - \theta_2$ together. Taking the discount factor, $\rho = 1$, this calculation gives: $l_n = 1 - q_{l,n} - \delta q_{l,u}$ and $l_u = \delta(1 - q_{l,n} - q_{l,u})$. Then, the producer's profit maximization problem becomes: $\max_{q_{l,n}, q_{l,u}} \Pi_l = q_{l,n}(l_n - (c_n + \gamma)) + q_{l,u} l_u$ s.t. $q_{l,u} \geq 0$, $q_{l,n} - q_{l,u} \geq 0$ and $1 - q_{l,n} - q_{l,u} \geq 0$. We further assume that $c_n + \gamma < 1 + \delta$ such that production is profitable.

The Lagrangian function of this maximization problem is $\mathcal{L} = q_{l,n}(l_n - (c_n + \gamma)) + q_{l,u} l_u + \lambda_1 q_{l,u} + \lambda_2(q_{l,n} - q_{l,u}) + \lambda_3(1 - q_{l,n} - q_{l,u})$ subject to the conditions $\frac{\partial \mathcal{L}}{\partial q_{l,n}} = 0$, $\frac{\partial \mathcal{L}}{\partial q_{l,u}} = 0$, $\lambda_1 q_{l,u} = 0$, $\lambda_2(q_{l,n} - q_{l,u}) = 0$, $\lambda_3(1 - q_{l,n} - q_{l,u}) = 0$, $\lambda_1 \geq 0$, $\lambda_2 \geq 0$, $\lambda_3 \geq 0$, $q_{l,u} \geq 0$, $q_{l,n} - q_{l,u} \geq 0$, $1 - q_{l,n} - q_{l,u} \geq 0$. There are two valid cases:

1. $\left(q_{l,n} = \frac{-c_n-\gamma+1+\delta}{2(1+3\delta)}, q_{l,u} = \frac{-c_n-\gamma+1+\delta}{2(1+3\delta)}, \lambda_1 = 0, \lambda_2 = \frac{\delta(2c_n+2\gamma-1+\delta)}{1+3\delta}, \lambda_3 = 0\right)$: Full remarketing is optimal, $q_{l,u} = q_{l,n}$. This case holds if $(1+\delta) > c_n + \gamma \geq \frac{1-\delta}{2}$.

2. $\left(q_{l,n} = \frac{1}{2}(1 + \frac{c_n+\gamma}{-1+\delta}), q_{l,u} = \frac{c_n+\gamma}{2(1-\delta)}, \lambda_1 = \lambda_2 = \lambda_3 = 0\right)$: Partial remarketing is optimal. This case holds if $c_n + \gamma < \frac{1-\delta}{2}$.

Appendix B: Proofs

B.1. Proof of Lemma 2

It can be shown that $\Pi^*_l - \Pi^{i*}_s$ is decreasing in γ for all $i \in \{R, NR\}$. Therefore, there exist thresholds $\hat{\gamma}^i_j, i \in \{R, NR\}, j \in 1, 2$ that solve $\Pi^*_l = \Pi^{i*}_s$, and below which the producer prefers leasing. The respective thresholds $\hat{\gamma}^i_j$ are given by:

$$\hat{\gamma}^{NR}_1 = -\frac{-1 + \delta + c_n(1 + \delta f(f+2)) - 1\delta f^2 + \delta^2 f^2 - 2\delta f + 2\delta^2 f}{1 + \delta f(f+2)} + \frac{\sqrt{(1-\delta)(1+\delta f(f+2))\left(c_n^2 - 2c_n(1+\delta f) + (1-\delta)(1+2\delta f)\right)}}{1 + \delta f(f+2)}$$

$$\hat{\gamma}^{NR}_2 = 1 - \frac{\sqrt{(1+3\delta)(1+\delta f(f+2))(1 - c_n + \delta f)^2}}{1 + \delta f(f+2)} - c_n + \delta$$

$$\hat{\gamma}_1^R = 1 - \frac{\sqrt{(1-\delta)(1+3\delta-\delta_c)^2 x}}{(1+3\delta-\delta_c)^2} - c_n - \delta$$
$$\hat{\gamma}_2^R = -\frac{\delta_c(c_n+2\delta)}{-1-3\delta+\delta_c}$$

where $x = (\delta\,(16+3c_n^2-8c_n+6c_n\delta_c+2\delta_c^2-6\delta_c)+\delta^2(1-6c_n)+(-1+c_n+\delta_c)^2-6\delta^3)$.

B.2. Proof of Proposition 1

Note that the thresholds under RTR, $\hat{\gamma}_j^R$, are a function of the clone quality, δ_c, and the thresholds without RTR, $\hat{\gamma}_j^{NR}$ are a function of the secondhand availability, f. Since Π_s^{R*} is decreasing in δ_c, the thresholds for the disposal cost under RTR $\hat{\gamma}_j^R$ are increasing in δ_c. It follows that the differences $\hat{\gamma}_1^R(\delta_c) - \hat{\gamma}_1^{NR}(f)$, and $\hat{\gamma}_2^{NR}(\delta_c) - \hat{\gamma}_2^{NR}(f)$ are increasing in δ_c.

At the boundaries of $\delta_c \in (0,\delta)$ and $f \in (0,1)$, we have the following results:

1. At $\delta_c = 0$ and $f = 0$: $\hat{\gamma}_1^R(0) - \hat{\gamma}_1^{NR}(0) < 0$ if $c_n > \frac{2-\sqrt{1+3\delta}}{3}$ and $\hat{\gamma}_2^R(0) - \hat{\gamma}_2^{NR}(0) < 0$.
2. At $\delta_c = 0$ and $f = 1$: $\hat{\gamma}_1^R(0) - \hat{\gamma}_1^{NR}(1) = 0$ and $\hat{\gamma}_2^R(0) - \hat{\gamma}_2^{NR}(1) = 0$.
3. At $\delta_c = \delta$ and $f = 0$: $\hat{\gamma}_1^R(\delta) - \hat{\gamma}_1^{NR}(0) > 0$ and $\hat{\gamma}_2^R(\delta) - \hat{\gamma}_2^{NR}(0) > 0$.
4. At $\delta_c = \delta$ and $f = 1$: $\hat{\gamma}_1^R(\delta) - \hat{\gamma}_1^{NR}(1) > 0$ and $\hat{\gamma}_2^R(\delta) - \hat{\gamma}_2^{NR}(1) > 0$.

Therefore, there exists a level of $\delta_c \in (0,\delta)$ such that $\hat{\gamma}_j^R(\delta_c) - \hat{\gamma}_j^{NR}(f) = 0$ for every value of $f \in (0,1]$. Above this level of δ_c, the difference is positive, hence RTR makes leasing more attractive. These δ_c levels are given by:

- $\hat{\gamma}_1^R(\delta_c) - \hat{\gamma}_1^{NR}(f) = 0$ if

$$\hat{\delta}_{c,1}(f) = \frac{(1+3\delta)\left(-c_n^2+c_n\left(1-\delta f^2\right)+\delta\left(1+f^2+2\delta f\right)\right)}{\left(-c_n^2+2c_n(1+\delta f)+\delta\left(1\left(f^2+3\right)+2\delta f(f+3)\right)\right)} - \frac{\sqrt{(1+3\delta)(c_n+2\delta)^2(1+\delta f(f+2))(1-c_n+\delta f)^2}}{\left(-c_n^2+2c_n(1+\delta f)+\delta\left(1\left(f^2+3\right)+2\delta f(f+3)\right)\right)}$$

Additionally, it can be shown that $\hat{\delta}_{c,1}(f) < 0$ if $c_n < \frac{f(1-\delta)}{1+f}$ and $\frac{\partial\delta_{c,1}}{\partial f} < 0$ if $c_n > \frac{f(1-\delta)}{1+f}$. Hence, the level of δ_c at which the disposal costs are equal is less than zero, and RTR makes leasing more attractive to the right of that region, which is for all feasible values of δ_c and f.

- $\hat{\gamma}_2^R(\delta_c) - \hat{\gamma}_2^{NR}(f) = 0$ if

$$\hat{\delta}_{c,2}(f) = \frac{(1-c_n+\delta)(1+\delta f(f+2)) + (1-c_n+\delta f)\sqrt{(1+3\delta)(1+\delta f(f+2))}}{(1+\delta f(f+2)) - (1-c_n+\delta f)\sqrt{(1+3\delta)(1+\delta f(f+2))}}$$

Additionally, it can be shown that $\frac{\partial\hat{\delta}_{c,2}}{\partial f} < 0$, since $c_n > \frac{f(1-\delta)}{1+f}$ when full remarketing is optimal.

B.3. Proof of Proposition 2

If $\hat{\gamma}^R > \gamma > \hat{\gamma}^{NR}$, the producer chooses selling without RTR and leasing under RTR. Therefore, without RTR, it holds that $\Pi_s^{NR*} > \Pi_l^*$ and hence $\Delta\Pi = \Pi_l^* - \Pi_s^{NR*} < 0$.

If $\hat{\gamma}^{NR} > \gamma > \hat{\gamma}^R$, the producer chooses leasing without RTR and selling under RTR. Therefore, under RTR, it holds that $\Pi_s^{R*} > \Pi_l^*$ and hence $\Delta\Pi = \Pi_s^{R*} - \Pi_l^* > 0$.

If $\gamma > \max(\hat{\gamma}^{NR}, \hat{\gamma}^R)$, the producer chooses selling both without and under RTR. Π_s^{R*} decreases in δ_c, hence $\Delta\Pi = \Pi_s^{R*} - \Pi_s^{NR*}$ decreases. $\Delta\Pi = 0$ at

$$\delta_c = \hat{\delta}_c^p = \frac{-(3\delta+1)\left(-c_n^2 - c_n\delta f^2 + c_n + \delta\left(f^2+2\delta f+1\right)\right)}{c_n^2 - 2c_n(\delta f+1) - \delta\left((2\delta+1)f^2+6\delta f+3\right)} + \frac{\sqrt{(3\delta+1)(c_n+2\delta)^2(\delta f(f+2)+1)(-c_n+\delta f+1)^2}}{c_n^2 - 2c_n(\delta f+1) - \delta\left((2\delta+1)f^2+6\delta f+3\right)}$$

and $\Delta\Pi < 0$ if $\delta_c > \hat{\delta}_c^p$.

B.4. Proof of Lemma 3

1. If $\gamma < \min(\hat{\gamma}^{NR}, \hat{\gamma}^{R})$, the producer leases both under and without RTR and there is no difference in product quantities.

2. If $\hat{\gamma}^{NR} > \gamma > \hat{\gamma}^{R}$, the producer leases in the absence of RTR and sells under RTR. Thus, under RTR, the total new production quantity is the sum of new original products and clones produced at each period, i.e. $q_{s,n}^{R*} + q_c^{R*} = 1/2$. Under leasing, it can be shown that $q_{l,n}^{*} < 1/2$. Therefore, the total production quantity increases due to RTR.

To compare the used quantities, note that $q_{s,u}^{R*}$ decreases with δ_c. Hence, $q_{s,u}^{R*} - q_{l,u}^{*}$ decreases with δ_c. When partial remarketing is optimal, $q_{s,u}^{R*} - q_{l,u}^{*} = 0$ at $\delta_c = \hat{\delta}_c^q$ and $q_{s,u}^{R*} - q_{l,u}^{*} > 0$ if $\delta_c < \hat{\delta}_c^q$. $\hat{\delta}_c^q = \frac{-1+2c_n(1+\delta)+\delta^2+\gamma(1+3\delta)}{(-1+c_n+\delta+\gamma)}$ when partial remarketing is optimal under leasing, and $\hat{\delta}_c^q = \frac{\gamma(1+3\delta)}{(c_n+2\delta+\gamma)}$ when full remarketing is optimal.

3. If $\hat{\gamma}^{R} > \gamma > \hat{\gamma}^{NR}$, the producer sells in the absence of RTR and leases under RTR.

- When partial remarketing is optimal, $q_{s,n}^{NR*}$ decreases in f if $c_n < \frac{1+f(2+f\delta)}{1+f}$. This condition holds in the range of the production cost c_n where partial remarketing is optimal, i.e. when $\frac{1-\delta}{2} > c_n > 0$. $q_{l,n}^{*} - q_{s,n}^{NR*}$ hence increases in f, and equals to zero at

$$f = \hat{f}_1 = -\frac{\sqrt{\delta(\delta-1)\left(4\gamma(-1+c_n+\gamma)+\delta^2+\delta(4\gamma-1)\right)} + \delta(-1+2c_n+\delta+2\gamma)}{2\delta(-1+c_n+\delta+\gamma)}$$

and $q_{l,n}^{*} - q_{s,n}^{NR*} > 0$ if $f > \hat{f}_1$, meaning that the switch to leasing causes an increase (decrease) in the new quantity when f is high (low).

$q_{s,u}^{NR*}$ increases in f, hence $q_{l,u}^{*} - q_{s,u}^{NR*}$ decreases. $q_{l,u}^{*} - q_{s,u}^{NR*} = 0$ at

$$f = \hat{f}_2 = -\frac{\sqrt{1-\delta}\sqrt{c_n^2(-(\delta-1)) + c_n(\delta(2-4\gamma)-2) - \delta\left(4\gamma^2+1\right)+1}}{2\delta(c_n+\delta+\gamma-1)} + \frac{c_n\delta + c_n + \delta + 2\delta\gamma - 1}{2\delta(c_n+\delta+\gamma-1)}$$

Hence $q_{l,u}^{*} - q_{s,u}^{NR*} < 0$ if $f > \hat{f}_2$, meaning that the switch to leasing causes a decrease (increase) in the used quantity when f is high (low).

- When full remarketing is optimal, $q_{s,n}^{NR*}$ decreases in f, hence $q_{l,n}^{*} - q_{s,n}^{NR*}$ increases, if $c_n < \frac{1+f(2+f\delta)}{1+f}$. $q_{l,n}^{*} - q_{s,n}^{NR*} = 0$ at

$$f = \hat{f}_3 = \frac{\sqrt{\delta\left(\delta(-1+2c_n+\delta+2\gamma)^2 - 4(-1+c_n-\delta+\gamma)(2\delta-3c_n\delta+\gamma)\right)}}{2\delta(-1+c_n-\delta+\gamma)} + \frac{\delta - 2c_n\delta - \delta^2 - 2\delta\gamma}{2\delta(-1+c_n-\delta+\gamma)}$$

It follows that $q_{l,n}^{*} - q_{s,n}^{NR*} > 0$ if $f > \hat{f}_3$ and $c_n < \frac{1+f(2+f\delta)}{1+f}$.

$q_{s,u}^{NR*}$ increases in f, hence $q_{l,u}^{*}-q_{s,u}^{NR*}$ decreases. $q_{l,u}^{*}-q_{s,u}^{NR*}=0$ at

$$f=\hat{f}_4=\frac{-1-\delta+c_n(1+\delta)+2\delta^2-2\delta\gamma}{2\delta(c_n+2\delta+\gamma)}+\frac{\sqrt{\left(1+\delta-c_n(1+\delta)+2\delta(\gamma-\delta)\right)^2+4\delta(c_n+2\delta+\gamma)(1-c_n+\delta-\gamma)}}{2\delta(c_n+2\delta+\gamma)}$$

and $q_{l,u}^{*}-q_{s,u}^{NR*}<0$ if $f>\hat{f}_4$.

4. $\gamma>\max(\hat{\gamma}^R,\hat{\gamma}^{NR})$, the producer sells both under and without RTR. It can be shown that $q_{s,n}^{NR*}<1/2$. Therefore, RTR leads to an increase in the total production volume, since under RTR, $q_{s,n}^{R*}+q_c^{R*}=1/2$. For the change in the used quantity as a result of RTR, note that $q_{s,u}^{R*}-q_{s,u}^{NR*}$ decreases in δ_c since $q_{s,u}^{R*}$ decreases. $q_{s,u}^{R*}-q_{s,u}^{NR*}=0$ at $\delta_c=\hat{\delta}_c^q(f)=-\frac{(f-1)\left(1+\delta-c_n+c_n\delta f+2\delta^2 f\right)}{(1+c_nf-f+2\delta f)}$ and $q_{s,u}^{R*}>q_{s,u}^{NR*}$ if $\delta_c<\hat{\delta}_c^q(f)$.

B.5. Proof of Proposition 3

The proof follows from Lemma 3. Assume $i_{pc}=i_p$, $i_{dc}=i_d$, and $i_{uc}=i_{u1}$.

1. If $\gamma<\min(\hat{\gamma}_c^{NR},\hat{\gamma}_c^R)$, $\Delta E=E_l-E_l=0$.
2. If $\hat{\gamma}^{NR}>\gamma>\hat{\gamma}^R$, $\Delta E=E_s^R-E_l$. The environmental impacts of selling under RTR and leasing are given by: $E_s^R=(i_p+i_d+i_{iu1})(q_{s,n}^{R*}+q_c^{R*})+i_{u2}q_{s,u}^{R*}$ and $E_l=(i_p+i_d+i_{u1})q_{l,n}^{*}+i_{u2}q_{l,u}^{*}$. From Lemma 3, if $\delta_c<\hat{\delta}_c^q$, $q_{s,n}^{R*}+q_c^{R*}>q_{l,n}^{*}$ and $q_{s,u}^{R*}>q_{l,u}^{*}$, therefore $E_s^R>E_l$ for all i_p,i_d,i_{u1},i_{u2}.

On the other hand, if $\delta_c>\hat{\delta}_c^q$, it follows from Lemma 3 that ΔE decreases in i_{u2}, hence in $\Omega=\frac{i_{u2}}{i_p+i_d+i_{u1}}$. When partial remarketing is optimal under leasing, the difference $\Delta E=0$ at

$$\Omega=\hat{\Omega}_1=\frac{(1+3\delta)(c_n+\gamma)(-1-3\delta+\delta_c)}{(1-\delta)(-c_n\delta_c-\delta_c(2\delta+\gamma)+\gamma(1+3\delta))}$$

and $\Delta E<0$ if $\Omega>\hat{\Omega}_1$.

When full remarketing is optimal under leasing, the same argument follows. The difference $\Delta E=0$ if

$$\Omega=\hat{\Omega}_2=-\frac{(c_n+2\delta+\gamma)(-1-3\delta+\delta_c)}{c_n\delta_c+\delta_c(2\delta+\gamma)-\gamma(1+3\delta)}$$

and $\Delta E<0$ if $\Omega>\hat{\Omega}_2$.

3. If $\hat{\gamma}^R>\gamma>\hat{\gamma}^{NR}$, $\Delta E=E_l-E_s^{NR}$. The environmental impacts of selling and leasing are given by: $E_l=(i_p+i_d+i_{u1})q_{l,n}^{*}+i_{u2}q_{l,u}^{*}$ and $E_s^{NR}=(i_p+i_d+i_{u1})q_{s,n}^{NR*}+i_{u2}q_{s,u}^{NR*}$. When $f<\hat{f}$, from Lemma 3 we have that $q_{l,n}^{*}<q_{s,n}^{*}$ and $q_{l,u}^{*}>q_{s,u}^{NR*}$. ΔE increases in i_{u2}, hence in Ω. When partial remarketing is optimal, $\Delta E=0$ at

$$\Omega=\hat{\Omega}_3=\frac{(1+3\delta)(\delta(-(f+1))(c_nf+c_n-f+\delta f)-\gamma(1+\delta f(f+2)))}{(1-\delta)\left(c_n(f-1)(\delta f-1)+\gamma(1+\delta f(f+2))+(f-1)\left(1+\delta+2\delta^2 f\right)\right)}$$

and $\Delta E<0$ if $\Omega<\hat{\Omega}_3$.

When full remarketing is optimal, $\Delta E=0$ at

$$\Omega=\hat{\Omega}_4=\frac{c_n(f-1)(\delta f-1)-\delta+\delta\gamma f^2+2\delta\gamma f+\gamma+2\delta^2f^2-2\delta^2 f+\delta f+f-1}{\delta(f-1)(-c_n(f+3)+\delta f+f+2)-\gamma\left(\delta f^2+2\delta f+1\right)}$$

and $\Delta E<0$ if $\Omega<\hat{\Omega}_4$.

When $f > \hat{f}$ and partial remarketing is optimal, from Lemma 3, we have $q^*_{l,n} > q^*_{s,n}$ and $q^*_{l,u} < q^{NR*}_{s,u}$. ΔE decreases in i_{u2}, hence in Ω. $\Delta E = 0$ at $\Omega = \hat{\Omega}_3$ and $\Delta E < 0$ if $\Omega < \hat{\Omega}_3$.
When $f > \hat{f}$ and full remarketing is optimal, from Lemma 3, we have $q^*_{l,n} < q^*_{s,n}$ and $q^*_{l,u} < q^{NR*}_{s,u}$. $\Delta E < 0$ for all i_p, i_d, i_{u1}, i_{u2}.

4. If $\gamma > \max(\hat{\gamma}^R, \hat{\gamma}^{NR})$, $\Delta E = E^R_s - E^{NR}_s$. The environmental impacts of selling under and in the absence of RTR are given by: $E^R_s = (i_p + i_d + i_{u1})(q^{R*}_{s,n} + q^{R*}_c) + i_{u2} q^{R*}_{s,u}$ and $E^{NR}_s = (i_p + i_d + i_{u1}) q^{NR*}_{s,n} + i_{u2} q^{NR*}_{s,u}$. From Lemma 3, if $\delta_c < \hat{\delta}_c(f)$, $q^{R*}_{s,n} + q^{R*}_c > q^*_{l,n}$ and $q^{R*}_{s,u} > q^*_{l,u}$. It follows that $\Delta E > 0$ for all i_p, i_d, i_{u1}, i_{u2}.
On the other hand, if $\delta_c > \hat{\delta}_c(f)$, the difference ΔE decreases in i_{u2}, hence in Ω. The difference is zero at:

$$\Omega = \hat{\Omega}_5 = \frac{(c_n + \delta f(f+1))(-1 - 3\delta + \delta_c)}{-c_n(\delta_c f + (f-1)(\delta f - 1)) + \delta_c((f-1) - 2\delta f) - (f-1)\left(2\delta + 2\delta^2 f\right)}$$

and $\Delta E < 0$ if $\Omega > \hat{\Omega}_5$.

B.6. Proof of Corollary 1

The proof follows directly from Propositions 2 and 3. In the case with $\gamma > \max(\hat{\gamma}^R, \hat{\gamma}^{NR})$, it can be shown that $\hat{\delta}^q_c(f) > \hat{\delta}^p_c(f)$, therefore case (i) is permissible, and in case (ii), $\delta_c > \max(\hat{\delta}^q_c(f), \hat{\delta}^p_c(f))$ reduces to $\delta_c > \hat{\delta}^q_c(f)$.

B.7. Proof of Proposition 4

Under leasing, consumers with the taste parameter $\theta \in [\theta_{l1}, 1]$ will always lease a new product, consumers with $\theta \in [\theta_{l2}, \theta_{l1})$ will always lease used, and the rest of the market, $\theta \in [0, \theta_{l2})$, will stay inactive. These thresholds are found as $\theta_{l1} = \frac{l_n - l_u}{1-\delta}$ and $\theta_{l2} = \frac{l_u}{\delta}$. Consumer θ gets net utility $\theta - l_n$ from leasing a new product and $\delta\theta - l_u$ from leasing a used product. Hence, under leasing, the total consumer surplus is given by:

$$S_l = \int_{\frac{l_n - l_u}{1-\delta}}^{1} (\theta - l_n) d\theta + \int_{\frac{l_u}{\delta}}^{\frac{l_n - l_u}{1-\delta}} (\delta\theta - l_u) d\theta$$

Under partial remarketing, we get $S_l = -\frac{c_n^2 + 2c_n(\delta + \gamma - 1) - \delta + \gamma^2 + 2(\delta - 1)\gamma + 1}{8(\delta - 1)}$. Under full remarketing, $S_l = \frac{(c_n - \delta + \gamma - 1)^2}{24\delta + 8}$.

If producer chooses selling in the absence of RTR, consumers with $\theta \in [\theta^{NR}_{s1}, 1]$ always purchase new products, and consumers with $\theta \in [\theta^{NR}_{s2}, \theta^{NR}_{s1})$ always purchase a secondhand product, with respective net utilities $\theta - p^{NR}_n + f p^{NR}_u$, and $\delta\theta - p^{NR}_u$. These thresholds are given by $\theta^{NR}_{s1} = \frac{p^{NR}_n - (1+f) p^{NR}_u}{1-\delta}$ and $\theta^{NR}_{s2} = \frac{p^{NR}_u}{\delta}$. Hence the total consumer surplus is:

$$S^{NR}_s = \int_{\frac{p^{NR}_n - (1+f)p^{NR}_u}{1-\delta}}^{1} (\theta - p^{NR}_n + f p^{NR}_u) d\theta + \int_{\frac{p^{NR}_u}{\delta}}^{\frac{p^{NR}_n - (1+f)p^{NR}_u}{1-\delta}} (\delta\theta - p^{NR}_u) d\theta$$

Plugging the variables in, we get $S^{NR}_s = \frac{(-c_n + \delta f + 1)^2}{8(\delta f^2 + 2\delta f + 1)}$. Furthermore, it can be shown that S^{NR}_s increases in f if $c_n > \frac{f(1-\delta)}{1+f}$.

If producer chooses selling under RTR, consumers with $\theta \in [\theta^R_{s1}, 1]$ always purchase new products, consumers with $\theta \in [\theta^R_{s2}, \theta^R_{s1})$ always purchase a secondhand product, and consumers with $\theta \in [\theta^R_{s3}, \theta^R_{s2})$ always purchase a clone. The respective net utilities are given by $\theta - p^R_n - p^R_u$, $\delta\theta - p^R_u$, and $\delta_c\theta - p^R_c$. These thresholds are found as $\theta^R_{s1} = \frac{p^R_n - 2p^R_u}{1-\delta}$, $\theta^R_{s2} = \frac{p^R_u - p^R_c}{\delta - \delta_c}$, and $\theta^R_{s3} = \frac{p^R_c}{\delta_c}$. Hence the total consumer surplus under selling with RTR is:

$$S_s^R = \int_{\frac{p_n^R - 2p_u^R}{1-\delta}}^{1} (\theta - p_n^R + p_u^R) d\theta + \int_{\frac{p_u^R - p_c^R}{\delta - \delta_c}}^{\frac{p_n^R - 2p_u^R}{1-\delta}} (\delta\theta - p_u^R) d\theta + \int_{\frac{p_c^R}{\delta_c}}^{\frac{p_u^R - p_c^R}{\delta - \delta_c}} (\delta_c \theta - p_c^R) d\theta$$

Plugging the variables in, we get:

$$\begin{aligned} S_s^R = &\frac{(\delta+1)^2(3\delta+1) + (1-5\delta)\delta_c^2 + (6\delta^2-2)\,\delta_c}{8(-3\delta+\delta_c-1)^2} \\ &+ \frac{c_n^2(3\delta - 3\delta_c + 1) - 2c_n\,(3\delta^2 + 4\delta + 2\delta_c^2 - 3(\delta+1)\delta_c + 1)}{8(-3\delta+\delta_c-1)^2} \end{aligned}$$

Furthermore, it can be shown that S_s^R increases in δ_c.

1. If $\gamma < \min(\hat{\gamma}^{NR}, \hat{\gamma}^R)$, $\Delta S = S_l - S_l = 0$.

2. If $\hat{\gamma}^{NR} > \gamma > \hat{\gamma}^R$, and partial remarketing is optimal under leasing, $\Delta S = S_s^R - S_l$ also increases in δ_c, and $\Delta S = 0$ if

$$\begin{aligned} \delta_c = \hat{\delta}_{c_n,1} = &\frac{-6\delta^3 + 6\delta + 6\delta\gamma^2 + 2\gamma^2 + 12\delta^2\gamma - 8\delta\gamma - 4\gamma}{2\,(c_n^2 + 2c_n(-\delta+\gamma+1) - 5(\delta-1)\delta + \gamma^2 + 2(\delta-1)\gamma)} \\ &+ \frac{9c_n^2\delta + \sqrt{\delta-1}(c_n+2\delta) - c_n^2 + 6c_n\delta^2 - 8c_n\delta + 12c_n\delta\gamma + 4c_n\gamma + 2c_n}{2\,(c_n^2 + 2c_n(-\delta+\gamma+1) - 5(\delta-1)\delta + \gamma^2 + 2(\delta-1)\gamma)} \\ &+ \frac{\sqrt{c_n^2(33\delta-1) + 4c_n\,(6\delta^2 - 7\delta + 4(3\delta+1)\gamma + 1) + 4x}}{2\,(c_n^2 + 2c_n(-\delta+\gamma+1) - 5(\delta-1)\delta + \gamma^2 + 2(\delta-1)\gamma)} \end{aligned}$$

where $x = (6\delta^3 - 4\delta^2 - \delta + (6\delta+2)\gamma^2 + 4\,(3\delta^2 - 2\delta - 1)\,\gamma - 1)$. $\Delta S > 0$ if $\delta_c > \hat{\delta}_{c_n,1}$. It can be shown that when partial remarketing is optimal, i.e. $(1-\delta)/2 > c_n + \gamma > 0$, $\hat{\delta}_{c,1} < 0$, therefore, $\Delta S > 0$ for all values of δ_c. Similarly, when full remarketing is optimal, the difference in consumer surplus, $\Delta S = S_s^R - S_l$ increases in δ_c. $\Delta S = 0$ if

$$\begin{aligned} \delta_c = \hat{\delta}_{c,2} = &\frac{(3\delta+1)\left(c_n\left(-\sqrt{c_n^2 - 4c_n(2\delta+4\gamma+1) + 4\left((2\delta+1)^2 - 2\gamma^2 + 4(\delta+1)\gamma\right)}\right) - c_n^2\right)}{2\,(c_n^2 + 2c_n(5\delta+\gamma+1) + 4\delta(4\delta+1) + \gamma^2 - 2(\delta+1)\gamma)} \\ &+ \frac{2\left(\delta\left(-\sqrt{c_n^2 - 4c_n(2\delta+4\gamma+1) + 4\left((2\delta+1)^2 - 2\gamma^2 + 4(\delta+1)\gamma\right)} + 4\delta + 2\right)\right)}{2\,(c_n^2 + 2c_n(5\delta+\gamma+1) + 4\delta(4\delta+1) + \gamma^2 - 2(\delta+1)\gamma)} \\ &+ \frac{2\delta(\gamma^2 - 2(\delta+1)\gamma) + c_n(3\delta+1)(2\delta+4\gamma+2)}{2\,(c_n^2 + 2c_n(5\delta+\gamma+1) + 4\delta(4\delta+1) + \gamma^2 - 2(\delta+1)\gamma)} \end{aligned}$$

and $\Delta S > 0$ if $\delta_c > \delta_{c,2}$. It can be shown that when full remarketing is optimal, i.e. $1+\delta > c_n + \gamma > (1-\delta)/2$, $\hat{\delta}_{c,2} < 0$, therefore, $\Delta S > 0$ for all values of δ_c.

3. If $\hat{\gamma}^R > \gamma > \hat{\gamma}^{NR}$, $\Delta S = S_l - S_s^{NR} > 0$. If partial remarketing is optimal under leasing, i.e. $c_n < f(1-\delta)/(1+f)$, S_s^{NR} decreases in f, therefore ΔS increases. $\Delta S = 0$ at

$$\begin{aligned} f = \hat{f}_1^{cs} = &\frac{c_n^2(-\delta) - c_n\delta^2 + c_n\delta - 2c_n\delta\gamma - \delta\gamma^2 - 2\delta^2\gamma + 2\delta\gamma}{\delta(c_n+\delta+\gamma-1)^2} \\ &+ \frac{\sqrt{(\delta-1)\delta\gamma\,(2c_n^3 + c_n^2(6\delta+5\gamma-6) + 2x + \gamma^3 + 4(\delta-1)\gamma^2 + (4\delta^2 - 9\delta + 5)\,\gamma)}}{\delta(c_n+\delta+\gamma-1)^2} \end{aligned}$$

where $x = c_n\left(2\delta^2 - 5\delta + 2\gamma^2 + 5(\delta-1)\gamma + 3\right) - (\delta-1)^2$.

$\Delta S > 0$ if $f > \hat{f}_1^{cs}$. It can be shown that when partial remarketing is optimal, $\hat{f}_1^{cs} > 1$, therefore $\Delta S < 0$ for all permissible values of f.

If full remarketing is optimal under leasing, i.e. $c_n > f(1-\delta)/(1+f)$, S_s^{NR} increases in f, therefore ΔS decreases. $\Delta S = 0$ at

$$f = \hat{f}_2^{cs} = -\frac{c_n^2\delta + c_n\delta(\delta+2\gamma-1) + \delta^3 - \delta^2 + \delta\gamma^2 - 2\delta^2\gamma - 2\delta\gamma}{\delta\left(c_n^2 + 2c_n(-\delta+\gamma-1) - 2\delta^2 + \delta + \gamma^2 - 2(\delta+1)\gamma + 1\right)} + \frac{\sqrt{\delta(c_n-\delta+\gamma-1)^2\left(\delta(2c_n+\delta-1)^2 + 2(\delta-1)\gamma(c_n-\delta-1) + (\delta-1)\gamma^2\right)}}{\delta\left(c_n^2 + 2c_n(-\delta+\gamma-1) - 2\delta^2 + \delta + \gamma^2 - 2(\delta+1)\gamma + 1\right)}$$

It can be shown that $1 > \hat{f}_2^{cs} > 0$, for $c_n > f(1-\delta)/(1+f)$. Therefore, $\Delta S < 0$ if $f > \hat{f}_2^{cs}$.

4. If $\gamma > \max(\hat{\gamma}^{NR}, \hat{\gamma}^{R})$, S_s^R increases in δ_c, hence $\Delta S = S_s^R - S_s^{NR}$ increases. $\Delta S = 0$ at

$$\delta_c = \hat{\delta}_c^{cs}(f) = \frac{x\sqrt{c_n^2\left(3\delta\left(3f^2+6f-8\right)+1\right) - 4y + 4\left(\delta^2\left(6f^2+4f+6\right) + \delta z + 12\delta^3 f + 1\right)}}{2\left(c_n^2 + c_n\left(4\delta f^2 + 6\delta f + 2\right) + \delta\left((6\delta-1)f^2 + 10\delta f + 5\right)\right)} + \frac{6c_n^2\delta + 6\delta^2 + 6\delta + 12\delta^3 f^2 + 2\delta^2 f^2 - 2\delta f^2 + 12\delta^3 f + 12\delta^2 f}{2\left(c_n^2 + c_n\left(4\delta f^2 + 6\delta f + 2\right) + \delta\left((6\delta-1)f^2 + 10\delta f + 5\right)\right)} + \frac{-3c_n^2\delta f^2 - 6c_n^2\delta f - c_n^2 - 6c_n\delta + 6c_n\delta^2 f^2 + 6c_n\delta f^2 + 8c_n\delta f + 2c_n}{2\left(c_n^2 + c_n\left(4\delta f^2 + 6\delta f + 2\right) + \delta\left((6\delta-1)f^2 + 10\delta f + 5\right)\right)}$$

where $x = (c_n + 2\delta)\sqrt{\delta f^2 + 2\delta f + 1}$, $y = c_n\left(6\delta^2 f^2 + \delta\left(5f^2 + 6f - 6\right) + 1\right)$, and $z = \left(3f^2 + 2f + 2\right)$.

$\Delta S > 0$ if $\delta_c > \hat{\delta}_c^{cs}(f)$.

Appendix C: Model Calibration

C.1. iPhones

We first determine the highest value for consumers' willingness to pay, θ. According to a survey in 2019, 10% of consumers are willing to make an upfront payment of \$2000 for the new iPhone (Simon-Kucher & Partners 2019). We therefore take $\theta = 2000$. We choose the iPhone 12 128GB as a representative product, with the price tag of \$849 at the time of writing (Apple 2021). We calculate the production cost by subtracting the profit margin from the price. Apple reports a 42.5% gross margin (Statista 2021), which gives (1-0.425)*849=\$488 as the production cost. Since our parameters are between 0 and 1, we divide them by θ to normalize, which gives $c_n = 488/2000 = 0.244$. For the durability parameter δ, we use Alev et al. (2019)'s estimate of 0.15. We take the disposal cost parameter $\gamma = 0.05$. We use data from Apple to calculate the relative environmental impact in the second-period of use for an iPhone. 85% of total carbon emissions for an iPhone 12 are created during production and transportation phases, 14% during use, and 1% during disposal (Apple 2020). Taking $i_{u1} + i_{u2} = 0.85$ and assuming $i_{u1} = i_{u2}$, we get $\Omega = i_{u2}/(i_{u1} + i_p + i_d) = 0.075$. Due to lack of estimates for secondhand availability f, and clone quality δ_c, we plot the comparisons for various levels of f and δ_c.

C.2. Washing Machines

We first determine the highest value for consumers' willingness to pay, θ. The prices for washing machines vary highly between approximately \$250 to \$2500, with machines around the \$1000 price range being most popular. Due to lack of better estimates, we take $\theta = \$2000$. We choose LG WM4000H Black Steel as a representative product in the average price range, \$1100 at the time of writing (Bogdan and McCabe 2021). We calculate the production cost by subtracting the profit margin from the price. LG Electronics reports a 26.9% gross margin (Wall Street Journal 2021), which gives (1-0.269)*1100=\$803 as the production cost. Since our parameters are between 0 and 1, we normalize these estimates by dividing them by θ, which gives $c_n = 803/2000 = 0.244$. We estimate the durability parameter from the new and used product costs. To do this, we searched for posts for LG WM4000H on Ebay. On 8.07.2021, there was one such post, with a bid of \$450. We calculate the relative value of a used washing machine (\$450) to a new machine (\$1100): $\delta = 450/1100 = 0.409$. For washing machines, leasing is more common than it is for mobile phones, which suggests that the barriers for leasing instead of selling should be lower. In our model, this is represented by the additional disposal cost, hence we assume a lower disposal cost for a washing machine than an iPhone, $\gamma = 0.025$. The use-phase impact of a washing machine is 80-90% of total (Fishbein et al. 2000). Taking $i_{u1} + i_{u2} = 0.8$ and assuming $i_{u1} = i_{u2}$, we get $\Omega = i_{u2}/(i_{u1} + i_p + i_d) = 0.66$. Due to lack of estimates for secondhand availability f, and clone quality δ_c, we plot the comparisons for various levels of f and δ_c.

Appendix D: Endogeneous Innovation Level

We follow the same solution strategy as in Appendix A, and change the model to include $\alpha \geq 1$ as the innovation level in the new product.

D.1. Leasing

With an innovation level of $\alpha \geq 1$, consumers with taste parameter θ get gross utility of $\alpha\theta$ from the new product, and the net utility of consumers who lease new products in every period become: $V_{l,n}(\theta) = \alpha\theta - l_n$. Then, the thresholds θ_1 and θ_2 are derived as: $\theta_1 = \frac{l_n - l_u}{\alpha - \delta}$ and $\theta_2 = \frac{l_u}{\delta}$.

The inverse demand functions are found as: $l_n = \alpha - \alpha q_{l,n} - \delta q_{l,u}$ and $l_u = \delta(1 - q_{l,n} - q_{l,u})$. Then, the producer's profit maximization problem becomes: $\max_{q_{l,n}, q_{l,u}} \Pi_l = q_{l,n}(l_n - (c_0 + c_i\alpha^2 + \gamma)) + q_{l,u} l_u$ s.t. $q_{l,u} \geq 0$, $q_{l,n} - q_{l,u} \geq 0$ and $1 - q_{l,n} - q_{l,u} \geq 0$. We further assume that $c_0 + c_i\alpha^2 + \gamma < \alpha + \delta$ such that production is profitable. There are two valid cases:

1. $q_{l,n} = q_{l,u} = \frac{-(c_0 + c_i\alpha^2 + \gamma) + \alpha + \delta}{2(\alpha + 3\delta)}$: Full remarketing is optimal. This case holds if $(\alpha + \delta) > c_0 + c_i\alpha^2 + \gamma \geq \frac{\alpha - \delta}{2}$. Plugging in the optimal quantities, the optimal profits as a function of α is $\Pi_l^*(\alpha) = \frac{(-(c_n + c_i\alpha^2) - \gamma + \alpha + \delta)^2}{(4(\alpha + 3\delta))}$. Then we solve for $\max_\alpha \Pi_l^*(\alpha)$ s.t. $\alpha \geq 1$ and $\alpha + \delta > c_0 + c_i\alpha^2 + \gamma > \frac{\alpha - \delta}{2}$. This problem is analytically intractable.

2. $\left(q_{l,n} = \frac{1}{2}(1 + \frac{c_0 + c_i\alpha^2 + \gamma}{-\alpha + \delta}), q_{l,u} = \frac{c_0 + c_i\alpha^2 + \gamma}{2(\alpha - \delta)}\right)$: Partial remarketing is optimal. This case holds if $c_0 + c_i\alpha^2 + \gamma < \frac{\alpha - \delta}{2}$. Plugging in the optimal quantities, the optimal profits is $\Pi_l^*(\alpha) = \frac{(c_n + c_i\alpha^2 + \gamma)^2 - 2(c_n + c_i\alpha^2 + \gamma)\alpha + \alpha^2 + 2 * (c_n + c_i\alpha^2 + \gamma)\delta - \alpha\delta)}{4(\alpha - \delta)}$. Then we solve for $\max_\alpha \Pi_l^*(\alpha)$ s.t. $\alpha \geq 1$ and $c_0 + c_i\alpha^2 + \gamma < \frac{\alpha - \delta}{2}$. This problem is analytically intractable.

D.2. Selling without RTR

In this case, the net utility of consumers from buying new products in every period is $V_{s,n}^{NR}(\theta) = \alpha\theta - p_{s,n}^{NR} + \rho f p_{s,u}^{NR}$. The thresholds $\theta_1^{NR}, \theta_2^{NR}$ become: $\theta_1^{NR} = \frac{p_{s,n}^{NR} - (1+f)p_{s,u}^{NR}}{\alpha - \delta}$ and $\theta_2^{NR} = \frac{p_{s,u}^{NR}}{\delta}$.

The market-clearing price $p_{s,u}^{NR}$ is the found as $p_{s,u}^{NR} = \frac{\delta((1+f)p_{s,n}^{NR} - f\alpha + f\delta)}{\alpha + f(2+f)\delta}$. We then solve for the inverse demand function and get $p_{s,n}^{NR}(q_{s,n}^{NR}) = \alpha - \alpha q_{s,n}^{NR} + f\delta - 2f\delta q_{s,n}^{NR} - f^2\delta q_{s,n}^{NR}$. Producer's profit maximization problem is: $\max_{q_{s,n}^{NR}} \Pi_s^{NR} = q_{s,n}^{NR}(p_{s,n}^{NR} - (c_0 + c_i\alpha^2))$ s.t. $q_{s,n}^{NR} \geq 0$, and $1 - (1+f)q_{s,n}^{NR} \geq 0$. We further assume that $c_n < \alpha + f\delta$ such that production is profitable. The optimal new product quantity is $q_{s,n}^{NR} = \frac{\alpha - (c_0 + c_i\alpha^2) + f\delta}{2(\alpha + f(2+f)\delta)}$. Plugging it in, the optimal profits as a function of α is: $\Pi_s^{NR^*}(\alpha) = \frac{\left(-\alpha + c_n + \alpha^2 c_i - \delta f\right)^2}{4(\alpha + \delta f(f+2))}$. Then we solve for $\max_\alpha \Pi_s^{NR^*}(\alpha)$ s.t. $\alpha \geq 1$ and $c_0 + c_i\alpha^2 < \alpha + f\delta$. This problem is analytically intractable.

D.3. Selling under RTR

In this case, the net utility of consumers from buying a new product every period is $V_{s,n}^R(\theta) = \alpha\theta - p_{s,n}^R + \rho p_{s,u}^R$. The net utility of consumers from buying a clone every period is $V_c^R(\theta) = \delta_c k\theta - p_c^R$ where $k = \alpha$ if the new product is cloned, and $k = 1$ if the old product is cloned. The thresholds on θ become: $\theta_1^R = \frac{p_{s,n}^R - 2p_{s,u}^R}{\alpha - \delta}$, $\theta_2^R = \frac{p_{s,u}^R - p_c^R}{\delta - \delta_c k}$ and $\theta_3^R = \frac{p_c^R}{\delta_c k}$.

Solving the inverse demand equations, we get these prices as follows: $p_n^R(q_{s,n}^R, q_c^R) = -2\delta_c k q_c^R - q_{s,n}^R(\alpha + 3\delta) + \alpha + \delta$, $p_{s,u}^R(q_{s,n}^R, q_c^R) = -\delta_c k q_c^R - 2\delta q_{s,n}^R + \delta$, and $p_c^R(q_{s,n}^R, q_c^R) = \delta_c k(1 - 2q_{s,n}^R - q_c^R)$.

The competitor solves the problem $\max_{q_c^R} \Pi_c^R = p_c^R q_c^R$ subject to the constraints: $1 \geq \theta_1^R \geq \theta_2^R \geq \theta_3^R \geq 0$ and $p_{s,u}^R \geq 0$. Similarly, the producer solves the problem $\max_{q_{s,n}^R} \Pi_s^R = (p_{s,n}^R - (c_0 + c_i\alpha^2)))q_{s,n}^R$ subject to $1 \geq \theta_1^R \geq \theta_2^R \geq \theta_3^R \geq 0$ and $p_{s,n}^R \geq 0$. We assume that $c_0 + c_i\alpha^2 < \alpha + \delta - \delta_c k$ such that production is profitable. This problem gives the following Nash Equilibrium: $0 < c_n < \alpha + \delta - \delta_c k$, $q_c^{R*} = \frac{c_n + 2\delta}{2(\alpha + 3\delta - \delta_c k)}$, $q_{s,n}^{R*} = \frac{c_n + \delta_c k - \alpha - \delta}{2(\delta_c k - \alpha - 3\delta)}$, $q_i^{R*} = 1 - 2q_{s,n}^{R*} - q_c^{R*}$.

In this case, the producer profits as a function of α is: $\Pi_s^{R^*}(\alpha) = \frac{(\alpha+3\delta)\left(\alpha - \left(c_n + \alpha^2 c_i\right) + \delta - \alpha\delta_c\right)^2}{4(\alpha + 3\delta + \alpha(-\delta_c))^2}$ if the new version is cloned. Then, the producer chooses the optimal innovation level to maximize profits as $\max_\alpha \Pi_s^{R^*}(\alpha)$ subject to the constraints $c_n + \alpha^2 c_i \leq \alpha + \delta - 2\delta_c$, $\alpha \leq \delta/\delta_c$, and $\alpha \geq 1$. This problem becomes analytically intractable.

If the old version of the product is cloned, the optimal profits as a function of the innovation level is: $\Pi_s^{R^*}(\alpha) = \frac{(\alpha+3\delta)\left(\alpha - \left(c_n + \alpha^2 c_i\right) + \delta - \delta_c\right)^2}{4(\alpha + 3\delta - \delta_c)^2}$. Then, the producer chooses the optimal innovation level to maximize profits as $\max_\alpha \Pi_s^{R^*}(\alpha)$ subject to the constraints $c_n + \alpha^2 c_i \leq \alpha + \delta - 2\delta_c$, and $\alpha \geq 1$.

We conducted $5^3 = 125$ numerical analyses by holding $c_0 = 0.2, \delta = 0.5, c_i = 0.1$ fixed and varying $\gamma = \{0.2, 0.4, 0.6, 0.8, 1\}, f = \{0.2, 0.4, 0.6, 0.8, 1\}$, $\delta_c = \{0.1, 0.2, 0.3, 0.4, 0.5\}$. For these parameters, we do not observe a case where RTR leads to a switch from leasing to selling. Note that this happens only in a small range of parameters, as discussed in Section 5.