PRIMARY AND SECONDARY MARKET STRATEGIES FOR REGULATORY COMPLIANCE AND PROFIT

A Thesis
Presented to
The Academic Faculty

by

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In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
Scheller College of Business

Georgia Institute of Technology
August 2016

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To my beloved parents, Yanming Huang and Puhong Chen, and my husband, Michael Zheng, for your company along this journey. Your unconditional love, trust and encouragement have made me stronger and better than I could ever imagine.

ACKNOWLEDGEMENTS

I would like to express my most sincere gratitude to my advisors Beril Toktay and Atalay Atasu, for your inspiration that helped shape my work, for your guidance that nurtured my growth as a scholar, for your mentorship that showed me what it takes to succeed in academia, and for your encouragement that supported my continuation in this journey of pursuing my Ph.D. I am grateful to have had the privilege to learn from you in the past five years.

I am thankful and appreciative to each of my committee members, Atalay Atasu, Beril Toktay, Eric Overby, Necati Tereyağoğlu, Vishal Agrawal, and Luyi Gui, for all of your help and support through the dissertation and scholarly process.

Many thanks to all the faculty members and the fellow Ph.D. students in the Operations Management department, for endowing me with knowledge and providing me with support and encouragement. I would also like to acknowledge the tremendous help I received from the faculty, staff, and colleagues at Scheller College of Business in Georgia Institute of Technology. Also a heartfelt thank-you to Wai-Ki Ching, my master's advisor, for being the first teacher that led me into the path of research and for being my mentor in so many different aspects.

I owe my deepest thanks to my loving family and friends. Dad, Mom, and Michael, thank you for always being by my side, I love you with my whole heart.

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SUMMARY

Incorporating sustainability into operational strategies has gained tremendous momentum among firms. An important driver is the need to comply with environmental legislation that grows in both coverage and stringency. Moreover, many firms also come to recognize the value of establishing sustainable operations to enhance profitability, especially with its potential to be scaled up by the rapidly increasing volume of production and end-of-life products. In this dissertation, I study firms' sustainable operational strategies either for complying with legislation or for improving profitability. In the first essay (Chapter II), I point out that, although largely overlooked by the literature, increasing product durability can be utilized, in addition to recyclability, as a design lever when a durable product producer is imposed with the responsibility of end-of-life product management. The analysis reveals that when trade-off between the two design options exists, legislation can lead to surprising design outcomes. The second essay (Chapter III) studies the strategies of Testing and Remanufacturing as instruments for a durable product manufacturer to tackle the lemons problem. The lemons problem arises in secondary markets as the sellers, being the original owners of the used products, take advantage of the superior quality information to strategically sell the low-quality items to the secondary markets while keeping the high-quality ones. This study reveals the unexplored functionalities of conducting testing and remanufacturing in resolving the lemons problem, which take effects through enabling the manufacturer a stronger control over the secondary markets. The third essay (Chapter IV) builds upon these insights and proposes a framework to empirically study the effectiveness of the Testing and Remanufacturing strategies in dealing with the lemons problem in the used automobile markets.

CHAPTER I

INTRODUCTION

Sustainable operations management is gaining increasing importance for firms to succeed in the market, both for complying with environmental legislation and for enhancing profitability in the market. Under the environmental pressure from the fast-expanding industrial production and the growing public awareness, environmental legislation with rising stringency is being developed and imposed on a wider scope of products. Complying with such legislation in an economically efficient way requires firms to optimally plan for and integrate sustainability into their operations starting from product design, sales to end-of-life product management. Even in the absence of legislation, sustainable strategies such as remanufacturing are also embedded with the potential to help firms improve their market performance. This dissertation studies sustainable operational strategies both as a way to comply with environmental legislation and to enhance profitability.

In the first essay (Chapter II), I study durable product producers who are responsible for the proper treatment of their end-of-life products under the take-back legislation based on Extended Producer Responsibility (EPR). By assigning producer responsibility, EPR-based legislation has the potential to not only achieve landfill diversion, but also incentivize eco-friendly product designs. In this study, I focus on the product design implications of EPR. In particular, I observe that the design incentives under EPR may involve an inherent trade-off that has not been explored to date: Durable product producers can respond to EPR by making their products either more recyclable or more durable, where the former will decrease the unit recycling cost while the latter will reduce the volume of recycling for the producer. When these two design attributes do not go hand-in-hand, as is the case for many product categories, product design implications of EPR can be subtle. I find that seemingly similar EPR implementation levers, namely recycling and collection targets, may have opposing effects in driving producers' design choices. Furthermore, more stringent legislative targets do not always guarantee improved product recyclability and durability. In particular, if the objective of EPR is to induce recyclable product designs, a low recycling target accompanied with a high collection target should be used. On the other hand, if the objective of EPR is to induce durable product designs, a low collection target accompanied with a high recycling target is more appropriate.

In the second essay (Chapter III), I study how the strategies of Testing and Remanufacturing can help resolve the lemons problem arising in the secondary market. To be specific, used products sold in the secondary market may be of high or low quality (which will be referred to as "peaches" and "lemons", respectively) due to previous usage or deterioration. The quality of any particular product unit is only known to the seller who originally owns it, but not to the buyers prior to purchase. Under this asymmetric information, buyers will offer a price that only reflects the average quality in the market. However, this price will be lower than the fair price of a peach and higher than that of a lemon. As such, lemon owners are willing to sell while peach owners prefer to hold. As a consequence of such strategic peach-holding behavior, the secondary market is filled with more lemons than peaches, which lowers the average market quality. In the literature, trade-in programs offered by manufacturers have been proposed as remedies. However, even with trade-ins, the lemons problem is not completely resolved, as the strategic peach-holding behavior still persists and dilutes the average market quality. In this essay, I show that by conducting testing or remanufacturing, the manufacturer is able to eliminate the strategic peach-holding behavior entirely. In that case, the used product sellers no longer take advantage of the superior quality information they have; and when they sell a used unit, they do so regardless of whether they have peaches or lemons. In other words, there will not be more lemons than peaches in the secondary market and hence the lemons problem is resolved. Furthermore, I also compare the Testing and Remanufacturing strategies, and derive a comprehensive guidance on how to choose from these alternative solutions to the lemons problem and how the product characteristics play a role. Building on these insights from the analytical analysis, in the third essay (Chapter IV), I propose a framework to empirically study the lemons problem and the effectiveness of Testing and Remanufacturing, in the context of used automobile markets. I develop testable hypotheses and also discuss the implications and potential contribution of the study.

CHAPTER II

DESIGN IMPLICATIONS OF EXTENDED PRODUCER RESPONSIBILITY FOR DURABLE PRODUCTS

2.1 Introduction

Extended Producer Responsibility (EPR) is a policy concept that requires producers to operate or finance the management of their end-of-life products through environmentally friendly processes such as recycling. By assigning product end-of-life management responsibility to producers, EPR legislation is expected to create incentives for producers to design products with environmentally superior attributes (OECD 2001). In particular, because EPR legislation emphasizes recycling (e.g., the WEEE Directive specifies recycling rate targets[1]), it is commonly assumed that it will induce eco-design incentives that are geared towards making products more recyclable (easier and cheaper to recycle). Yet durable goods producers - and most products covered under EPR are durable - have an additional lever at their disposal: investing in durability. In contrast to recyclability that acts on unit cost, durability acts on volume: A more durable product can be priced higher and sold to fewer customers while maintaining profitability. Surprisingly, however, a durable good producer's durability choice in response to EPR has received limited attention (see §2.2 for a detailed discussion). In this paper, we fill this void.

These are timely questions: In recent years, recognizing that most electronic products are durable, durability has emerged as a stated eco-design objective. This is the case both in Europe and in the US. For example, the Sustainable Production and

[1] A recycling rate target is defined as the percentage, by weight, of the product that needs to be recycled.

Consumption Unit of the European Commission now considers both recyclability and durability as key eco-design attributes (Misiga 2012). EPR legislation in Rhode Island states that its purpose is encouraging the design of electronic products that are more durable and more recyclable (RIDEM 2013). The environmental rationale on durability is that durability may lead to "source reduction," the most preferred form of waste reduction (U.S. EPA 2013), by suppressing new production due to two effects: life extension and demand response (a more durable product can be priced higher as described above). However, it is hard to specify a durability target that is akin in ease of enforcement to a recycling rate or a collection rate target[2]: This would require regulating how quickly a product's market value should depreciate or how many years a product should last (both of which have been utilized in the literature as durability measures), neither of which is viable. Therefore, another open question is: How do recycling and collection rate targets imposed by EPR, especially as they become more stringent, indirectly affect durability choice? This is another question this paper seeks to answer.

How recyclability and durability interact matters greatly in this context. On one hand, they may be synergistic design attributes, i.e., they can be enhanced by similar design changes. Eichner and Runkel (2003) argue that both attributes positively correlate with the weight of the product: Cars with thicker aluminum frames are more durable due to their higher rigidity and more recyclable due to a higher content of recyclable material. Similarly, a desktop computer with an aluminum casing is cheaper to recycle and more durable than one with a plastic casing (HP 2009). On the other hand, these two attributes may conflict, as in the following examples: Using screws rather than adhesives increases durability because screws are more chemically stable and withstand heat better, but this increases the recycling cost (i.e., reduces

[2]A collection rate target is defined as the proportion of total product volume sold that needs to be collected for recycling.

recyclability) as screws require labor for disassembly (Bonnington 2014). Apple replaced PVC by TPE in the sheathings of its new generation lightning cables. These cables are more recyclable yet less durable because TPE is softer (Apple 2015). NiMH batteries are more recyclable than NiCd batteries because they contain more nickel. However, NiMH batteries can be recharged fewer times than the NiCd batteries, i.e., they are much less durable (Langrova 2002).

Photovoltaic Panels (PVPs), which have recently been added to the scope of the WEEE Directive, exhibit a similar durability-recyclability trade-off in multiple design dimensions. For PVPs, choosing the main technology for the photovoltaic cells is an important design decision. Currently, the two most prevalent alternatives that are mature enough for commercial use are crystalline silicon (c-Si) and thin-film technologies. In general, the thin-film PVPs are more recyclable than the c-Si PVPs because the thin-film panels contain precious rare metals such as indium and gallium, which can be recovered by recycling and have positive recycling value. However, a c-Si PVP outperforms a thin-film-based one in product durability because it has a lower degradation rate (Jordan and Kurtz 2012). To be more specific, PVPs bring value to consumers by converting sunlight into electric power, so when the efficiency of this functionality depreciates more slowly, as reflected by a lower degradation rate, it means the products are more durable. The trade-off between recyclability and durability exists in determining the build of PVPs as well. A frameless PVP structure facilitates recycling due to easier disassembly, but may compromise the durability when compared to a framed design (Besiou and Wassenhove 2015). One reason is that frameless PVPs are more vulnerable to damage, especially in a dusty or humid environment. Moreover, the glass-glass frameless PVP modules have a higher degradation rate than the glass-polymer framed modules, which indicates lower durability (Jordan and Kurtz 2012). Finally, the design decision on the encapsulant material (which is a layer of adhesive in PVPs) may also involve a durability-recyclability trade-off.

Silicone encapsulants are less recyclable than EVA-based encapsulants (NovoPolymers 2015) but are more durable as they are more resistant to discoloration-based deterioration.

In this paper, we develop a model to shed light on a durable good producer's choice of durability and recyclability under EPR when these two design attributes interact. In particular, we focus on EPR legislation imposing recycling and collection targets, inspired by the WEEE Directive of the European Commission (Europa-Environment 2012), probably the most influential EPR legislation to date, covering 27 countries in Europe for the majority of electrical and electronic equipment categories. We first derive a cornerstone technical result: a joint closed-form characterization of the optimal recyclability and durability choices. To the best of our knowledge, this is the first paper to provide structural results about the durability-recyclability interaction by endogenizing durability choice in a market subject to EPR.

We leverage this characterization to derive a number of managerial insights. When recyclability and durability are synergistic design attributes, a more stringent recycling rate target indeed leads to the most favorable design outcome: a product that is more recyclable and durable. However, a producer's design choices can be quite counter-intuitive when the two attributes conflict (as in the above examples). Relatively low recycling targets work as intended, i.e., durable goods producers should design for recyclability, but this may come at the expense of durability. However, further increases in recycling targets may drive producers to switch to designing more durable products at the expense of recyclability. This effect is even stronger for producers with higher profit margins.

Furthermore, a similar analysis of the collection targets reveals that seemingly similar EPR implementation levers have very different effects on a durable good producer's design choices. Collection targets have the complete opposite effect compared to the recycling targets: Relatively low collection targets imply that durable goods producers should design for durability, which helps reduce collection volume obligations by reducing sales volume, but this may come at the expense of lower recyclability. Interestingly, further increases in collection targets may drive producers to switch to designing more recyclable, yet less durable products despite the increased collection volume obligations this strategy may imply. This effect is further strengthened when recycling a unit is profitable and implies a competitive market for access to end-of-life products. In that case, a durable good producer always designs more recyclable but less durable products as collection targets become more stringent. We show that under some conditions, the emphasis on lower durability in response to stringent collection targets translates to increased production and disposal volumes.

We conclude that implicit assumptions on EPR-driven product design changes may not necessarily hold in durable goods markets. In particular, a stricter recycling target does not necessarily translate to a more recyclable product. Interestingly, there are some instances where higher durability may be observed without directly targeting durability. Moreover, depending on the economics of recycling, the collection rate lever can work in different ways. The policy implication is that in durable goods markets, the design outcomes associated with different EPR implementation levers such as collection and recycling targets (and their stringency level choices) should be carefully evaluated and these policy tools should be adapted to the product category.

To demonstrate how the implications of chosen policy levers on product design can be analyzed, we perform a calibrated numerical study for PVPs, a product category that was recently added in the WEEE Directive Recast and that faces clear trade-offs between recyclability and durability as explained above. The set-up of the WEEE Directive is especially interesting for our analysis, as its recent recast (Europa-Environment 2012) calls for collection and recycling targets to become more stringent over time. We focus on the design trade-off in the choice between c-Si and thin-film technologies for the PV cells. Using real market data and expert input from the

PVP industry, our analysis allows us to investigate the implications of the WEEE Directive Recast on PVP producers' technology choice, illustrating the advantages and pitfalls of EPR on design for the environment. This analysis demonstrates the importance of not using uniform legislative targets regarding recycling and collection rates for all product categories, but rather adapting these targets to product and market characteristics and environmental impact priorities.

2.2 Literature Review

This work draws on and contributes to EPR-related research at the interface of operations management and environmental economics. Environmental economists have long studied the economic and environmental implications of EPR, particularly to analyze and compare the efficiency of different EPR policy instruments. Among those are (i) financial instruments such as production taxes, advance recycling fees, and refunds (see Turner and Pearce 1994, for a discussion); (ii) information- based instruments, e.g., labeling requirements mandating producers to display the environmental characteristics of their products (Lindqvist 2000); and (iii) administrative instruments, in the form of requirements imposed on producers, such as product take-back mandates (Lee 2002, Toffel 2003). See Callcott and Walls (2002), Eichner and Pething (2001), Fullerton and Wu (1998) and Dinan (1993) for further discussion as to how these different policy instruments compare.

We differ from this stream of research by our operational focus, i.e., we provide a detailed analysis of design choices under product take-back mandates (which are prevalent for a variety of reasons; see Atasu and Van Wassenhove 2010, for a detailed discussion) in the presence of a durability-recyclability trade-off in design. Focusing on operational questions has proven useful in studying various issues regarding environmentally sustainable practices in business (see Guide and Van Wassenhove 2007, Atasu et al. 2008, Ferguson and Souza 2010, for reviews). Studies in this vein include (i) reverse logistics for used or recovered products (Fleischmann et al. 2001, De Brito and Dekker 2004, Savaskan et al. 2004); (ii) inventory management with remanufactured products (Toktay et al. 2000, DeCroix 2006); (iii) consumer returns management (Guide et al. 2006, Ferguson et al. 2006); (vi) joint management of new and remanufacturered products in the market (Debo et al. 2005, Tereyagoglu et al. 2015); (v) sustainability of different business models (Agrawal et al. 2012, Ulku et al. 2012); and (vi) sustainable production via responsible sourcing by producers (Kraft et al. 2013, Kraft and Raz 2015) or by suppliers (Agrawal and Lee 2015). In particular, we contribute to the recent operations management literature investigating the implications of environmental legislation in different operational settings. Related research covers topics including (i) the effect of disclosure mandates on producers' efforts to evaluate their environmental impacts (Kalkanci et al. 2015); (ii) the effect of emission legislation on carbon leakage (Islegen and Reichelstein 2011, Drake 2012); and (iii) the effect of consumer subsidies or environmental taxes on the adoption of green technologies (Cohen et al. 2015, Chamama et al. 2015, Krass et al. 2013). Recent research that shares our focus on EPR legislation includes (i) the effect of incorporating reuse targets in EPR on remanufacturing and the environment (Karakayali et al. 2015, Esenduran et al. 2014); (ii) the effect of collection and recycling cost structures and competition on the efficiency of EPR (Atasu et al. 2009, Toyasaki et al. 2011) and different stakeholders' perspectives (Atasu et al. 2012); (iii) cost allocation in collective EPR implementations considering network-based operations (Gui et al. 2015) and exogenous cost sharing mechanisms (Atasu and Subramanian 2012, Jacobs and Subramanian 2011); (iv) the effect of secondary market interference practices (Alev et al. 2014); and (v) the effect of EPR on producers' new product introduction decisions (Plambeck and Wang 2009) and product design choices (Atasu and Subramanian 2012, Subramanian et al. 2009, Atasu and Souza 2012, Raz et al. 2015, Esenduran and Kemahlioglu-Ziya 2015, Esenduran et al. 2015, to name a few).

Our work is closely related to the last group of papers that explore the product design implications of EPR. Yet, to the best of our knowledge, none of these study EPR-driven design changes for durable products, or the associated durability-recyclability trade-off.

Our consideration of the design decisions on both recyclability and durability attributes has commonalities with new product development research that involves design with respect to multiple quality dimensions (Lacourbe et al. 2009, Chen 2001, Krishnan and Zhu 2006, Kim and Chhajed 2002, Chambers et al. 2006). We contribute to this stream by integrating a general model of design interactions in a durable goods setting to study the influence of EPR legislation on eco-design attributes. Our work also contributes to research in the durable goods literature (cf. Waldman 2003 for a comprehensive review) that analyzes a producer's pricing and design decisions (see Coase 1972, Bulow 1982, 1986, Kim 1989, Choi 1994, Waldman 1996, Hendel and Lizzeri 1999, Huang et al. 2001, Agrawal et al. 2012, 2015). To the best of our knowledge, the effect of EPR on a producer's product durability choice has not been studied to date and our results show that the effect of EPR can be quite nuanced.

2.3 Model

In this section we build a discrete-time, infinite-horizon model to analyze the implications of EPR on a durable good producer that designs its product for durability and recyclability. Periods are indexed by $t \geq 0$ and the timeline of events is as follows. At period $t = 0$, a legislator announces the EPR obligations imposed on the producer. Given the EPR obligations, the producer determines its product design, namely the durability and recyclability of the product. In each subsequent period $t > 0$, the producer sets its new product sales price p^t, recycles a portion of end-of-life products arising from past sales, and consumers make purchasing decisions given product durability and price.

Below, we first describe the assumptions regarding our market equilibrium analysis for $t > 0$, and characterize the demand. After that, we describe the model assumptions regarding the producer's product design decisions under EPR, which helps us formulate the producer's objective.

2.3.1 Demand Characterization

We consider a discrete-time, infinite-horizon, sequential game between a producer selling a single durable product and consumers, given a product with durability $\delta \in [0, 1]$ and recyclability $\rho \geq 0$. We assume that the product of interest has a two-period lifetime (Desai and Purohit 1998, Huang et al. 2001, Hendel and Lizzeri 1999, Agrawal et al. 2015). A product can be in one of three states during its lifetime: *new* during the first period of use, *used* during the second period of use, and *end-of-life* after two periods of use. We assume it still provides consumer utility after one period of use, but none after two periods of use.

The market size remains constant in each period t. Each consumer uses at most one unit of product at any time. Without loss of generality, we normalize the market size to a unit mass of customers indexed by their type θ. To capture market heterogeneity, we assume θ is uniformly distributed in $[0, 1]$. A consumer type θ obtains a gross utility of θ and $\delta\theta$ from using new and used products for a period, respectively, where product durability is denoted by δ and represents the relative value of a used product compared to a new one, implying a depreciation or value loss after use that is typical for durable products. At the end of every period, consumers who own a product that still has useful life left may choose to sell the used product on the secondary market at the market-clearing price $p_u^t \doteq p_u^t(p^t)$ and purchase a new one. In analyzing the game between the producer and the consumers, we focus our analysis on stationary equilibria, where the price stays constant in time (Hendel and Lizzeri 1999, Huang et al. 2001, Plambeck and Wang 2009, Agrawal et al. 2015); i.e., $p^t = p$

and $p_u^t = p_u$. This rules out transient effects due to only new products being present in the first period.

We assume that the consumers are forward looking. We also assume that all information regarding the cost structures and preferences is common knowledge, and all players have a common discount factor γ. Given the two-period lifetime of a product, we need only focus on two-period customer strategies. Moreover, the consumer utility from holding on to the product after using it for one period is equivalent to selling the one-period-old product at that point and buying a used one on the secondary market (cf. Appendix A.1 of Agrawal et al. 2015). Therefore, under stationarity, the per-period net utility from purchasing a new product is $\theta - p + \gamma p_u$, that from purchasing a used product is $\delta\theta - p_u$ and that from remaining inactive is 0. Furthermore, the net utility from these actions is independent of the consumer's past actions. Consequently, there are only three undominated consumer strategies: buy new products in every period (Bn), buy used products in every period (Bu), and always remain inactive (RI); see also Hendel and Lizzeri (1999a), pp. 1099-1100 for an intuitive explanation of this. The per-period utilities of consumers choosing these undominated strategies are denoted by: $V[Bn, \theta] = \theta - p + \gamma p_u$, $V[Bu, \theta] = \delta\theta - p_u$ and $V[RI, \theta] = 0$, respectively. The differences $V[Bn, \theta] - V[Bu, \theta]$ and $V[Bu, \theta] - V[RI, \theta]$ are increasing functions in θ. Therefore, there exist $\theta_1, \theta_2 \in [0, 1]$ such that consumers of type $\theta \in (\theta_1, 1]$ choose Bn, those of type $\theta \in (\theta_2, \theta_1]$ choose Bu and all others remain inactive. Then the demand for new products, $q(p, \delta)$, can be written as $q = 1 - \theta_1$ and the secondary market clearing price p_u can be obtained by solving $\theta_2 - \theta_1 = 1 - \theta_1$. This analysis gives $\theta_1 = \frac{p+\delta+\gamma\delta}{1+\delta+2\gamma\delta}$, $\theta_2 = \frac{-1+2p+\delta}{1+\delta+2\gamma\delta}$ and $q = 1 - \theta_1 = \frac{1+\gamma\delta-p}{1+\delta+2\gamma\delta}$. For simplicity, we take $\gamma = 1$ in the remaining of the paper, i.e., $q = 1 - \theta_1 = \frac{1+\delta-p}{1+3\delta}$.

2.3.2 Design Choices

We model the EPR obligations based on the WEEE Directive implementations in Europe, and consider a collection rate target $\lambda \in [0, 1]$ and a recycling rate target $R \in [0, 1]$ imposed on the producer (see §2.5.3 for a discussion on other forms of EPR implementation). We assume that the collection rate target requires the producer to collect a minimum λ fraction of all end-of-life products, mimicking the WEEE Directive that specifies a percentage of total products put on the market that producers are required to collect (DBIS 2012). The recycling rate target requires the producer to recycle at least R percentage (by weight) of each unit of product collected. This modeling choice also follows from the recycling rates of the WEEE Directive that are defined in terms of the percentage by weight per appliance, which can vary from $50\% - 80\%$ depending on product category (Europa-Environment 2010).

The recycling rate target directly influences the economics of recycling: End-of-life products consist of parts that have different recycling value, and recycling typically concentrates on the parts that have the highest value. For example, cellphone recycling focuses on harvesting the precious metal used in the circuit boards and soldering, such as gold, silver and copper. As the recycling percentage of a cellphone increases, recycling extends to also include the pure handset casings and then the mixed plastics, which have lower recycling value (Mobile Muster 2015). Similarly, for a desktop computer, the CPUs, memory cards, and motherboards are usually the components that recycling focuses on due to their precious metal content and hence higher value. If a higher recycling rate is desired from the item, then the less valuable parts such as the wires, aluminum heat sink or even the plastic casings will be recycled (SMF 2012). Therefore, for recycling every unit of product, the marginal recycling value (denoted as $f(r)$) can be represented as a non-increasing step function in the recycling level (denoted as r and $r \in [0, 1]$), with the steps corresponding to different materials/components of the product. $f(r)$ can also be negative for certain values of

r, which indicates a cost incurred to recycle some parts of the product. This can be the case for products such as CRT monitors: While the yoke and circuit boards have positive recycling value, the leaded glass imposes a cost (MRI 2014). We approximate this relation by a linear function and let $f(r) = \alpha - \beta r$. Here, α represents the marginal recycling value from the most valuable parts (such as the gold from cellphones, or the CPUs from desktop computers). β represents the degree to which the marginal recycling value drops as the recycling level increases, for example, β for CRT monitors may be large because when the level of recycling rises from only including the yoke (with valuable materials) to also including the leaded glass components (costly to process), the marginal recycling value drops dramatically. In the absence of a given recycling target being specified by EPR legislation, the profit-maximizing producer would optimally only recycle the parts of each product unit that generate positive marginal recycling value. In other words, $r^* = \min\{1, \max\{0, \overline{r}\}\}$, where $\overline{r}$ solves $f(\overline{r}) = 0$, and the unit recycling value, i.e., the total recycling value obtained from one unit at the chosen recycling rate, equals $\int_0^{r^*}(\alpha - \beta\phi)d\phi$. If the recycling rate target enforced by EPR is more stringent ($R > r^*$), the producer is mandated to recycle some parts that do not generate positive marginal recycling value and the unit recycling value obtained ($\int_0^R(\alpha - \beta\phi)d\phi$) would be lower and could even be negative.

To lower the unit economic burden associated with mandated recycling, the producer can design for recyclability. For instance, when products are designed for ease-of-disassembly or use more recyclable materials, the unit recycling value will be higher. To model such design improvements for recyclability (denoted by ρ) in a tractable manner, we assume that the marginal recycling value at any recycling level increases by ρ. In other words, $f(r, \rho) = \alpha + \rho - \beta r$. As such, for a given recycling level r, recycling a unit with recyclability level ρ brings a unit recycling value of $v(r, \rho) = \int_0^r(\alpha + \rho - \beta\phi)d\phi = -\frac{1}{2}\beta r^2 + (\alpha + \rho)r$ (which can be negative). For a given collection target λ, this implies an effective unit recycling value of $\lambda v(r, \rho)$.

Alternatively, a producer subject to EPR legislation can design for durability, which we assume is equivalent to choosing δ. Increasing durability implies a higher consumer utility from buying new products. Therefore, it enables the producer to price the products higher and sell a smaller quantity, resulting in fewer end-of-life products and hence a smaller volume of products to recycle. This reduces the cost of complying with EPR legislation.

The producer's design decisions on durability (δ) and recyclability (ρ) influence the production costs. To capture this, we assume that a product that is non-durable and non-recyclable can be produced at cost $m > 0$ per unit, and that the cost of producing a unit of product with durability δ and recyclability ρ is given by $g(\rho, \delta) = m + \tau\rho^2 + b\delta^2 + d\rho\delta$, where $\tau, b \geq 0$[3].

This formulation considers durability and recyclability as different quality dimensions as in Krishnan and Zhu (2006). The coefficients τ and b reflect the rate of cost increase driven by the relevant design attribute, and the associated terms are quadratic to reflect decreasing returns in these design attributes (Purohit 1994, Atasu and Subramanian 2012). The last term in this formulation captures the possible interaction between recyclability and durability choices in product design (paralleling Krishnan and Zhu 2006). When the two attributes are synergistic as in the example of thick aluminum panels in cars, or of metal in desktop computer casings, $d < 0$. However, when there is a trade-off between durability and recyclability as in the example of PVPs, $d > 0$, reflecting a higher cost to realize improvements in both attributes.

2.4 *The Equilibrium Characterization*

Following the stationary demand characterization provided in §2.3.1, we assume that the producer maximizes its per-period profit in steady state. Given the sequential nature of the model, we solve the producer's profit maximization problem by backward

[3] Any collection (c_c) and recycling cost (c_p) that is incurred at a unit level (independent of recycling rate) can be captured by adjusting the unit production cost by $\lambda(c_c + c_p)$.

induction: Let $\Pi(p, r; \rho, \delta) = q(p, \delta) \cdot (p - g(\rho, \delta) + \lambda v(r, \rho))$ denote the producer's per-period steady-state profit given durability δ and recyclability ρ, and the associated recycling, collection and production costs provided in §2.3.2 under a mandated collection rate λ (which we assume to be binding due to costly recycling or competition for profitable recycling; both cases are discussed in §2.5.2). We first solve $\max_{p,r} \Pi(p, r; \rho, \delta)$ subject to $r \geq R$ in steady state. Let $\Pi^*(\rho, \delta)$ denote the solution to this problem. Then, the producer's design problem can be formulated as $\max_{\rho,\delta} \Pi^*(\rho, \delta)$.

Substituting previously derived expressions into the profit function, we obtain:

$$\Pi(p, r; \rho, \delta) = \left(\frac{1 + \delta - p}{1 + 3\delta}\right) \left(p - (m + \tau\rho^2 + b\delta^2 + d\delta\rho) + \lambda((\alpha + \rho)r - \frac{1}{2}\beta r^2)\right). \tag{1}$$

Lemma 2.1 characterizes the producer's recycling level and pricing decisions as well as the resulting demand in steady state for given (ρ, δ). In our analysis, we assume $2\beta\tau > \lambda$ so that (A1) is jointly concave with respect to (ρ, r). We also restrict the analysis to parameters $(m, \tau, b, d, \alpha, \beta)$ where for at least some values of $(\rho, \delta, r, \lambda)$, the unit profit margin is non-negative and the unit recycling value is lower than the unit production cost. All proofs are provided in the Appendix.

Lemma 2.1 *Given a product design with ρ and δ, the optimal recycling level $r^*(\rho, \delta)$ and the new product price $p^*(\rho, \delta)$ can be summarized as follows. When $\frac{\alpha+\rho}{\beta} \leq R$, $r^*(\rho, \delta) = R$; when $R < \frac{\alpha+\rho}{\beta} < 1$, $r^*(\delta, \rho) = \frac{\alpha+\rho}{\beta}$; and when $1 \leq \frac{\alpha+\rho}{\beta}$, $r^*(\delta, \rho) = 1$. The optimal price $p^*(\rho, \delta) = \frac{1}{2}\left(1 + \delta + g(\rho, \delta) - \lambda((\alpha + \rho)r^*(\rho, \delta) - \frac{1}{2}\beta(r^*(\rho, \delta))^2)\right)$. The corresponding new product demand is $q(p^*(\delta, \rho), \delta) = \frac{1}{2(1+3\delta)}\Big(1 + \delta - g(\rho, \delta) + \lambda((\alpha + \rho)r^*(\rho, \delta) - \frac{1}{2}\beta(r^*(\rho, \delta))^2)\Big)$.*

Lemma 2.1 identifies three recycling scenarios that will be observed in equilibrium, which map well to the range of recycling choices in practice. The first case (i.e., $r^* = R$) represents scenarios where voluntary recycling is not profitable enough and hence the recycling target is binding at optimality. This outcome represents the case of regulated markets for most electronics, either due to low recycling margins (α is small) as in the case of fluorescent lamps, or a quick drop in the marginal recycling value when the recycling level increases (β is high) as is typical in CRT recycling. The second case, $r^* = \frac{\alpha+\rho}{\beta}$, represents voluntary (and partial) recycling beyond compliance requirements, which represents the case of the car industry subject to legislation such as the End of Life Vehicles Directive, where voluntary recycling has reportedly exceeded the compliance requirement levels (Smink 2006). Finally, the last case with full recycling, i.e., $r^* = 1$, represents markets for valuable commodities such as aluminum cans. Given this characterization of the producer's optimal recycling and pricing decisions for a given design profile, we next investigate the producer's design choices.

To build intuition as to the producer's design choices, we first start with a simple benchmark scenario that ignores the possible design interactions between durability and recyclability, i.e., we assume $d = 0$. Proposition 2.2 presents the producer's recyclability choice for a given durability level.

Proposition 2.2 *Let $d = 0$. The optimal recyclability choice (and the corresponding optimal recycling level) can be summarized as follows. When $\alpha \leq R(\beta - \frac{\lambda}{2\tau})$, $\rho^* = \frac{R\lambda}{2\tau}$ and $r^* = R$; when $R(\beta - \frac{\lambda}{2\tau}) < \alpha < \beta - \frac{\lambda}{2\tau}$, $\rho^* = \frac{\alpha\lambda}{2\beta\tau-\lambda}$ and $r^* = \frac{2\alpha\tau}{2\beta\tau-\lambda}$; and when $\beta - \frac{\lambda}{2\tau} \leq \alpha$, $\rho^* = \frac{\lambda}{2\tau}$ and $r^* = 1$.*

Proposition 2.2 states that in the absence of a durability-recyclability interaction, the recyclability choice of the producer will be primarily driven by the baseline recycling value α, which is a measure of recycling benefits that can be obtained from recycling in the absence of design for recyclability. Two intuitive observations from this proposition are that (i) as α increases, the recyclability choice of the producer will increase and (ii) the recycling target will be binding only if α is sufficiently low. Moreover, ρ^* does not depend on δ, the durability level of the product: In the absence of the design interaction, the choice of recyclability boils down to minimizing the unit cost subject to the recycling target requirement.

Given this observation, we next characterize the producer's optimal durability choice. The analysis reveals that the unit profit margin of a non-durable product at its optimal recyclability level is key; we call this quantity A[4]. A increases when the product has a higher recycling value potential (higher α or lower β), or a lower production cost (m). In turn, given A, the producer's profit for a given δ can be written as $\Pi(\delta) = \frac{1}{4(1+3\delta)}(\delta - b\delta^2 + A)^2$ (see Lemma 2 in the Appendix for a derivation), which leads us to one of the important technical results in this paper.

Proposition 2.3 *Let* $d = 0$, $\overline{A}(b) \doteq \frac{1}{3}(5-13b)$, $\widehat{A}(b) \doteq \frac{2}{243}(27+8b) + \frac{2}{243}\sqrt{\frac{729+972b+432b^2+64b^3}{b}}$ *if* $b < 3/4$ *and 2/3 otherwise, and* $\delta_{int} \doteq \frac{(3-4b)+\sqrt{(3-4b)^2+3b(2-3A)}}{18b}$. *The optimal durability choice of the producer is characterized as follows: When* $0 \le b < \frac{1}{5}$, *then* $\delta^* = 1$ *if* $A < 1-b$ *and 0 otherwise; when* $\frac{1}{5} \le b < \frac{5}{13}$, *then* $\delta^* = 1$ *if* $A < \overline{A}(b)$, $\delta^* = \delta_{int}$ *if* $\overline{A}(b) \le A < \widehat{A}(b)$, *and* $\delta^* = 0$ *otherwise; and when* $\frac{5}{13} \le b$, *then* $\delta^* = \delta_{int}$ *if* $A < \widehat{A}(b)$, *and 0 otherwise.*

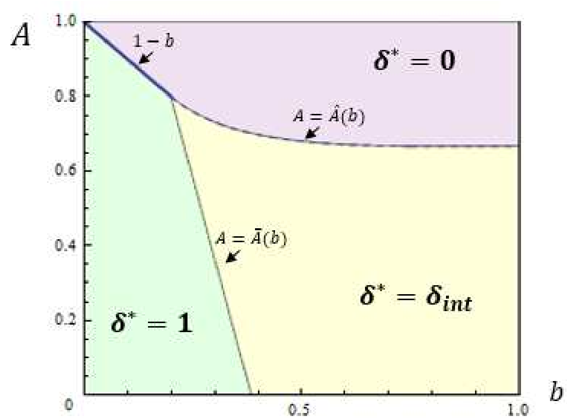


Figure 1: The optimal durability δ^* as a function of A and b.

Proposition 2.3 characterizes the optimal durability choice of the producer in the

[4]Following Proposition 2.2, A is given by $1 - m + \lambda(R\alpha - \frac{2\beta\tau-\lambda}{4\tau}R^2)$, $1 - m + \frac{\alpha^2\tau\lambda}{2\beta\tau-\lambda}$, $1 - m + \lambda(\alpha - \frac{2\beta\tau-\lambda}{4\tau})$ for the three cases represented in equilibrium, respectively.

absence of the durability-recyclability interaction in design, which is illustrated in Figure 1: The optimal durability choice of the producer simply depends on the marginal cost of designing for durability (b), and the unit profit margin for a non-durable product (evaluated at the optimal recyclability level). In essence, a large unit profit margin from a non-durable product (i.e., high A) implies that the producer would like to sell as many of those products as possible. Hence, the larger the A, the lower the optimal durability choice of the producer. Note that a number of factors determine the magnitude of A: In particular, a higher recycling target R (weakly) reduces A - that is, more stringent recycling targets will lead the producer to design equally or more durable products. In contrast, a large α, or a low β and m imply a larger A, meaning that products that are inherently easier to recycle and cheaper to produce will be subject to design for product obsolescence (low durability), irrespective of the directional improvement achieved by more stringent recycling targets. To the best of our knowledge, this is the first closed-form characterization of a producer's durability choice, jointly considering the implications of EPR and markets for durable goods (i.e., the interaction between new product sales and secondary markets), which advances our understanding of the interactions between EPR and durable goods markets. It also lays the foundation for analyzing the design interaction we focus on, which is investigated next.

We now turn to the case of a non-zero interaction term $d \neq 0$. While omitted here for brevity, we first prove a result paralleling Proposition 2.2 to characterize the optimal recyclability choice in this case (see Lemma 3 in the Appendix for details). Proposition 2.4 then characterizes the optimal durability choice.

Proposition 2.4 *The producer's profit function is of the form* $\Pi_j(\delta) = \frac{F_j^2}{4(1+3\delta)}(\delta - b_j\delta^2 + A_j)^2$ $\forall d$, *defined by a set of* F_j, b_j *and* A_j *(detailed in the Appendix). The optimal durability choice is unique and of the form* $\delta^* = \arg\max_j \left\{\Pi_j(\delta_j^*)\right\}$.

Proposition 2.4 essentially states that the optimal durability characterization in the presence of a non-zero interaction term $d \neq 0$ follows from the characterization in Proposition 2.3 with $d = 0$. The only difference is that depending on the value d, there exist sets of mutually exclusive and collectively exhaustive cases with corresponding expressions of F_j, b_j and A_j such that the producer's profit $\Pi(\delta)$ is fully characterized by a high-order polynomial. Yet the characterization of the optimal δ within each case j (denoted as δ_j^*) is identical to that in Proposition 2.3, and the globally optimal unique δ^* is easily obtained by a profit comparison across those cases. The significance of this result is that it provides us with a closed-form solution that allows us to analyze the implications of EPR on the design of durable products, which we investigate in detail in the next section.

2.5 The Effect of EPR on the Design of Durable Products

We are now poised to answer the core research questions posed in this paper by investigating how the recycling and collection targets affect the producer's design choices. We start with the simpler case of a synergistic design interaction.

Proposition 2.5 *When $d \leq 0$, the optimal durability and recyclability choices are (weakly) increasing in the recycling target R and the collection target λ.*

When there is a synergistic design interaction between durability and recyclability choices (e.g., as in desktop computers), an increase in the recycling and collection targets (R and λ) leads to a simultaneous increase in recyclability and durability: More stringent recycling or collection targets naturally generate a positive impetus for increasing ρ^* and δ^* because when higher collection and recycling levels are mandated, the former increases the marginal recycling value, whereas the latter helps reduce the sales volume and hence the volume of recycling.

The same intuition however, does not hold when the two attributes are conflicting in design (as in the examples provided in the introduction), i.e., when $d > 0$. Accordingly, in what follows, we focus our attention to $d > 0$. We further focus on the case where the recycling target is binding (i.e., $r^* = R$) in equilibrium, which allows us to focus on legislation-induced design choices. To derive the key insights while keeping the analysis concise, we assume $b = \tau$, i.e., the costs of improving the two attributes are comparable. We first analyze the effect of the recycling target R, and then analyze the same for the collection target λ.

2.5.1 Recycling Targets

Proposition 2.6 *When $d > 0$, $\exists\ R_{dl}, R_d$, where $0 \leq R_{dl} \leq R_d \leq 1$ such that the optimal durability δ^* decreases if $R \in [R_{dl}, R_d]$ and (weakly) increases otherwise.*

Proposition 2.6 provides an important result regarding the directional impact of the recycling target R on the producer's choice of product durability. In particular, this result reveals that the durability choice is non-monotonic in the recycling target when $d > 0$, and that there exists a range of the recycling target in which an increase in R implies reduced durability. This result can be explained by analyzing the effect of R on the recyclability choice and its interaction with the durability level, which is explored in the next proposition and illustrated in Figure 2.

Proposition 2.7 *When $d > 0$, (i) $\exists\ R_r, R_{rr}$ where $0 \leq R_r \leq R_{rr} \leq 1$ and $\overline{d} \geq 0$, such that the optimal recyclability is decreasing if $R \in [R_r, R_{rr}]$ and (weakly) increasing otherwise; (ii)$R_{rr} = 1$ when $d > \overline{d}$; and (iii) $R_d \leq R_r$, with $R_d = R_r$ when $m \leq \overline{m}$.*

The first part of Proposition 2.7 says that the effect of R on the producer's recyclability choice is also non-monotonic. That is, there exists a range of R for which increasing R may reduce the producer's recyclability choice. Furthermore, the second part of the proposition states that when the design trade-off is critical (i.e., $d > \overline{d}$), ρ^* decreases over the entire range $[R_{rr}, 1]$. The last part of the proposition states that when the marginal production cost of a (non-recyclable, non-durable) product

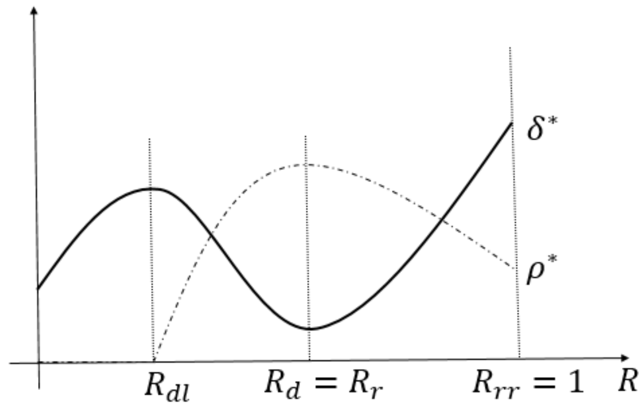


Figure 2: A sketch of the effect of R on δ^* and ρ^* when $d > \overline{d}$ and $m \leq \overline{m}$.

is sufficiently small, the range where the recyclability of a product goes down perfectly coincides with the range where the product durability increases. In sum, this proposition clarifies the design dependency we explore under EPR as follows:

When there is a conflict between the two design options, design improvements will need to concentrate more heavily on the attribute that more effectively eases the economic burden of recycling obligations, but the effectiveness of each design option heavily depends on the chosen recycling targets. Propositions 2.6 and 2.7 explain the resolution to the design trade-off as follows (illustrated in Figure 2 for the parameter range in which the design trade-off is most influential): At low R levels (i.e., R remains below R_{dl}), an increase in R implies increased durability only ($\rho^* = 0$). This happens because at low values of R, the marginal value of making the product more recyclable is lower than the same at high values of R ($\frac{\partial^2 v(R,\rho)}{\partial \rho \partial R} > 0$). Therefore, when $R \leq R_{dl}$, the producer relies on increasing durability alone. Beyond ($R > R_{dl}$), however, the marginal value of recyclability is more substantial, and the producer starts investing in recyclability. Given the design interaction, this makes durability expensive to maintain. Thus, the producer reduces product durability. This trend continues only up to a certain point (R_r), beyond which the cost of making the product more recyclable implies a narrow profit margin, and the producer instead invests in increasing durability so as to increase the product price and hence the unit margin. An additional benefit of increasing durability is reducing the sales volume, and hence the total cost associated with recycling. Because of the design interaction in cost, the producer starts decreasing the product recyclability once R goes beyond this threshold. The key conclusion from this analysis is that very stringent recycling targets do not necessarily imply the highest levels of recyclability; rather they will drive the producer towards more durable but less recyclable designs.

In sum, the non-monotonicity of ρ^* and δ^* with respect to the recycling target implies that legislation that aims to promote easier recycling cannot assume higher recycling targets will drive producers towards more recyclable designs. Rather, in the presence of a design trade-off between durability and recyclability, producers may opt for durability improvement at the expense of diminished recyclability. Inducing durable goods producers to maximize the recyclability of their products may imply imposing rather conservative recycling targets. This however, may come at the expense of reducing product durability, i.e., design for obsolescence.

2.5.2 Collection Targets

We next investigate the implications of a binding collection target on the producer's design choices. In doing so, we distinguish between two scenarios: costly and profitable recycling. We first focus our analysis on $v(R, 0) \leq 0$, i.e., recycling is costly. We then consider the implications of profitable recycling for $v(R, 0) > 0$, under which the producer needs to compete with third parties to gain access to end-of-life products with recoverable value. As before, we focus our analysis on cases where the recycling target is binding.

2.5.2.1 Costly Recycling

Proposition 2.8 *When $d > 0$, $\exists \lambda_d \geq 0$ such that the optimal durability is decreasing if $\lambda \geq \lambda_d$, and (weakly) increasing otherwise.*

Proposition 2.8 states that the producer's durability choice is non-monotonic in the collection rate target as well. While the non-monotonicity is similar to the situation with the recycling rate target, interestingly the collection target's effect on the design choices of interest is reversed. In particular, very stringent collection targets can backfire and drive the producer to design products with lower durability. As before, this effect is driven by the conflict between recyclability and durability, which can be further clarified with the help of Proposition 2.9 below.

Proposition 2.9 *When $d > 0$, $\exists \lambda_{rl}, \lambda_r$ such that $0 \leq \lambda_{rl} \leq \lambda_r \leq 1$ and the optimal recyclability choice is decreasing in $\lambda \in [\lambda_{rl}, \lambda_r]$, and (weakly) increasing otherwise. Furthermore, $\lambda_r \leq \lambda_d$.*

Similar to the earlier discussion on the recycling rate targets, the presence of the design trade-off may render simultaneous increase in recyclability and durability too costly. As such, the producer needs to rely more on one lever than the other. Propositions 2.8 and 2.9 collectively resolve the design trade-off under the collection rate target as follows: At a low collection target λ, the producer utilizes the durability lever first as it has a direct impact on the sales volume and hence the collection volume (i.e., a more durable product sells at a higher price and leads to a lower sales volume), and reduces the product recyclability. When the collection rate target goes beyond a certain threshold (λ_r) though, the marginal benefit of increased durability starts shrinking and the producer starts designing for recyclability as well. When the collection rate further increases beyond a certain threshold (λ_d), the benefit from recyclability dominates the same from durability, as recyclability increases the recycling value for each unit of the higher collected volume. Therefore, the producer chooses more recyclable but less durable product designs.

2.5.2.2 Profitable Recycling and Competition for Valuable Waste

When the inherent recyclability in a product is sufficiently high (e.g., α is large enough) or a binding recycling rate target maintains a net profit from recycling in a regulated market (i.e., $v(R, 0) > 0$), we need to consider an important phenomenon: competition for cores (i.e., end-of-life products) by third parties who are attracted to the collection and recycling market (see Esenduran et al. 2015 for a detailed discussion). For example, the removal of toxic materials from batteries led to a flourishing battery recycling industry involving a large number of third-party recyclers (BU 2015). In the remainder of this section, we analyze recyclability and durability choices under such third-party competition.

Since EPR requires only the producer to collect λ portion of end-of-life products for recycling (Esenduran et al. 2015), we first need to analyze the implications of competition with independent third parties, based on which we can study the implications of λ on the design decisions of durability and recyclability when waste has value. To model such competition, we consider the existence of n independent for-profit third parties in the collection and recycling market along with the producer. The third parties and the producer pay buyback prices to consumers for returning end-of-life products to their recycling facilities. We assume that the producer, facing the product end-of-life obligation, has built enough capacity to accept and recycle any returns that arrive. In contrast, the capacities of the individual third parties are limited. Yet without loss of generality, we assume that in equilibrium there is sufficient aggregate third-party capacity to cover the whole collection and recycling volume. (We also study more restrictive values of total third-party capacity in the Appendix, and we show that all the major insights remain robust.) We also assume that the unit recycling value extractable by the third parties from each returned unit, denoted by w, will be lower than that for the producer. This could be due to such factors as not having the best adapted technology or not being familiar with the design specifications.

To capture the effect of the collection target on the competition and the buyback prices, we construct a model similar to the one in Arnold (2001). To adapt the model to our setting, we consider that when consumers are faced with this capacitated market, they perform a random search among the producer and all the third parties to decide where to return the core. In every search attempt, the consumer incurs a cost s (which can be regarded as a search or delivery cost). When the consumer encounters a third party that is currently out of capacity, another search (along with the associated cost) is needed, until the core is accepted for a buyback payment. In this case, with third parties who set their buyback prices for profit maximization, we derive the buyback price for the producer to secure the collection rate of λ to be $p_\lambda = w - s((2-\lambda)^2 - 1)$ (see details in the Appendix).

With a binding collection target λ for the producer and the corresponding buyback price p_λ, we first calculate the consumer demand of new products to be $\frac{(1+\delta)-p+(p_\lambda - s)}{1+3\delta}$. Comparing this to the demand in §2.3.1, the change in demand is due to consumers' anticipation that each product will generate an expected net extra value $p_\lambda - s$ at the end-of-life when returned for recycling. Then the producer maximizes the following profit by determining the recyclability and durability in the design stage, and then setting the market price and the actual recycling level:

$$\Pi(p, r; \rho, \delta) = -\frac{(1+\delta) - p + (p_\lambda - s)}{1+3\delta}\left(p - (m + \tau\rho^2 + d\rho\delta + b\delta^2) + \lambda(-\frac{1}{2}\beta r^2 + (\alpha+\rho)r - p_\lambda)\right).$$

We analyze this problem following a similar procedure as discussed in previous sections. The next proposition sheds light on the design incentives created by the collection target.

Proposition 2.10 *When $v(R, 0) > 0$ and $d > 0$, ρ^* is (weakly) increasing and δ^* is (weakly) decreasing in λ.*

Proposition 2.10 suggests that improving recyclability in a competitive market in fact may have an additional benefit because of the following: As before, when making the decisions on recyclability and durability to deal with the EPR obligation, the producer is essentially comparing the marginal benefits of the two attributes, while controlling the associated cost. First, to meet a higher collection target, the producer is also retaining a larger percentage of the marginal return from improving recyclability, hence it is profitable to invest more on recyclability. Meanwhile, a higher ρ^* creates a pressure to compromise durability to achieve cost-effectiveness in the presence of the design trade-off. Second, expanding demand has an additional benefit now because every new product can be sold at a higher price to reflect the buyback value of the product at end-of-life, but part of this benefit is "free" to the producer since a portion of the buyback payments to consumers are made by third parties. Consequently, the producer redirects more investment from durability to recyclability.

In sum, the analysis in this section suggests that the direct impact of very stringent collection targets may be a combination of design for recycling and product obsolescence (i.e., reduced durability), and more so if the inherent recycling value in the product of interest is already high.

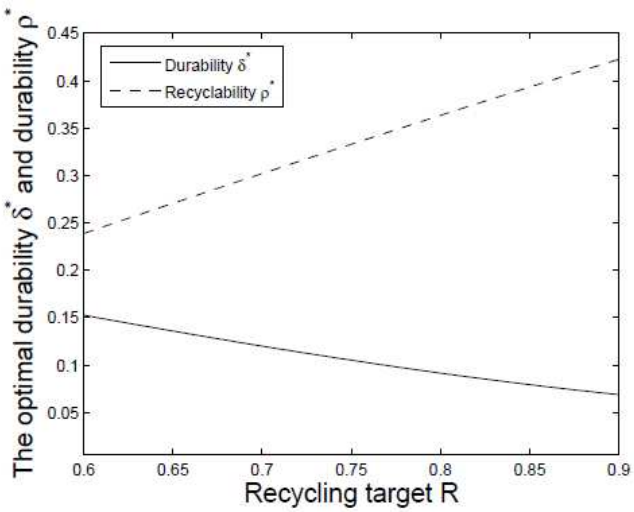
2.5.3 Welfare and Environmental Implications

The analysis above suggests that due to the inherent trade-off between product durability and recyclability, the design implications of EPR for durable products may not be straightforward. In particular, our results show that stringent recycling targets may drive the producer to design more durable yet less recyclable products, and that stringent collection targets may drive the producer to design for recyclability at the expense of reduced durability.

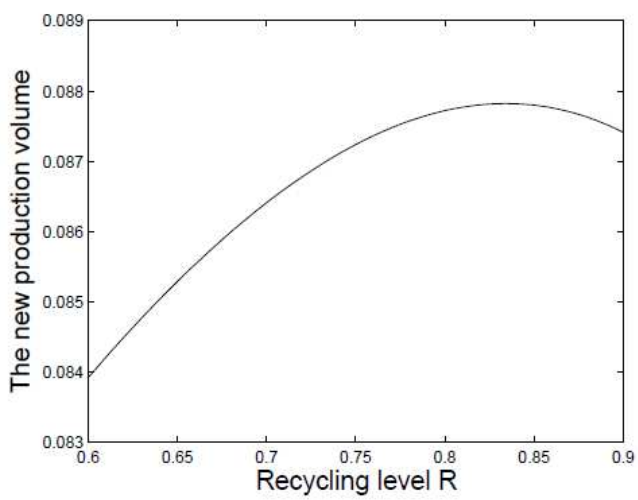
In turn, these contrasting effects of recycling and collection targets on the two design for environment options suggest that EPR may not necessarily increase welfare in a durable goods setting. To shed light onto this issue, consider an additive welfare measure that consists of three traditional economic measures: producer profits, consumer surplus and environmental externalities (see Atasu et al. 2009, Jacobs and Subramanian 2011, Atasu and Souza 2012, Krass et al. 2013, for similar approaches). In our context, it is straightforward to show that both producer profits and consumer surplus measures decrease in the stringency of the recycling and collection targets. Hence, imposing stricter R and λ will only improve welfare if the environmental externalities are reduced by such increases. In the existing literature (e.g., Atasu et al. 2009), which often overlooks product durability, this is often the case. When product durability is considered, on the other hand, a reduction in environmental externalities through increased targets is not guaranteed. For instance, Propositions 2.7 and 2.9 suggest that even though the fraction of products that end up in landfills may go down with higher R and λ, more hazardous substances may find their ways to landfill streams due to reduced product recyclability. Similarly, Propositions 2.6, 2.8 and 2.10 show that an emphasis on design for obsolescence may imply increased production and higher landfilling. To shed further light onto this observation, consider the following result:

Proposition 2.11 *$\exists$ $\overline{\alpha_R}$, $\underline{m_R}$ and $\overline{m_R}$ such that $q(p^*(\rho^*, \delta^*), \delta^*)$ is increasing in R if $\overline{\alpha_R} < \alpha$ and $\underline{m_R} < m < \overline{m_R}$, and decreasing otherwise. In addition, $\exists$ $\overline{\alpha_\lambda}$, $\underline{m_\lambda}$, $\overline{m_\lambda}$, such that $q(p^*(\rho^*, \delta^*), \delta^*)$ is increasing in λ if $\overline{\alpha_\lambda} < \alpha$ and $\underline{m_\lambda} < m < \overline{m_\lambda}$.*

Proposition 2.11 states that increasing collection or recycling targets can increase the overall production and the associated waste generation. In particular, products that have moderate production costs can face this dilemma. For such products, if the inherent recycling value is high, increased recycling or collection targets can lead to increased production because of an emphasis on increasing recyclability at the expense of durability. Figure 3 shows such an example with respect to R. In sum, the



(a) The optimal δ^* and ρ^* as a function of R.



(b) The new production volume as a function of R.

Figure 3: The rebound effect of legislation on the new production volume.
$\alpha = 0.45$, $\beta = 1.15$, $\tau = 1$, $b = 1$, $d = 0.8$, $m = 0.76$

take-away from this figure is that the environmental impact and welfare implications of EPR are not clear cut in the durable goods context.

In closing this section, we also note that our discussion so far has focused on instances of legislation where a producer would directly reap the benefits of what it has sown with respect to recyclability improvements in its products. However, it is also important to note that there are other forms of EPR implementations under which a producer's capability of fully realizing its return on recyclability can be limited. In particular, collective EPR implementations that use weight- or volume- based cost allocations that do not take into account product recyclability, or advance recycling or disposal fees based EPR implementations (see Atasu and Van Wassenhove 2011 and Plambeck and Wang 2009 for examples) can significantly hinder a producer's ability to capture its recyclability investments. The implications of our analysis for such circumstances are as follows: A limitation in the return on recyclability investments can be modeled as a lower return on investments in recyclability in the form of a multiplier $\chi < 1$ in front of ρ in the unit recycling value function $v(R, \rho)$. This will imply a lower ρ^* in equilibrium, and that an increase in the stringency of collection and recycling targets will drive the producer more towards adjusting product durability.

2.6 The Case of Photovoltaic Panels under the WEEE Directive

Our work provides a framework for analyzing the producer response to EPR legislation under the economics of a particular industry and product. To illustrate the insights that can be generated by such an analysis, we choose the PVP industry. PVPs are particularly relevant for our framework for four main reasons: First, PVPs are the most recently added product category under the WEEE Directive Recast that imposes ambitious collection and recycling targets: PVP producers have to meet a 65% collection target by 2019, and an 80% recycling target by 2018. Second, there are two dominant technologies, c-Si and thin-film, which differ in their recyclability and durability. In particular, the c-Si technology produces more durable and less recyclable PVPs than the thin-film technology (see details below). Third, PVPs already have active secondary markets; hundreds of used PVP transactions (with thousands of panels sold) can be found in online consumer-to-consumer trade channels on a daily basis (Ebay 2015) and there already exist third parties selling used PVPs (SecondSol 2015). Finally, PVP producers face tight profit margins, well below 10% before interest and taxes (BNEF 2013, Ng 2014). As such, the product end-of-life obligation imposed by EPR will significantly affect PVP producers' profit margins. In turn, although there may be many factors influencing a PVP producer's technology choice, the implications of EPR cannot be ignored. In particular, PVP producers will need to carefully weigh future recycling cost liabilities associated with potentially higher end-of-life volumes (through less durable but more recyclable panels produced under the thin-film technology) and potentially higher unit recycling costs (through less recyclable but more durable panels produced under the c-Si technology) in making this choice.

To shed some light on this trade-off, we conduct a calibrated numerical study using data from industry reports and practitioner interviews (Coker 2015, Haroon 2015). We set the current status where legislation is absent as the baseline case, and compare it to the scenarios where legisla- tion with binding collection and recycling targets is enforced. As discussed earlier, the durability- recyclability trade-off exists in multiple design dimensions for PVPs. An important one is to choose the technology for the PV cells. Currently, the major commercialized technology categories are c-Si and thin-film. The c-Si technology was the first in the market, and it still dominates with more than 90% market share in 2013 (Fraunhofer 2014). On the other hand, the thin-film technology requires less material in manufacturing and exhibits higher flexibility in application, and hence thin-film investments are expected to grow (GBI 2011, TSS 2015). The thin-film technology con- sists of three primary technologies, including Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe) and Amorphous Silicon (a-Si). We focus on CIGS, as it is a leading technology in the thin-film category in terms of both efficiency and market share. We use the subscripts $j = 1, 2$ for the c-Si and CIGS technologies, respectively.

We conduct the calibration study in four steps. First, we look into the economics of recycling. We consider an estimated current collection rate $\lambda_0 = 20\%$ in the baseline case (BIO 2011). Under a binding collection target, the collection rate will be λ ($> 20\%$) as required by legislation. Recycling will both incur processing costs (i.e., costs of treatment for recycling) and generate recoverable material value. The processing costs, denoted as c_j, can vary significantly between different recycling procedures and facilities. These costs are also expected to change in the coming years due to the fast evolving dynamics of the PVP recycling industry. Therefore, we use a processing cost of $c = \$200$/ton as a benchmark (Choi and Fthemakis 2014, Fthenakis and Moskowitz 1999, BIO 2011) and then show how the result changes with different processing cost values. We derive recoverable material values from the PVP composition and raw material price data (see Appendix for details of the data and the calculation procedure). We convert all the unit values and costs into dollars per kilowatt (\$/kW), which is the measure commonly used in the industry. Considering both the recoverable material value and the processing costs, we calculate the recycling value parameters $\alpha_j + \rho_j$ and β_j. Based on these values for each technology, in the baseline case without legislation (where an additional subscript 0 is used), we calculate the optimal recycling levels r_{j0}^* and the unit recycling values $v_{j0} = -\frac{1}{2}\beta_j(r_{j0}^*)^2 + (\alpha_j + \rho_j)r_{j0}^*$ (see the Appendix for details). Notably, $v_{10} = 8.3$ and $v_{20} = 10$, suggesting that PVPs with the CIGS technology have a higher unit recycling value than those with the c-Si technology, because of their higher rare metal content that can be recovered through recycling (e.g., indium and gallium). When a binding recycling target is in effect, the unit recycling values become $v_j = -\frac{1}{2}\beta_j R^2 + (\alpha_j + \rho_j)R$.

Second, we estimate the durabilities of PVPs with the c-Si and the CIGS technologies. As discussed earlier, the degradation rate reflects how the efficiency of converting sunlight into electric power – the most important functionality of PVPs to generate consumer valuation – depreciates with time. In particular, when used panels are traded in consumer secondary markets (e.g., on ebay or other established marketplaces online), the remaining efficiency after degradation largely determines the resale value, which is consistent with our model. Therefore, the degradation rate is a good proxy for product durability in this context. Studies show that the degradation rates for c-Si and CIGS technologies are approximately 0.5%/year and 0.96%/year, respectively (Jordan and Kurtz 2012, Coker 2015, Haroon 2015). Moreover, PVPs commonly have an expected lifespan of 25 years, which makes a 12.5-year period consistent with our model assumption of a two-period product useful life. Therefore, we estimate the durabilities as $\delta_1 = (1-0.5\%)^{12.5} = 0.94$ and $\delta_2 = (1-0.96\%)^{12.5} = 0.89$; i.e., the c-Si technology is more durable than the CIGS technology. This comparison once again highlights the durability-recyclability trade-off in PVPs: While the CIGS technology is more recyclable, c-Si is more durable.

Third, we study the market for PVPs. Recall that in our model, we assume consumer types (θ that reflects the consumers' product valuations) to be uniformly distributed over $[0, 1]$. In reality, however, the distribution of consumer types can have a more general support on $[0, X]$ with $X > 0$. We infer the values of X_j by using the current PVP market prices p_j and production costs g_j obtained from market studies and reports, based on a generalization of our equilibrium model with $p_j = \frac{1}{2}(X_j(1+\delta_j)-g_j+\lambda_0 v_j)$. This analysis allows us to calibrate our study with $X_1 = 1.26 \times 10^3$ and $X_2 = 1.43 \times 10^3$ (see Appendix for details). We extend our model to account for general X_j values. In this case, the producer profits in equilibrium can be calculated as $\Pi_{j0} = \frac{(X_j(1+\delta_j)-g_j+\lambda_0 v_{j0})^2}{4X_j(1+3\delta_j)}$ in the baseline case and $\Pi_j = \frac{(X_j(1+\delta_j)-g_j+\lambda v_j)^2}{4X_j(1+3\delta_j)}$ when legislation with a binding recycling target R and collection target λ is enforced.

Finally, we analyze the influence of EPR on the producers' product technology choices through its impact on profitability: As discussed earlier, maintaining positive profit margins is a challenge for PVP producers, where margins are tight (BNEF 2013, Ng 2014). As such, the influence of EPR on a PVP producer's profit can be expected to be substantive. To this end, we calculate the relative change in profit due to EPR for a given product technology choice as $\Delta\Pi_j = \frac{\Pi_j - \Pi_{j0}}{\Pi_j}$, where the technology j with the larger $\Delta\Pi_j$ is more vulnerable to legislation because the end-of-life obligation causes a more significant erosion to its profit margin. While various factors may influence a producer's technology choice, $\Delta\Pi_j$ is useful for illustrating the directional impacts of EPR on the possible technology choice of a PVP producer. Focusing on this measure, Figure 4 suggests that the c-Si technology (that is more durable but less recyclable) will face a lower profit margin erosion from a high recycling target under EPR, and the more recyclable but less durable CIGS technology's profit margin erosion will be lower only if the collection target imposed by EPR is very high.

The figure also suggests that the effect of EPR on these technology choices will depend on market dynamics with respect to processing cost efficiency improvements for recycling (represented by the shifting dashed lines in the figure): The more efficient the PVP recycling process, the lower the EPR-driven profit margin erosion with the CIGS technology. This is an important observation for our purposes because only a low volume of the panels have reached end-of-life to date due to their long lifespans, implying that the PVP recycling market is not mature enough to operate at a sufficiently high volume that achieves economies of scale (Besiou and Wassenhove 2015). At the current processing cost of \$200/ton, our results suggest that with a recycling target above 70%, which is within the range proposed by the WEEE Directive Recast, the profit margin erosion of the more durable c-Si technology is lower than the CIGS technology (as shown by the solid line in the figure). As such, the proposed recycling targets encourage producers to choose a technology with higher

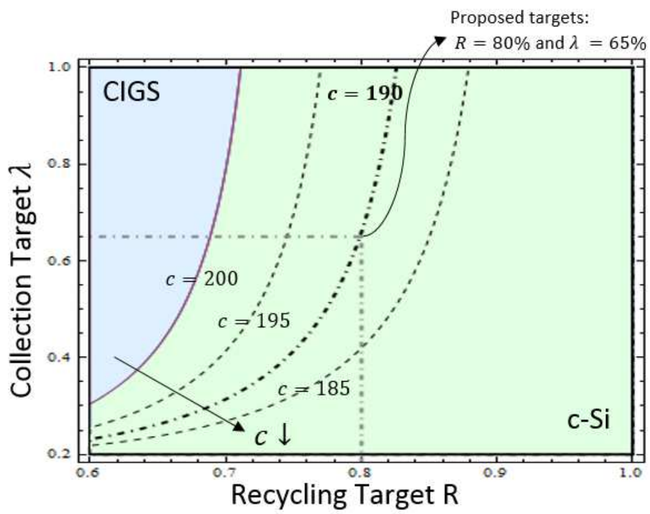


Figure 4: Predicted PVP technology choice under different collection and recycling targets and processing cost efficiency levels

durability and lower recyclability. As volumes increase and the processing cost goes down (e.g., below \$190/ton), however, the region within which the profit margin erosion of the CIGS technology is lower expands (as shown by the dashed lines). In other words, provided that a certain processing cost efficiency is achieved through scale economies over time, the CIGS technology can be preferred for a wider range of legislative targets. Only then will EPR have achieved its objective of making PVPs more recyclable, especially if supported by high collection targets.

2.7 Conclusions

In this paper, we analyze a durable good producer's design choices regarding product durability and recyclability under EPR. In particular, we posit that design incentives induced by EPR are not restricted to design for recyclability. Rather, EPR can also provide incentives to alter product durability. This could be a direct incentive: Designing durable products can reduce production, and in turn the volume of products a producer is responsible for recycling under EPR. This could also be an indirect incentive: If the producer chooses to increase product recyclability, the design trade-off may result in reduced durability.

Our analysis regarding the effect of recycling targets, a key component of EPR implementations such as the WEEE Directive, on producers' EPR-driven design choices, suggests the following: When recyclability and durability are synergistic design attributes, i.e., they are reinforcing, stringent recycling targets work as intended: They lead a producer to design easier to recycle and more durable products. Essentially, easier to recycle product designs help increase unit recycling value at the end-of-life, and durable product designs (directly) reduce the total volume a producer has to recycle. In contrast, when recyclability and durability are conflicting design attributes, i.e., improving either dimension makes it harder to improve the other as in the example of PVPs, the effect of recycling targets can be ambiguous. Our analysis regarding this design trade-off suggests that low but sufficiently stringent recycling targets will drive product design for recyclability, yet this will be at the expense of product durability. However, the opposite may occur under high recycling targets, and a producer will improve durability at the expense of recyclability. This suggests that contrary to intuition, recycling target stringency - a lever that appears to deal purely with recycling processes, does not necessarily imply producer incentives to design for recyclability. More importantly, very strict recycling targets may even compromise recyclable product designs, and more so if the base production costs are already low.

Another interesting finding from our analysis is that the effect of increased collection targets on EPR-driven product design choices differs substantially from that of recycling targets. To be more specific, when a durability-recyclability trade-off exists in product design, a low but sufficiently stringent collection target induces an increase in durability while compromising recyclability. In contrast, a high collection target induces an increase in recyclability while compromising durability. In particular, when recycling is valuable (be it driven by commodity price dynamics for recycled materials or the inherent product characteristics), higher collection targets always imply more recyclable yet less durable product designs.

From the policy maker perspective, our results suggest that the environmental implications of EPR may be far from intuitive in the case of durable products: Although recycling and collection targets appear to focus on environmental concerns associated with the end-of-life phase of the product life-cycle, they may also influence the production and use phases in the product life-cycle through their effect on design for durability. In view of this, we show that seemingly similar legislative targets may work in opposing directions in driving producers' design choices (see Plambeck and Wang 2009 for a similar discussion in the context of new product introduction frequency). More importantly, more stringent legislative targets do not always guarantee improved environmental performance (see Esenduran et al. 2015 and Krass et al. 2013 for similar discussion). In particular, our results suggest that if the policy maker's objective is to induce recyclability (i.e., increase landfill diversion or achieve higher quality of recycling), a low recycling target accompanied with a high collection target may be ideal. Likewise, if the policy maker's objective is to reduce consumption through durability via EPR, a high recycling target accompanied by a low collection target may be ideal.

We conclude that the economic and environmental impact of increasing legislative stringency is more subtle than appears at first glance. As illustrated by our calibrated data analysis for PVPs, our model provides a framework for analyzing the producer response to different legislative targets under the economics of the particular industry and product. Such an analysis can support the setting of legislative targets that are adapted to different product categories.

CHAPTER III

LEMONS, TRADE-INS, AND REMANUFACTURING

3.1 Introduction

A crucial premise for any trade to take place in the market is for the trading price to match the quality of the product. When product quality information cannot be credibly communicated, it threatens the well-functioning of the market. Secondary market of durable products is particularly vulnerable to such risks, which is referred to as the lemons problem as studied by Akerlof in his seminal paper (Akerlof, 1970). To be more specific, used durable products for sale in the secondary market may be of diverse qualities, due to the embedded production variations that only show up through use (e.g., semi-conductors) or the different patterns of previous usage (e.g., on-time maintenance vs. abuse). However, while information on the quality of any particular used item is known to the seller as being the original owner, it may not be observable to the buyers prior to purchase. Under such asymmetric information, the buyers can only estimate the average quality in the market, based on which they offer the buying price. This price will then be lower then the fair price of the high-quality items (hereafter referred to as *peaches*) and higher than that of the low-quality ones (the *lemons*). Therefore, it incentivies the sellers to hold on to the (under-priced) peaches but sell the (over-priced) lemons into the market. Such behavior of strategically holding only the peaches pushes down the average market quality. As a result, the lemons problem arises and trade activities in the secondary market are suppressed.

When the lemons problem strikes, it hurts the resale value of the products to be realized in the secondary market. The markets of used automobiles typically suffer from the lemons problem because the quality difference can be quite significant but not easily observable. As a result, even cars in good-condition are commonly traded at low prices. Another demonstrating example is the Microsoft's Xbox 360: When some of the devices were hacked into from the online gaming network and later banned by the company, the market prices of used Xboxes plummeted almost immediately. That is because now the actual qualities (whether they are still supported by Microsoft in this case) can vary across used items but are only known to the sellers. To avoid this negative impact, academic efforts have been made to explore different ways to attack the lemons problem. One of the proposed solutions is to lease new products rather than selling them (Hendel and Lizzeri, 2002, Johnson and Waldman, 2003). The rationale behind leasing is that, unlike selling, the manufacturer maintains ownership of the products, and therefore has the additional control over the option price at which the lessees can buyout the used products at the end of the leasing term. By properly setting this price, the manufacturer exerts influence on the quality threshold, below which the lessees release the cars to the secondary market, consequently changing the average market quality. Despite this potential of leasing in providing certain alleviation, studies also suggest that leasing can only entirely resolve the lemons problem under a very limited condition, where each consumer's valuation of the product strictly falls into one of the two types (Hendel and Lizzeri, 2002).

A different approach to deal with the lemons problem is to offer trade-in programs, as discussed in Rao et al. 2009. When a consumer trades in the used product upon the purchase of a new one, the manufacturer typically offers a discount on the new purchase (i.e., the *trade-in discount*) in addition to making the buyback payment for the used unit; and the manufacturer later resells the trade-in used items as-is in the secondary market. In essence, the trade-in programs take effect in attacking the lemons problem because the trade-in discount increases the effective payment and hence encourages more peach owners to also sell the peaches into the secondary market, which brings up the average quality. Nevertheless, the trade-in program is neither a perfect solution, because it can be shown that the strategic peach-holding behavior is not entirely eliminated. That means there are still more lemons than peaches in the secondary market, and the lemons problem persists. This motivates us to search for a better solution.

To identify a viable direction for our search, we delve into the root of the lemons problem. The information asymmetry in fact creates two types of mismatches that, in combination, eventually cause the lemons problem. On the one hand, as mentioned above, the offering price by the buyers mismatches (falls below) the fair price of the peaches and (goes above) that of the lemons. Meanwhile, on the other hand, the product quality perceived by the buyers (i.e., the average market quality) also mismatches the actual peach- and lemon-qualities. This understanding is revealing in explaining the reason why the manufacturer can alleviate the lemons problem both by leasing (with the option price) and trade-in (with the trade-in discount): They address the price aspect of the problem and narrow the price gap between the one offered by the buyers and the one demanded by the sellers. More importantly, the argument also tells why these two solutions are not strong enough: Neither of them actively address the quality aspect of the problem. Distilling from this discussion is the valuable insight that the key to resolve the lemons problem lies in constructing a mechanism that can also address the quality aspect of the problem.

To execute this idea, note that with the trade-in programs, the manufacturer accepts the trade-in products before reselling them as-is. The possession in this process provides the manufacturer with an opportunity to actively interfere with the quality of the used products. In particular, we study two strategies to achieve that. One is Testing, with which the manufacturer first identifies the quality of each trade-in product through testing, and then sells the lemons and peaches separately in the secondary market. The another strategy is Remanufacturing, with which the manufacturer first tests the trade-in items, and then remanufactures them such that it ensures all the products for resale will be of the same quality. Notably, although both strategies reveal the quality information in the resale secondary market, it is not trivial that they necessarily resolve the lemons problem. That is because when the used products are first released into the market (to the manufacturer through trade-ins, to be specific), information asymmetry still exists; i.e., sellers can still take advantage of their superior quality information and stick with the strategic peach-holding behavior to sell more lemons than peaches, giving rise to the lemons problem. In this paper, we study the effectiveness of Testing and Remanufacturing in the lemons context, which has never been explored in the literature. Furthermore, we also investigate how these strategies influence the market on both the consumers' purchasing and trade-in patterns and the manufacturer's pricing decisions.

This study contributes to the literature as we innovatively propose and analytically confirm the strategies of Testing and Remanufacturing as effective solutions that are able to entirely eliminate the lemons problem, and we further reveal their impacts on the market. Another contribution of the paper is that we take the results forward to also derive a useful and comprehensive guidance for manufacturers on whether to use Testing or Remanufacturing when faced with the lemons problem, and how to properly account for the product characteristics in this decision-making process. We conclude that for products that are more durable or more costly to produce, Remanufacturing will be a better option that yields higher manufacturer profit. Remanufacturing is also preferred when the relative quality difference between lemons and peaches is small for more durable products, or when the relative quality difference is large for less durable products.

The reminder of the paper is organized as follows. We first review related research to position our paper in the existing literature in Section 3.2. We describe the problem and construct the model in Section 3.3. We set the case where the manufacturer only offers trade-ins (studied in Rao et al. 2009) as the benchmark case; and then summarize the analytical results of this case, some of which as derived in Rao et al. (2009), in Section 3.4. Section 3.5 and 3.6 investigate the Testing and Remanufacturing strategies, respectively. We characterize the manufacturer's optimal decisions and the resulting market outcome in each case, and then contrast the results to the benchmark case with only the trade-in programs to highlight the effects of the testing and remanufacturing processes in resolving the lemons problem. Section 3.7 compares Testing and Remanufacturing, and derives a comprehensive guidance for manufacturers on how to make the optimal choice from the two strategies, and how to account for the product characteristics. Finally, we present the insights and concluding remarks in Section 3.8 that also discusses future research issues.

3.2 Literature review

Our paper draws on and contributes to several streams of research including durable goods with a special focus on secondary markets, trade-ins and remanufacturing. We review related papers in each stream and position our research at the point of their intersection.

The secondary markets play a significant role for durable goods, especially with their rapidly growing sizes. For example, in the U.S., the volume of used car transactions is approximately three times as large as that of new cars. Their importance is also reflected by the keen interest it receives in the durable goods literature. Existing research has explored different effects of secondary markets such as the possible cannibalization that influences the demand and price of the new product sales (Valerie 2008, Volker and Martin 2003), and the allocative and market segmentation effects (Anderson and Ginsburgh 1994, Porter and Sattler 1999) etc. Our research focuses on developing strategies to actively interfere with the secondary market. Examples of secondary market inference for different purposes include the follows: Hendel and Lizzeri (1999b) discuss the use of leasing instead of selling to gain more market power in the secondary market, because leasing allows the manufacturer to maintain product ownership even after the expiration of the leasing contract. For example, the manufacturer can limit the volume of used products by scrapping some of the off-lease items. The paper shows that leasing has a positive impact on profitability because it enables active control over price of the used goods so that the manufacturer can better exploit the market segmentation effect of the secondary market to extract more consumer surplus. Bulow (1982) also shows that gaining stronger control by leasing helps alleviate the time inconsistency problem. Charging a relicensing fee to buyers of refurbished items, discussed in Oraiopoulos et al. (2002), is another way to influence the secondary market. The underlying mechanism is to adjust the actual resale value by this fee, so as to increase profit by obtaining an optimal balance between the positive (resale value) and the negative (cannibalization) effects exerted by the secondary market. In this paper, secondary market interference is motivated by the attempt to resolve the lemons problem, and the strategies we consider include offering trade-in programs, conducting testing or remanufacturing.

Trade-in programs are widely used as a marketing strategy. For example, they can be utilized to practice price discrimination for inducing higher sales or extracting more consumer surplus (van Ackere and Reyniers 1993, 1995, Agrawal et al. 2008); they also help attract the return of cores for profitable remanufacturing (Ferrer and Whybark 2001, Heese et al. 2005), and Ray et al. (2005) study the optimal design of the trade-in programs for the remanufacturable used products; moreover, Levinthal and Purohit (1989) show that trade-ins can accelerate the diffusion process for new product generations by inducing earlier retirements of the old versions. The focus of trade-ins in our paper is their effect on interfering with the secondary market, in particular, on tackling the lemons problem. In this regard, our research is closely related to Rao et al. (2009). The paper illustrates that the lemons problem can be alleviated by offering trade-ins that essentially increase the effective payment made to the sellers through the trade-in discount. This encourages more peaches to also be released into the secondary market, and therefore increases the average quality and remedies the problem. Our paper adds significant enrichment to this stream of research by first delving into the root of the lemons problem and deriving an revealing explanation of the strength and weakness of the trade-in programs. Building on that understanding, we are also able to propose better solutions including conducting testing and remanufacturing.

Remanufacturing has been extensively studied in the sustainable operations literature, mainly with a focus on the value recovery aspect, as remanufacturing performs necessary value-added repair or reprocessing to enhance the quality of used products and render them sellable again, typically at a cost that is lower than the new production. Remanufacturing can also be used to interfere with the secondary market: Ferguson and Toktay, 2006 shows that remanufacturing benefits the manufacturer by deterring third-party entrance and competition in the secondary market. To our best knowledge, this paper is the first to propose and explore conducting remanufacturing to deal with the lemons problem. We show that it is indeed an effective lever and we further delineate its underlying mechanism and impacts on the market in this context. In addition to this contribution to the literature, we also provide useful and valuable insights that readily speak to manufacturers of different products by deriving a comprehensive guidance on how to choose the optimal secondary market strategies in the existence of the lemons problem and how the product characteristics should be accounted for.

3.3 The Model

We construct a discrete-time, infinite-horizon model to study a manufacturer selling durable products to consumers. Periods are indexed by $t \geq 0$.

3.3.1 The Market

We assume that each product has a two-period useful life to capture the product durable nature (Desai and Purohit 1998, Huang et al. 2001). A product is called *new* and *used*, respectively, in the first and second period of its lifespan; then it becomes valueless at the end of the second period. All new products are of identical quality. After one period of use, however, a new product can deteriorate into a peach with probability α ($0 \leq \alpha \leq 1$), or a lemon with probability $1 - \alpha$. To keep the analysis concise, we do not consider skewness in product quality and assume $\alpha = \frac{1}{2}$. The information on the quality realization is asymmetric for any particular used product: It is only known to the first-period owner of the product, but not observable to the buyers before purchase.

3.3.2 The Manufacturer

At $t = 0$, the manufacturer chooses the secondary market strategy. We compare three options in this paper, namely, *Trade-in*, *Testing*, and *Remanufacturing*. In every sequential period $t > 0$, the manufacturer produces new products at the unit cost c, and then sells them at the price p^t. Moreover, (i) with the Trade-in strategy, the manufacturer accepts trade-ins of used products from consumers upon their purchase of new ones. In a trade-in, the manufacturer offers a discounted price p_T^t for the new product, in addition to paying the price p_u^t for the used unit. $p^t - p_T^t$ is the trade-in discount. End-of-life products are excluded from the trade-in program, as it is a common practice that firms explicitly require the products to be in working condition to qualify for any trade-in discounts (Apple 2013b). After receiving the trade-in used products, the manufacturer then sells all of them as-is to the secondary market at the used product price p_u^t, where p_u^t is endogenously determined by the secondary market through market clearing.[1] (ii) With the Testing strategy, the manufacturer still offers the trade-in program to acquire used products in the same way as described above. The difference is that, instead of selling as-is, now the manufacturer first conducts testing to identify the qualities of the used products. The manufacturer then reveals this quality information by selling the lemons and peaches separately in the secondary market. (iii) With the Remanufacturing strategy, the manufacturer takes one step further than the Testing strategy: After accepting the used items through trade-ins and testing for their qualities, the manufacturer remanufactures to ensure that every unit is now of the peach-quality. Then the manufacturer sells the remanufactured products in the secondary market.

3.3.3 The Consumers

There exists a unit mass of consumers with different product valuations denoted by θ. We capture the consumer heterogeneity by assuming θ to be uniformly distributed over $[0, 1]$. A consumer of type θ obtains a per-period utility of θ, $\delta\theta$, and $\delta(1-s)\theta$, respectively from a new product, a peach, and a lemon, with $0 < \delta < 1$ and $0 < s < 1$. δ reflects the value depreciation over time through use, and is therefore referred to as the product durability: A product with a higher δ is more durable as it maintains its value better even in the later stage of its useful life. s captures the relative quality inferiority of a lemon compared to a peach, and hence also indicates the extent of the quality uncertainty.

In every period $t > 0$, the manufacturer determines the prices corresponding to its secondary market strategy choice, followed by the consumers making their purchasing and trade-in decisions. We focus on the stationary equilibria, where all the prices

[1] When the trade-in program is available, all consumers who replace their used product with a new one will sell the used item to the manufacturer through trade-ins rather than selling to the consumer secondary market, because the former also offers the trade-in discount in addition to the buyback payment p_u^t.

and the aggregate consumer behavior remain constant over time and all explicit time dependence t can be dropped from the notations (Hendel and Lizzeri 1999, Huang et al. 2001, Plambeck and Wang 2009, Agrawal et al. 2015). This helps rule out the transient effects due to only new products being sold in the first period.

3.4 Benchmark: The strategy with Trade-in

To highlight the effects of quality intervention by the Testing and Remanufacturing strategies, we first study the benchmark case where the manufacuturer adopts the Trade-in strategy as studied in Rao et al. (2009). We present the main results derived by following similar solution procedures in Rao et al. (2009) but with different parameterization that is consistent with our model setup to facilitate later discussion and comparison. We also incorporate constraints that ensure non-negative sales volumes and allow a positive unit production cost to add rigor and depth in the analysis. The details of this case and the main conclusions are summarized below.

In every period, depending on the new product prices with and without trade-ins (i.e., p and p_t) set by the manufacturer, the consumers can choose their single-period actions from the followings: to buy a new product, to buy a used one from the secondary market, to keep the used product for the second period if a new one was bought in the last period, or to remain inactive. To fully characterize the consumer behavior given that the durable products last for two periods, Result 3.1 identifies the consumer strategies that describe the consumer actions at two consecutive periods.

Result 3.1 *When the manufacturer adopts the Trade-in strategy, there are four non-dominated consumer strategies: (I) Always buy a new product in every period (NN); (II) Buy a new product; in the next period, keeps the product if it deteriorates into a peach but sells it if it deteriorates into a lemon (NP); (III) Always buy a used product in every period (UU); (IV) Always remain inactive in every period (II).*

Each consumer, depending on his own type θ, will self-select into following one of the four strategies that yields the highest utility. As a result, the market is divided into four segments.

Result 3.2 *In equilibrium, the market segmentation outcome is as follows:*[2]

Case(I) *When* $0 < \delta \leq \frac{4}{4+s}$.

$\exists \theta_1^{TI1}, \theta_2^{TI1}, \theta_3^{TI1}$ *with* $0 < \theta_3^{TI1} \leq \theta_2^{TI1} \leq \theta_1^{TI1} < 1$, *such that the optimal strategy for a consumer of type* θ *will be: (I) NN, when* $\theta \in (\theta_1^{TI1}, 1)$; *or (II) NP, when* $\theta \in (\theta_2^{TI1}, \theta_1^{TI1}]$; *(III) UU, when* $\theta \in (\theta_3^{TI1}, \theta_2^{TI1}]$; *and (IV) II, when* $\theta \in (0, \theta_3^{TI1}]$.

Case(II) *When* $\frac{4}{4+s} \leq \delta < 1$.

$\exists \theta_1^{TI2}, \theta_2^{TI2}$ *with* $0 < \theta_2^{TI2} \leq \theta_1^{TI2} < 1$, *such that the optimal strategy for a consumer of type* θ *will be: (I) NP, when* $\theta \in (\theta_1^{TI2}, 1)$; *(II) UU, when* $\theta \in (\theta_2^{TI2}, \theta_1^{TI2}]$; *and (III) II, when* $\theta \in (0, \theta_2^{TI2}]$.

Result 3.3 *The optimal prices and the resulting profit for the manufacturer are summarized as follows, the superscript* TI *indicates that the Trade-in strategy is adopted.*

	Case(I) $0 < \delta \leq \frac{4}{4+s}$	*Case(II)* $\frac{4}{4+s} \leq \delta < 1$
p^{TI}	$1+\delta-\frac{2(-1+\delta)(-4+3(-4+s)\delta)(-2+2c+(-2+s)\delta)}{-32+\delta(-64+96\delta+s(48+(-48+s)\delta))}$	$1+\delta+\frac{(-2+(-2+s)\delta)(-2+2c+(-2+s)\delta)}{-6+(-10+7s)\delta}$
p_u^{TI}	$-\frac{\delta\left(-32c+32(-2+c+s)\delta+(64+(-32+s)s)\delta^2\right)(8-8\delta+s(-4+3\delta))}{(-8+(8+s)\delta)(-32+\delta(-64+96\delta+s(48+(-48+s)\delta)))}$	$\frac{(-1+s)\delta(2+4c+(6-5s)\delta)}{-6+(-10+7s)\delta}$
Π^{TI}	$\frac{2(-1+\delta)(-2+2c+(-2+s)\delta)^2}{-32+\delta(-64+96\delta+s(48+(-48+s)\delta))}$	$-\frac{(-2+2c+(-2+s)\delta)^2}{4(-6+(-10+7s)\delta)}$

Based on the market characterization, Rao et al. (2009) points out that the size of the NP segment shrinks under Trade-in, so this strategy alleviates the lemons problem. To see the reason, note that in the secondary market, the root of the lemons problem is that the qualities of products are uncertain, and whether a particular used product is a lemon or a peach is solely known to the seller but not to the buyers.

[2] *Note that Case(II) in Result 3.2 is not included in Rao et al. (2009), it emerges from the boundary condition where the size of the NN segment reduces to zero.*

Under this asymmetric information, buyers can only estimate the average quality in the market, based on which they offer the buying price. Notably, this price will be lower than the fair price of peaches as long as there are some lemons. This creates the adverse incentive for used product owners to hold on to the peaches but sell off the lemons. As a result of having these strategic peach-holders (i.e., the NP segment), the secondary market is filled with more lemons than peaches and hence has lower average quality, suppressing trade activities. The Trade-in strategy offers trade-in discount in addition to the buyback payment for the used item, essentially increasing the total payment made to consumers for trading in. The additional financial reward then translates into a correcting incentive that encourages more used product owners to deviate from the strategic peach-holding behavior and release also the peaches they have into the secondary market. As the NP segment diminishes, Trade-in alleviates the lemons problem that leads to low average quality in the secondary market.

However, in spite of this favorable effect of the Trade-in strategy, the strategic peach-holding behavior still exists, evident by the persistence of the NP segment. In other words, Trade-in is not capable of resolving the lemons problem entirely. We seek explanation for this weakness of Trade-in by delving into the bottom of the lemons problem: It essentially involves two types of mismatches. On the one hand, the offering price by the buyers mismatches with the fair price demanded by the peach-owners. Meanwhile, on the other hand, there is also a mismatch between the peach-quality and the quality perceived by the buyers, i.e., the average market quality. Since Trade-in, while utilizing the price lever by offering the trade-in discount, is only able to address the price mismatch, it cannot fully resolve the problem although providing partial alleviation. This understanding of the nature of the problem is revealing: It suggests a direction for constructing a stronger solution, which is to add back the missing piece, i.e., to also incorporate the quality lever. This rationale motives us to study two strategies in the next sections. One is the Testing strategy, which allows the manufacturer to obtain the quality information and then communicate it with the secondary market. The other one is the Remanufacturing strategy, where the manufacturer takes one more step to directly intervene with the used product quality.

Rao et al. (2009) also shows that an increase in the relative quality inferiority of lemons (s) or in the product durability (δ) both reduces the volume of trade in the secondary market and requires the manufacturer to offer a higher trade-in discount. The reason is that as the lemon-quality is lower than the peach-quality by δs, a rise in δ or s means that the lemons become worse lemons, and it exacerbates the extent of the quality uncertainty and hence the lemons problem in the secondary market. Consequently, trade activities are dampened, and a bigger financial incentive by the trade-in discount is needed to alleviate the lemons problem. While these results demonstrate the market impacts of the lemons problem, they may not be comprehensive enough to capture all the secondary market dynamics, because Rao et al. (2009) has normalized the unit production cost c to be zero.

In this paper, we relax this assumption and allow $0 \leq c \leq 1$. To see the significance of accounting for the costly production, we augment the analysis on the volume of trade in the secondary market with c and present the result in Part (I) of Corollary 3.4. Depending on the production cost, the conclusion can vary considerably. In particular, the volume of trade is influenced by both (i) the lemons problem, and (ii) the interactions between the primary market (for new products) and the secondary market. When δ increases, the former factor has a negative impact and pushes down the volume of trade as discussed, but the latter factor has a positive impact especially when c is high. Under a high value of c, new products are scarce in the primary market, which limits the cannibalization of the secondary market on the primary sales even when products are more durable. Meanwhile, increase in durability helps the products better serve the market because the used items become closer alternatives to the new ones and hence supplement the (low-volume) new products to satisfy the market demand. Therefore, higher δ drives up both the new and the used product volumes due to the primary-secondary market interaction. When this effect dominates the effect of the lemons problem, the volume of trade in the secondary market may in fact increase in δ as shown in the corollary. As pointed out by Hendel and Lizzari (1999), the primary-secondary market interaction is an important factor in thoroughly understanding the impacts of the lemons problem; for example, the interaction is the exact reason why the secondary market does not shut down completely, which is in sharp contrast to the prediction in Akerlof (1970). We capture the unit production cost and demonstrate that it may have other significant implications later.

Corollary 3.4 *(I) The volume of trade in the secondary market is increasing in δ when the unit production cost is small enough, but is (concavely) increasing then decreasing in δ when c is large enough.*

(II) The volume of new product sales is decreasing in δ when c is small enough, but increasing in δ when c is large enough.

3.5 The Strategy of Testing

As discussed above, strategic peach-holders that cause the lemons problem, persist even with the Trade-in strategy, because the strategy only addresses the price aspect of the problem by the trade-in discount. Therefore, we expect that we can construct more effective solution by also utilizing a quality lever. Motivated by this, we study the Testing strategy that allows the manufacturer to practice quality intervention in the secondary market.

In this case, the new production, the primary market sales and the trade-in process remain the same. However, after acquiring the used products through trade-ins, the manufacturer first tests all of them to identify their qualities, assuming at a zero unit testing cost.[3] Then the manufacturer communicates the quality information to the market by setting different prices p_l and p_p to sell the lemons and the peaches separately. Although it may seem straightforward that the lemons problem goes away when the manufacturer reveals the quality information in the resale. Nevertheless, the lemons problem in fact still threatens the market, but now the manufacturer, instead of the buyers in the secondary market, is directly bearing the associated cost. This is because when used products are traded in to the manufacturer, the product qualities are still only known to the original owners, and the manufacturer pays the uniform unit price determined by the overall market quality without knowing whether a particular product is a lemon or a peach. In this case, the used product owners can still strategically hold on to the peaches and sell the lemons; consequently, more lemons are released, and the manufacturer can only resell them at a lower price.

We first characterize the consumer behavior. Denote the consumer purchasing actions in the current and the last periods as a and a', respectively. We derive the payoffs of a type θ consumer in the current period from different action choices, as summarized in Table 1 below. Note that the payoffs depend on both a and a' (for example, a consumer can trade in a used unit if a new one was bought in the last period). Moreover, a consumer can only keep a peach/lemon when a new one was bought in the last period, and infeasible cases are represented by a dash. Based on the payoffs, we study the consumer strategies.

Lemma 3.5 *In the stationary equilibrium when the manufacturer adopts the Testing strategy, there are six non-dominated consumer strategies: (I) Always buy a new product in every period (NN); (II) Buy a new product; in the next period, keep the*

[3]For a wide category of products, network devices for example, although testing incurs a significant upfront fixed cost such as purchasing the testing equipment, the variable testing cost for each additional unit is low, which justifies the assumption of zero unit testing cost.

Table 1: Consumer payoff table under the Testing strategy.

$a\backslash a'$	Buy a new	Keep a peach	Keep a lemon	Buy a peach	Buy a lemon	Remain inactive
Buy a new	$\theta - p_t + p_u$	$\theta - p + p_u$	$\theta - p + p_u$	$\theta - p + p_u$	$\theta - p + p_u$	$\theta - p + p_u$
Keep a peach	$\delta\theta - p_u$	–	–	–	–	–
Keep a lemon	$\delta\theta(1-s)-p_u$	–	–	–	–	–
Buy a peach	$\delta\theta - p_p$	$\delta\theta - p_p$	$\delta\theta - p_p$	$\delta\theta - p_p$	$\delta\theta - p_p$	$\delta\theta - p_p$
Buy a lemon	$\delta\theta(1-s) - p_l$	$\delta\theta(1-s)-p_l$	$\delta\theta(1-s)-p_l$	$\delta\theta(1-s)-p_l$	$\delta\theta(1-s)-p_l$	$\delta\theta(1-s)-p_l$
Buy a reman	$\delta\theta - p_r$	$\delta\theta - p_r$	$\delta\theta - p_r$	$\delta\theta - p_r$	$\delta\theta - p_r$	$\delta\theta - p_r$
Inactive	0	0	0	0	0	0

product if it deteriorates into a peach but sells it if it deteriorates into a lemon (NP); (III) Buy a new product; in the next period, keep the product regardless of the quality realization (NH); (IV) Always buy a peach in every period (PP); (V) Always buy a lemon in every period (LL); (VI) Always remain inactive and buy nothing (II).

The expected per-period utility for a type θ consumer from the different strategies are (I) NN: $V_{NN}[\theta] = \theta - p_t + p_u$; (II) NP: $V_{NP}[\theta] = \frac{(1+\alpha\delta)\theta}{1+\alpha} + \frac{(pt-pu)(-1+\alpha)-p\alpha}{1+\alpha}$; (III) NH: $V_{NH}[\theta] = \frac{1+\delta(1-(1-\alpha)s)}{2}\theta - \frac{p}{2}$; (IV) PP: $V_{PP}[\theta] = \delta\theta - p_p$; (V) LL: $V_{LL} = \delta(1-s)\theta - p_l$ (VI) II: $V_{II}[\theta] = 0$.

Given the sequential nature of the game, we solve the problem backwards, starting from the optimal consumer strategies and the resulting market segmentation outcome, and then characterize the manufacturer's optimal pricing decisions. We present the results in Proposition 3.6 (All proofs are relegated to the Appendix).

Proposition 3.6 *When the manufacturer adopts the Testing strategy, it maximizes the profit by setting the prices to be: $p^{Test} = \frac{-2(1+c)+(-8+3c(-2+s)+5s)\delta+(-6+(7-2s)s)\delta^2}{-4+(-12+7s)\delta}$, $p_t^{Test} - p_u^{Test} = \frac{-4(1+c)+2(-8+c(-2+s)+5s)\delta+(-2+s)^2\delta^2}{-8+2(-12+7s)\delta}$, $p_p^{Test} = \frac{\delta(2c(-4+s)+s(8+s)\delta-2(s+8\delta))}{-8+2(-12+7s)\delta}$, and $p_l^{Test} = \frac{(-1+s)\delta(4c+(8-5s)\delta)}{-4+(-12+7s)\delta}$; the corresponding optimal manufacturer profit is $\Pi^{Test} = \frac{(-2+2c+(-2+s)\delta)^2}{4(4-(12-7s)\delta)}$.*

Given the prices, $\exists \theta_1^{Test}, \theta_2^{Test}, \theta_3^{Test}$ with $0 < \theta_3^{Test} \leq \theta_2^{Test} \leq \theta_1^{Test} < 1$, such that a consumer of type θ optimally chooses the strategy (I) NN, when $\theta \in (\theta_1^{Test}, 1)$, (II) PP, when θ $in(\theta_2^{Test}, \theta_1^{Test}]$, (III) LL, when $\theta \in (\theta_3^{Test}, \theta_2^{Test}]$, and (IV) II, when

$\theta \in (0, \theta_3^{Test}]$.

This is a result of notable significance as it shows that the manufacturer can eliminate the lemons problem by the Testing strategy. It is confirmed by the disappearance of the NP segment, which means that when a consumer sells a used item, he does so regardless whether he has a lemon or a peach. In other words, now the market no longer suffers from having more lemons than peaches caused by the asymmetric quality information emerges when the used products are released into the market (to the manufacturer in this case) by their first-period owners.

As discussed earlier, the quality information asymmetry of the used items causes the mismatch in price (between the fair price of peaches and the buying price offered by the buyers), and the mismatch in quality (between the peach-quality and the buyers' perceived quality, i.e., the average market quality). The Trade-in strategy, with its trade-in discount that increases the effective payment to the peach-holders, works solely on the price aspect and hence only alleviates the problem but fails to eliminate it entirely. The Testing strategy, on the other hand, makes up the deficiency of Trade-in by also utilizing the quality lever. Compared to reselling the trade-ins as-is as with the Trade-in strategy, the additional testing process that identifies the used product qualities critically allows the manufacturer to actively practice quality intervention in the secondary market. Specifically, the manufacturer executes the intervention by revealing the qualities and selling the lemons and peaches separately. In this process, while removing the quality mismatch in the secondary market, the manufacturer also gains the pricing control over the used products (as it can now set the prices of the lemons and peaches). This additional control, along with the pricing power over the new products, is then strategically exploited by the manufacturer in combination, which eventually prices out the NP segment and eliminates the lemons problem. We further point out that pricing out the NP segment is realized by redirecting the NP consumers to either the NN or the PP segment: Under the optimal pricing by the manufacturer, the effective cost of replacing a used product (which is $p_t - p_u$) is lower under the Testing strategy compared to the Trade-in case, making NN a captivator for consumers. On the other hand, p_p is determined so as to render buying peaches with their uniform quality a better option to attract consumers away from the NP segment, especially for the lower type consumers.

Another interesting observation from this result is that while a unique trade-in discounted new product price p_t and used product price p_u exist at optimality with Trade-in, p_t and p_u are always coupled with Testing. With Testing, p_u only acts as the acquisition price of the used units, so p_u is coupled with p_t because the acquisition concurs with the offering of the discounted new product price p_t in trade-ins. As such, for consumers, $p_t - p_u$ is the effective price of replacing a used item with a new one through trade-in; and for the manufacturer, the trade-in process can be equivalently regarded as paying $p - p_t + p_u$ for the used item and charging the regular price p for the replacing new purchase. In contrast, with Trade-in where used items are sold as-is, the manufacturer has no direct pricing control over used products and p_u is also the price for the resale. As a result, p_u is decoupled from p_t and individual optimal values exist to maximize the manufacturer profit.

In the emergence of the lemons problem, only the strategic peach-holders reap benefit from taking advantage of the superior quality information they have, at the expense of the market (e.g., average secondary market quality is dragged down and buyers of used items could be paying a high-than-fair price to only receive lemons). To see it another way, for the manufacturer in particular, the profit margin from the NP segment is always dominated: A close scrutiny of the NP segment tells that a portion of these consumers buy a new product and then hold on to it for two periods because the product deteriorates into a peach. Their purchasing pattern follows that of the NH consumers and they generate the same profit margin. The rest of the NP consumers buy a new product and then replace it in the next period as it turns into a lemon. While this resembles the behavior of the NN consumers, the NP consumers sell only lemons to the manufacturer, which are of lower resale value. Therefore, the profit margin from the NP segment is always lower than either the NN or the NH segment. The implication of this discussion is that the manufacturer should be better off when it is able to eliminate the lemons problem, and this is confirmed by the profit comparison that shows $\Pi^{TI} < \Pi^{Test}$.

3.6 The Strategy of Remanufacturing

In addition to Testing, the manufacturer can also adopt Remanufacturering for utilizing the quality lever to tackle the lemons problem. Specifically, with this strategy, the manufacturer takes in the trade-in products and tests them as in the Testing case, but now it also remanufactures the lemons into the peach-quality, incurring a unit cost of us. The unit cost accounts for the higher expense to remanufacture a worse lemon (with larger quality inferiority s); and u is the remanufacturing cost coefficient, $0 < us < c$ so that remanufacturing comes with cost saving compared to new production as is typically in practice. Next, the manufacturer sets the price p_r to resell the processed lemons along with the peaches, all of the peach-quality, in the secondary market as remanufactured products. For consumers, the options of single-period purchasing action and the associated payoffs are similar to the Testing case, except that "Buy a lemon" and "Buy a peach" are no longer available but instead, consumers can now choose to "Buy a remanufactured product" that yields a per-period utility of $\delta\theta - p_r$ for a consumer of type θ.

We can show that under Remanufacturing, there are five non-dominated consumer strategies. They are: NN, NP, NH, II and RR (referring to always buying remanufactured products in every period). We next characterize the manufacturer's optimal decisions and the resulting market segments (presented in increasing order of δ).

Proposition 3.7 *When the manufacturer adopts the Remanufacturing strategy,*

$\exists u_{s1}, u_{s2}, u_{l1}, u_{l2} \in (0, \frac{c}{s})$, such that at optimality in the stationary equilibrium:

Case(I) When $0 < \delta \leq \frac{2}{2+s}$:

	Subcase RS1	*Subcase RS2*
	$0 < u \leq u_{II1}$	$u_{II1} \leq u \leq u_{II2}$
p^{RS}	$\frac{1}{4}(2+2c-(-2+s)\delta)$	$\frac{1}{4}(2+2c-(-2+s)\delta)$
p_r^{RS}	$\frac{\delta(-2-2c+(-2+s)\delta)}{-4+2(-2+s)\delta}$	$\frac{\delta\left(4c(-1+\delta)+2su(-1+\delta)+s^2u\delta+8(-1+\delta)\delta\right)}{-4+\delta(-8+(12+s^2)\delta)}$
$p_t^{RS} - p_u^{RS}$	$\frac{1}{8}(6+2c+(-2+s)\delta)$	$\frac{(-4(2+2c+su)-24\delta+\left(8(5+c)+2(1+c)s^2+(-2+s)^2su\right)\delta^2+2\left(-4+s^2\right)\delta^3)}{(4(-4+\delta(-8+(12+s^2)\delta)))}$
Market Segments	*II RR NN*	*II RR NH NN*

	Subcase RS3
	$u_{II2} \leq u < \frac{c}{s}$
p^{RS}	$\frac{1}{4}\left(2-(2+s)\delta-\frac{(2c+su+4\delta)(-2+(-6+s)\delta)}{2+6\delta}\right)$
p_r^{RS}	$\frac{\delta(2c+su+4\delta)}{2+6\delta}$
$p_t^{RS} - p_u^{RS}$	$\frac{2-2(-4+\delta)\delta+2c(1+\delta)+su(1+\delta)}{4+12\delta}$
Market Segments	*II NH*

Case(II) When $\frac{2}{2+s} \leq \delta \leq 1$:

	Subcase RL1	*Subcase RL2*	*Subcase RL3*
	$0 < u \leq u_{I1}$	$u_{I1} \leq u \leq u_{I2}$	$u_{I2} \leq u < \frac{c}{s}$
p^{RL}	$-\frac{(2c+su+4\delta)(-2+(-2+s)\delta)}{4+12\delta}$	$\frac{1}{4}(2+2c-(-2+s)\delta)$	$\frac{1}{4}(2+2c-(-2+s)\delta)$
p_r^{RL}	$\frac{\delta(2c+su+4\delta)}{2+6\delta}$	$\frac{2-2su-8\delta+2c(-1+\delta+s\delta)+\delta(6\delta+s(-1+(2+s)u+5\delta))}{8(-1+\delta+s\delta)}$	$\frac{1}{8}(-2+2c+(6+s)\delta)$
$p_t^{RL} - p_u^{RL}$	$\frac{2-2(-4+\delta)\delta+2c(1+\delta)+su(1+\delta)}{4+12\delta}$	$\frac{-6+2c(-1+\delta+s\delta)+\delta\left(8+5s+s^2u-(2+s)\delta\right)}{8(-1+\delta+s\delta)}$	$\frac{1}{8}(6+2c+(-2+s)\delta)$
Market Segment	*II RR NN*	*II NH RR NN*	*II NH*

Proposition 2.3 shows that the manufacturer can adopt Remanufacturing to eliminate the NP segment and therefore resolve the lemons problem. This is a nontrivial and revealing result because, similar to the Testing strategy, although there is no quality information asymmetry in the resale secondary market as all the remanufactured products are uniformly of the peach-quality, the lemons problem could still emerge when the used products are first sold to the manufacturer through trade-ins, while the manufacturer is bearing the associated cost.

To also address the quality aspect of the lemons problem is the crucial underlying mechanism of the Remanufacturing strategy to surpass Trade-in as a solution, while Trade-in solely works on the price aspect. Under Remanufacturing, the quality intervention is executed by entirely removing the quality inferiority and ensuring the uniform (peach-) quality of the remanufactured products now available in the secondary market. Achieving this with the additional remanufacturing process has empowered the manufacturer to price the remanufacturered products and strengthen its control over the secondary market. In particular, the remanufactured and the new product prices are strategically chosen together at optimality such that consumers will be better off deviating from the strategic peach-holding behavior to other market segments of NN, NH or RR. Further studying the specific prices reveals that pricing out the NP segment in this case is achieved by the strategic combination of: increasing the effective price of replacing a used product $(p_t - p_u)$ to reduce the consumer utility from NP related to NH, or increasing the price of buying a new product without trade-in (p) to render NP less desired by consumers compared to NN, or to offer remanufactured products at the properly-set price p_r as an attractive substitute.

It is also interesting to observe that the market segmentation result heavily depends on the cost of remanufacturing, captured by u. When u is very high, the high cost of keeping the remanufacturing promise to the secondary market severely erodes into the overall profitability. This drives the manufacturer to give up on serving the NN segment (by setting very high new product prices) because it later comes with the lemon trade-ins that incur the associated remanufacturing cost. As a result, only the NH and II segments remain in existence. At another extreme, when u is very low, the manufacturer optimally prefers to sell more remanufactured products because they generate additional revenue, and the NN segment is kept as a source of used items for remanufacturing. Hence, the manufacturer is incentivized to price out the NH segment for expanding the RR and NN segments.

The value of u is also important in determining whether the manufacturer should conduct remanufacturing or not. As discussed previously, it is in the manufacturer's interest to safeguard the secondary market from the threat of the lemons problem, because only the first-period owners reap benefit from their information advantage when the lemons problem arises. However, the manufacturer now also incurs cost in remanufacturing. Therefore, Remanufacturing only yields a higher profit than Trade-in when the cost of remanufacturing, captured by u, is below a certain threshold (details of the threshold are included in the Appendix).

Under different secondary market strategy choices, the impacts of the product characteristics s and δ can vary considerably, which we explore next (the superscript "Reman" denotes the optimal values under Remanufacturing).

Corollary 3.8 *The manufacturer profit under Trade-in (Π^{TI}) is of U-shape in s when c is low enough and δ is high, monotonically increasing in s when c is low and δ is also low, and monotonically decreasing in s otherwise. In contrast, the profit under Remanufacturing (Π^{Reman}) is always monotonically decreasing in s.*

The corollary points out that under Remanufacturing, the profit of the manufacturer is always impaired by the quality inferiority. This is because by accepting trade-ins and incurring the cost of remanufacturing the lemons, the manufacturer is in fact undertaking the adverse financial consequence of the low product quality. Consequently, the manufacturer is expected to be better motivated to improve its product quality under Remanufacturing. In contrast, such is not true under Trade-in when used products are only sold as-is. Since the profit function can be increasing in s for certain ranges of δ and c, within which there will be no incentive for the manufacturer to reduce the inferiority and make better products. This comparison suggests that the manufacturer's adoption of Remanufacturing rather than Trade-in may be a favorable signal for product quality.

Corollary 3.9 *The volume of new production Vol_N^{TI} is increasing in s when c is small enough but decreasing in s when c is large enough. In contrast, Vol_N^{Reman} is always monotonically decreasing in s.*

Under Remanufacturing, the manufacturer bears the risk of incurring remanufacturing cost for receiving lemons through trade-ins, and the cost increases in s. Therefore, a higher s translates into the incentive for the manufacturer to sell less new products and reduce the later cost liability. On the other hand, similar incentive is absent under Trade-in because the financial consequence of having lemons in the market is directly born by the buyers in the resale secondary market. Contrarily, the manufacturer may want to increase new production as s rises, especially when production is less expensive. That is because the more pronounced effect of a high s for the manufacturer in this case, is that it reduces the overall attractiveness of buying used products, limiting the cannibalization of the new product sales. As such, expanding the new production, which is the only source of revenue for the manufacturer under Trade-in, is preferred.

3.7 Testing vs. Remanufacturing, Which One Is Better?

Our analysis has confirmed that incorporating not only the price lever but also the quality lever, by following the Testing or Remanufacturing strategy, is effective to tackle the lemons problem: Both strategies eliminate the strategic consumer behavior that takes advantage of the superior quality information and hence avoid having disproportionally more lemons than peaches released into the secondary market to bring down the average market quality. In comparison then, how should the manufacturer choose between them and how do the product characteristics play a role? The answer is not immediately clear because on the one hand, Testing saves the cost of remanufacturing; but on the other hand, Remanufacturing can generate a larger revenue stream in resale after the value-added remanufacturing process. We provide the answer in this section.

To compare the two strategies, we first relax an implicit assumption we have made in the previous analysis: that the manufacturer resells all the trade-in used products back to the secondary market after conducting testing or remanufacturing. The assumption is kept from Rao et al. (2009) to maintain modeling consistency, so as to facilitate the comparison with the Trade-in strategy studied in Rao et al. (2009), and highlight the effectiveness of Testing and Remanufacturing that also address the quality aspects in resolving the lemons problem. Moreover, the analysis with this assumption also provides rich and valuable insights. However, this restriction may not be necessarily imposed, as the manufacturer can decide the optimal resale quantity, while scraping the rest, to further maximize profit. Exercising the quantity option to interfere with the secondary market of durable products has been shown to have some interesting implications for the environmental impacts (Agrawal et al., 2012) and the the implementation of environmental regulation (Alev et al., 2016). Moreover, allowing the quantity choice also removes the unfavorable bias towards Remanufacturing in the comparison, which is purely caused by imposing the remanufacturing and the associated cost to all the used products. Therefore, we are interested in studying how it effects the market and the strategy choices for dealing with the lemons problem.

3.7.1 The Strategy of Testing with the Quantity Choice

In this case, the Testing strategy is the same as we described except that instead of reselling all the lemons and peaches, the manufacturer has the option to choose the quantities of lemons and peaches for the resale in the secondary market and then discard the rest of the used items with no residual value. To highlight the impact of the additional quantity decisions by the manufacturer, we focus on the product volumes and the resulting market segments (presented in increasing order of the consumer type θ) in the market at optimality.

Proposition 3.10 *When the manufacturer adopts the Testing strategy with the quantity choice for the resale of lemons and peaches, let x^{TestQ} and y^{TestQ} represent the quantities of peaches and lemons that are discarded by the manufacturer after being acquired and tested, then*

	Subcase TQ1	*Subcase TQ2*	*Subcase TQ3*
	$0 < c \leq \frac{1-\delta}{3}$	$\frac{1-\delta}{3} \leq c \leq \frac{4-4\delta+3s\delta}{8}$	$\frac{4-4\delta+3s\delta}{8} < c \leq 1$
x^{TestQ}	$\frac{1}{4}\left(1+\frac{3c}{-1+\delta}\right)$	0	0
y^{TestQ}	$\frac{-1+c+\delta}{4(-1+\delta)}$	$\frac{4-8c-4\delta+3s\delta}{8-8\delta+18s\delta}$	0
Market Segments	*II PP NN*	*II LL PP NN*	*II LL PP NN*

Every unit of peaches and lemons put back to the secondary market becomes an additional source of revenue for the manufacturer. Meanwhile, however, the higher volume of lemons and peaches drives down their market prices and they may then lead to more severe cannibalization of new product sales. Discarding some used units helps maintain the desired balance between these two opposing effects to enhance profitability. When the unit production cost increases, the cost of scrapping also increases as only the value of one-period of the product's useful life is realized in the market. This explains the decrease in the discarded volume in the production cost. Moreover, lemons are discarded before peaches due to their lower resale value. Finally, this result also reaffirms the significance of capturing the effect of the production cost.

3.7.2 The Strategy of Remanufacturing with the Quantity Choice

When the manufacturer has the quantity choice under the Remanufacturing strategy, it determines how many remanufactured items (including the peaches and the processed lemons) to be resold after acquiring and testing all the trade-in used products. It is obviously reasonable to discard a lemon before the remanufacturing if it is not eventually put back in the secondary market, so the manufacturer will be discarding all the lemons before any peaches (that can in fact be resold without incurring additional remanufacturing cost).

Proposition 3.11 *When the manufacturer adopts the Remanufacturing strategy with the quantity choice for the resale of the remanufactured products, let x^{RQ} and y^{RQ} denote the quantities of peaches and lemons that are discarded after the acquisition and testing, then*

Case I : $0 < \delta < \frac{2}{2+s}$

	Subcase RSQ1	*Subcase RSQ2*
	$0 < c \leq \frac{1-\delta}{3}$ $0 < u < \frac{c}{s}$	$\frac{1-\delta}{3} < c \leq Min\left[\frac{-2+2\delta-3s\delta}{-6+4s}, 1\right]$ $Max\left[0, \frac{-2\delta+6c\delta+2\delta^2}{4s+5s\delta}\right] \leq u < \frac{c}{s}$
x^{RQ}	$\frac{1}{4} + \frac{3c}{4(-1+\delta)}$	0
y^{RQ}	$\frac{-1+c+\delta}{4(-1+\delta)}$	$\frac{2-2c+\delta}{8+10\delta}$
Market segments	*II RR NN*	

	Subcase RSQ3	*Subcase RSQ4*
	$\frac{1-\delta}{3} < c < Min\left[\frac{-2+2\delta-3s\delta}{-4+2s}, 1\right]$ $Max\left[0, \frac{-\delta+2c\delta+\delta^2}{s+2s\delta}\right] < u \leq$ $Min\left[\frac{-2\delta+6c\delta+2\delta^2}{4s+5s\delta}, \frac{2c\delta}{2-2\delta+3s\delta}, \frac{c}{s}\right]$	$\frac{1-\delta}{2} < c < 1$ $0 < u \leq Min\left[\frac{-2c\delta-4\delta^2}{-2-6\delta+s\delta}, \frac{-\delta+2c\delta+\delta^2}{s+2s\delta}\right]$
x^{RQ}	0	0
y^{RQ}	$\frac{1}{2}\left(1 + \frac{2c-3su}{-1+\delta} + \frac{su}{\delta}\right)$	0
Market segments	*II RR NN*	

	Subcase RSQ5	*Subcase RSQ6*
	$\frac{-2+2\delta-3s\delta}{-6+4s} \leq c < Min\left[1, \frac{-4+4\delta^2-4s\delta^2+s^2\delta^2}{-4+2s\delta}\right]$ $\frac{4\delta-12c\delta-8\delta^2+12c\delta^2-2cs\delta^2+4\delta^3-s^2\delta^3}{-8s-4s\delta+12s\delta^2-6s^2\delta^2+2s^3\delta^2)} \leq u < \frac{c}{s}$	$\frac{-2+2\delta-3s\delta}{-6+4s} < c < Min\left[1, \frac{-4+4\delta^2-4s\delta^2+s^2\delta^2}{-4+2s\delta}\right]$ $Max\left[\frac{4\delta-8c\delta-8\delta^2+8c\delta^2+4\delta^3-s^2\delta^3}{-4s-4s\delta+8s\delta^2-2s^2\delta^2+s^3\delta^2}, \frac{2c\delta}{2-2\delta+3s\delta}\right] \leq$ $u \leq \frac{4\delta-12c\delta-8\delta^2+12c\delta^2-2cs\delta^2+4\delta^3-s^2\delta^3}{-8s-4s\delta+12s\delta^2-6s^2\delta^2+2s^3\delta^2}$
x^{RQ}	0	0
y^{RQ}	$\frac{-4+(-2+s)^2\delta^2+c(4-2s\delta)}{-16+4\delta(-2+(6+(-3+s)s)\delta)}$	$\frac{1}{2} + \frac{su}{2\delta} + \frac{-c+su}{2+(-2+s)\delta} + \frac{c-2su}{-2+(2+s)\delta}$
Market segments	*II RR NH NN*	

	Subcase RSQ7	*Subcase RSQ8*
	$\frac{-2+2\delta-3s\delta}{-4+2s} < c < 1$ $\frac{-2c\delta-4\delta^2}{-2-6\delta+s\delta} \leq u \leq$ $Min[\frac{-4+4c-4c\delta-2cs\delta+4\delta^2-4s\delta^2+s^2\delta^2}{-4s-4s\delta+2s^2\delta}, \frac{4\delta-8c\delta-8\delta^2+8c\delta^2+4\delta^3-s^2\delta^3}{-4s-4s\delta+8s\delta^2-2s^2\delta^2+s^3\delta^2}]$	$\frac{-4+4\delta^2-4s\delta^2+s^2\delta^2}{-4+2s\delta} \leq c < 1$ $\frac{-4+4c-4c\delta-2cs\delta+4\delta^2-4s\delta^2+s^2\delta^2}{-4s-4s\delta+2s^2\delta} \leq u < \frac{c}{s}$
x^{RQ}	0	0
y^{RQ}	0	0
Market segments	*II RR NH NN*	*II NH*

Case II with $\frac{2}{2+s} \leq \delta < 1$ will generate similar insights as Case I presented in the proposition and hence relegated to the Appendix. Although the manufacturer sells both lemons and peaches under Testing but only remanufactured products under Remanufacturing, discarding used items remains a mechanism that helps control the volume and price of the resale products and obtain the optimal balance between earning additional resale revenue and not causing too much cannibalization of the new product sales. The cost of this control increases as the production cost increases because mid-life units will be deprived of the opportunity to realize value in the secondary market, leading to a decrease in the total discarded volume. On the other hand, the effect of the remanufacturing cost is similar to our previous discussion without the quantity choice: The market segmentation outcome at optimality changes from only having new and remanufactured product buyers and inactive consumers (with II RR and NN segments in the market) when u is very low, to only having holders and inactive consumers (II and NH segments in the market) when u is very high.

3.7.3 The Optimal Strategy Choice

We compare Testing and Remanufacturing, both with the quantity choice, to identify the optimal strategy that yields the higher profit for the manufacturer and explore how the product characteristics exert influences. We use representative numerical examples to demonstrate the results.

The Effect of Product Durability δ

Figure 5 shows that when product durability δ is high, it is better for the manufacturer to choose Remanufacturing over Testing. Recall that the remanufacturing process incurs the unit cost of us to make up for the quality difference δs between the lemons and peaches. Observe that δs is amplified by δ, in which case the remanufacturing brings higher value-added to the products. In other words, when δ is high, the cost incurred for remanfucuting has a higher return, making Remanufacturing a better strategy choice.

The Effect of Production Cost c

Figure 5(b) shows that when production cost c is high, Remanufacturing is more likely to be the optimal strategy for the manufacturer. As we pointed out earlier, more costly new production strengthens the manufacturer's desire to find ways for each product unit to better realize its market value. Such incentive drives the manufacturer's preference towards Remanufacturing, because it conducts a value-added process to the used items to enhance their market attractiveness and value for resale.

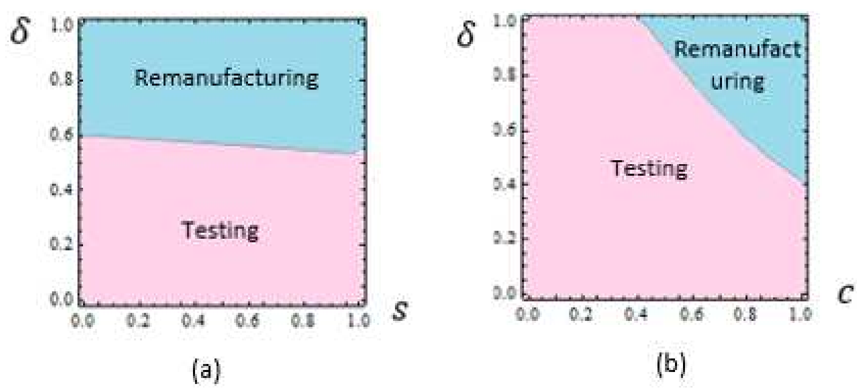


Figure 5: Effect of product durability and production cost on optimal strategy choice, with $c = 0.8$ & $u = 0.3$ for (a) and $s = 0.5$ & $u = 0.3$ for (b)

The Effect of Product Inferiority s

The effect of s on the choice between Testing and Remanufacturing is more complicated. Remanufacturing tends to be supported over Testing by a high s when δ is low (reprenseted by Figure 6(a)), or by a low s when δ is high (Figure 6(b)). Note that first, a small s combined with a small δ favors the Testing strategy. The reason is as follows: In that case, the total quality difference between lemons and peaches (δs) is small, so the effort of remanufacturing and incurring the associated cost may not be worthwhile, as lemons are already close alternatives to peaches and can be directly resold, as under Testing. Second, when δs is large, resulting from a large s

and a large δ, selling the lemons and peaches separately is again a better strategy because with their diverse qualities, the two types of products spread further apart and cover a larger portion of the market while not causing too much competition with each other. Therefore, only when δs falls into a moderate range, Ramnufacturing is the superior choice.

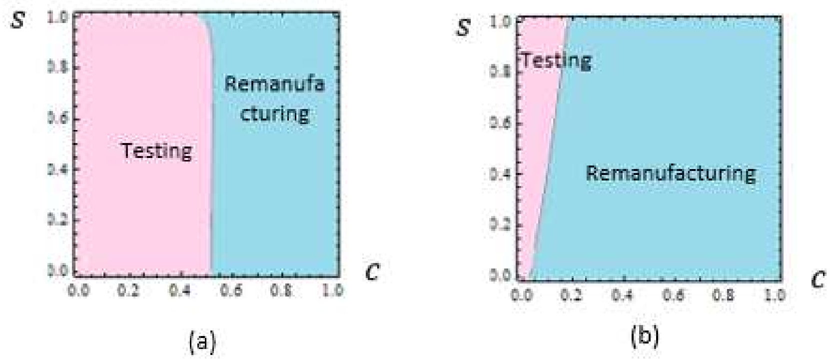


Figure 6: Effect of product quality inferiority on optimal strategy choice with $u = 0.05$, and $\delta = 0.2$ for (a) and $\delta = 0.9$ for (b)

3.8 Conclusions

This study takes the manufacturer's perspective to identify the optimal strategy to deal with the lemons problem arises in the secondary market of durable products. A wide range of industries, such as automobiles and IT equipments, suffer from the lemons problem that is caused by the information asymmetry on used product quality. Offering trade-in programs has been proposed as a solution, but we point out that in spite of its certain merits, it fails to completely resolve the problem. We delve into the root of the lemons problem and reveal that the weakness of Trade-in is because it only addresses the price aspect of the problem. The lemons problem, however, involves the price mismatch between the fair price of the peaches and the buyers' offering price, as well as the quality mismatch between the peaches and the average products in the secondary market as perceived by the buyers. The trade-in discount only serves as a financial incentive to narrow the price gap: It effectively increases the payment for consumers to also release their peaches to the market, which then brings up the average quality and ameliorates the lemons problem.

To overcome this weakness in dealing with the lemons problem, we innovatively propose the strategies of Testing and Remanufacturing in this paper. Interest in these strategies is motivated by the rationale that both Testing and Remanufacuturing enable the manufacturer to actively practice quality intervention with the market. Therefore, they should each make an effective solution. We indeed confirm that both strategies are able to fully resolve the lemons problem. Under both strategies, even though the first-period owners still possess superior quality information, the manufacturer is able to divert them away from the strategic peach-holding behavior by strategically exerting influences on both the primary and the secondary markets. Notably, it is exactly the testing or remanufacturing process that gains the manufacturer the market power to enable its control over the secondary market. We present an in-depth discussion on the underlying mechanism to explain how the quality lever takes effect in the secondary market.

In addition to introducing and confirming Testing and Remanufacturing as effective instruments to deal with the lemons problem, we make another useful and valuable contribution to both the literature and the industry: We derive comprehensive insights on how firms can optimally choose between Testing and Remanufacutring, as well as how the characteristics of their products, such as the product durability, the quality difference between used items, and the production cost, should be accounted for. Beyond providing thorough understanding of the lemons problem and the solutions on the conceptual level, the results and the discussion in this paper also form a rich foundation for empirical study that embeds with substantial potential to generate more detailed strategic guidance for specific industries.

CHAPTER IV

A FRAMEWORK FOR EMPIRICALLY STUDYING SECONDARY MARKET STRATEGIES

4.1 Introduction

Secondary markets of durable products carry the important role of offering trade opportunities that allow consumers who are willing to pay the higher price for new replacements to offload their used products, and channel these items to other consumers as lower-price alternative purchase options. The effectiveness of this reallocation function of the secondary market, however, could be dampened by the lemons problem: First, the value depreciation of used products can vary significantly across units, either due to the production defects that only show up after usage or the previous use patterns of the original owners. In the secondary market, the sellers, being the original product owners, have superior information about the residual qualities of the units for sales. However, due to the nature of trade (i.e., that products are sold by individuals rather than the manufacturer), the sellers typically cannot credibly communicate the quality information when the information is not observable to buyers prior to purchase. As a result of the asymmetric information, buyers are only willing to offer a price based on the average market quality. This price will be lower than the fair price of a high-quality used product (a *peach*) and higher than that of a low-quality one (a *lemon*). Consequently, the owners are incentivized to follow the strategic peach-holding behavior, i.e., to sell the lemons but hold on to the peaches, resulting in a secondary market filled with more lemons than peaches. Although the sellers may reap benefit from the lemons problem when they sell the lemons above the fair price, buyers may be over-charged. As a result, the secondary market fails to properly match products of different qualities to consumers with different product valuations, and the resulting market dynamics bring down the average market quality and hence suppress trade activities. This motivates the research question of the paper: Is there a way for the manufacturer to take an active role in the secondary market and design strategies to resolve the lemons problem?

Used automobile markets provide an interesting context to study this problem for multiple reasons. First, automobiles have active and well-established secondary markets, with a total trade volume well exceeding new production. Second, the lemons problem has long been documented in these markets. Third, manufacturers of automobiles have constructed different approaches and strategies for the secondary markets of their products to tackle the lemons problem, which facilitates rich research on the topic. Specifically, we can compare and study the impacts of different Certified Pre-Owned (CPO) programs offered by the manufacturers that resell used vehicles after inspection and reconditioning. Based on our results, we will also derive guidance on the optimal designs of the CPO programs for the manufacturers of products with different characteristics. In the literature, used vehicle markets have been utilized to study certain characteristics of the lemons problem. For example, Peterson and Schneider (2016) demonstrate that there exists an inverse relation between observed and unobserved qualities in the sales of used cars. Beyond that, these markets also provide the empirical evidence for exploring other topics of the secondary market of durable products, such as how the different incentives to trade lead to different trade patterns (Esteban and Shum, 2007), and the effect of transaction cost on the secondary and primary markets (Gavazza et al., 2014).

In the literature, trade-in programs have been proposed to be able to alleviate the lemons problem. These programs offer a discount on the new product price for consumers who trade in the used items upon the purchase of new ones, and then sell the used items as-is into the secondary market (Rao et al., 2009). Huang et al. (2016)

further delve into the root of the lemons problem and point out that: The lemons problem, caused by the quality information asymmetry, involves both a (quality) mismatch between the peach-quality and the average market quality expected by the buyers, as well as a (price) mismatch between the fair price of peaches demanded by the sellers and the buying price offered by buyers. The trade-in programs are only able to utilize the price lever to close the price mismatch, but are ineffective about the quality aspect of the problem. Therefore, it is not strong enough to completely eliminate the lemons problem. In addition to explaining the weakness of the trade-in programs, the paper proposes the strategy of Testing or Remanufacturing as more effective solutions. The former is referring to the fact that the manufacturer, after acquiring the trade-in used products, conducts testing to identify the product quality, and then resells the lemons and the peaches separately in the secondary market. The latter is referring to the fact that the manufacturer remanufactures the products after testing for the resale. The key underlying working mechanism for both strategies is to enable the manufacturer to actively address the quality aspect of the problem, by either finding a way to credibly communicate the quality information to the market (e.g., selling products of different qualities separately as under Testing), or by removing the quality differences through additional product processing (e.g., as under Remanufacturing). In doing so, the manufacturer gains stronger control over the secondary market, with which it can now strategically influence pricing jointly in both the primary and the secondary markets. Eventually, these strategies deter the strategic peach-holding behavior and eliminate the lemons problem.

A closer scrutiny of the CPO programs suggests its connection to the existing research and hence the suitability of this choice of context for our study. The first CPO program was launched by Mercedes-Benz in the early 1990s, designed to free buyers of used vehicles from the worry of getting lemon cars and to enhance the resale value. This function of CPO programs soon earned popularity among most major manufacturers. For a used vehicle to qualify for CPO in resale, it has to meet certain *qualification criteria* determined by each manufacturer, typically including specifications of the age and the mileage of the car. For example, the qualification criteria for Lexus is that the car has to be less than six years and within 70,000 miles. Vehicles that fail the criteria cannot be sold under CPO, in which case they may be sold as-is. The qualified ones will then go through inspection and reconditioning following another set of *vehicle criteria*. Taking Lexus for example again, the criteria include a 161-point inspection and fixing identified problems up to a certain standard. Moreover, the manufacturer also chooses what warranty to offer for the CPO vehicles. As such, the CPO can be regarded as a strategy that effectively lies somewhere between the Testing and the Remanufacturing strategies we mentioned: Selling vehicles with CPO resembles the sales of the peaches and selling those without CPO is similar to the sales of lemons under the Testing strategy. When the qualification criteria of the manufacturer are set to be loose such that most used vehicles will eventually be sold with CPO, then the manufacturer is approximately following the Remanufacturing strategy. Establishing this connection, we can use the empirical evidence from the car industry to test the results of the effectiveness and the optimal choice of the strategies in resolving the lemons problem for Testing and Remanufacturing.

4.2 Hypothesis Development

In this section, we draw upon results from Huang et al. (2016) to develop testable hypotheses for the empirical study.

One of the main contributions of the paper is to show that both Testing and Remanufacturing remove the strategic peach-holding behavior and resolve the lemons problem. Notably, under the strategies of Testing and Remanufacturing, the lemons problem no longer exists in the used product resale, because the manufacturer discloses the product qualities either by selling products of different qualities separately or by ensuring quality uniformity through conducting remanufacturing. However, the lemons problem could in fact persist in the market because when the original owners of the products first release the used products into the market (i.e., to manufacturers through trade-ins), they still possess superior quality information that is unknown to the manufacturer, which propagates the strategic peach-holding behavior. In light of this, the results in the paper are revealing as they prove that the strategies of Testing and Remanufacturing, by enabling the manufacturer to gain a stronger control over the secondary market, are capable of completely deterring the first-period owners from strategic peach-holding and hence resolve the lemons problem. These results form the foundation for our first hypothesis.

> *Hypothesis 1: The average quality of used products sold into the secondary market increases when CPO programs are offered.*

In addition to exploring Testing and Remanufacturing as solutions to the lemons problem, Huang et al. (2016) also derive a set of conclusions for the optimal strategy choice between Testing and Remanufacturing, based on which we establish the hypotheses below.

As discussed earlier, when the manufacturer sells some of the used vehicles with CPO along with a significant portion without (e.g., those fail the qualification criteria), then the manufacturer effectively follows a strategy that resembles Testing. In contrast, when the majority of the resale vehicles come with CPO, then it is more likely that the manufacturer adopts a strategy that is similar to Remanufacturing. Therefore, we infer whether the manufacturer is more likely adopting Testing or Remanufacturing from the following defined portion:

$$portion = \frac{volume\ of\ resale\ vehicles\ with\ CPO}{volume\ of\ resale\ vehicles\ with\ CPO\ +\ volume\ of\ resale\ vehicles\ without\ CPO}$$

where the value of the portion close to 1 stands for Remanufacturing, and Testing otherwise. A strict alignment with the analytical framework and results in Huang et al. (2016) would mean that all the "resale vehicles" in the equation refer to the ones sold by the dealer. An alternative formulation of the portion for our empirical study could be to also capture the volume of used vehicles privately traded among consumers. We will be making the choice depending on the availability and the characteristics of the data.

Huang et al. (2016) point out that when the vehicles are more durable, it scales up the relative quality difference between peaches and lemons and results in a higher total quality difference. In that case, conducting remanufacturing that makes up the quality deficiency of lemons will bring in a higher value-added. As such, Remanufacture will be the more favorable strategy for the manufacturer to improve profitability. Building on this, we construct Hypothesis 2.

> *Hypothesis 2: The portion of used vehicles sold with CPO increases with the vehicle durability.*

Huang et al. (2016) also demonstrate that the manufacturer is better-off with Remanufacturing than Testing when the production cost is high. The underlying rationale is that when production is more costly, the manufacturer would want to guarantee that each unit of production is indeed worthwhile and generates sufficient return. Therefore, the manufacturer has stronger incentives to enhance the product resale value in the secondary market. Since the resale value can be better realized by selling after remanufacturing, the manufacturer's tendency to follow Remanufacturing, captured by the portion of CPO vehicles, should increase in the production cost. This result translates into the hypothesis below.

> *Hypothesis 3: The portion of used vehicles sold with CPO increases with the unit production cost.*

The relative quality difference between peaches and lemons can be captured by the product reliability that, when multiplied with the product durability, measures the total quality difference. When the product is low (with a low reliability and a low durability), lemons are already close alternatives to peaches in the market. In this case, it is better for the manufacturer to simply sell the lemons without remanufacuting and incurring the additional associated cost; i.e., Testing is a better choice. In contrast, when the product is high (with a high reliability and a high durability), selling peaches and lemons separately is again superior for maximizing manufacturer profit: In this case, the peaches and lemons together, with their diverse qualities, are able to achieve a wide market coverage without causing too much competition among themselves. Therefore, only when the product of reliability and durability falls into a moderate range (a low reliability accompanied with a high durability, or a high reliability combined with a low durability), Remanufacturering should be chosen, as stated in the hypotheses below.

Hypothesis 4a: The portion of used vehicles sold with CPO increases with reliability for low-durability vehicles.

Hypothesis 4b: The portion of used vehicles sold with CPO decreases with reliability for high-durability vehicles.

4.3 Key Characteristics of the Empirical Setting

In this section, we discuss the measures of some of the key variables in the problem.

Product Durability: In the durable goods literature, durability is typically captured by the value depreciation of the product during the later stage of its useful life, compared to a new unit (Desai and Purohit 1998, Huang et al. 2001). This measure can be obtained by studying the prices of used vehicles of different ages, from sources such as *Kelly Blue Book* (Rao et al. 2009).

Product Reliability: Product reliability captures the quality differences among used vehicles and hence can be measured by the consumer ratings, for example, available from *Consumer Reports* magazine (Rao et al. 2009). Alternatively, since the lower-quality used cars are more likely to be associated with more frequent breakdowns or failure. Therefore, repair records such as the repair rate or the associated repair expenditure, also included in *Consumer Reports* can be another measure of product reliability (Porter and Sattler, 1999).

Production Cost: One way to approximately interpolate the production cost is to first collect information on invoice price at which the manufacturer sells the vehicles to dealers, and then factor in the profit margin of the manufacturer, which will be available from the annual financial reports of the manufacturers.

Remanufacturing Cost: For some of the CPO programs, the dealer announces a fee for undertaking (or contracting with auto-shops for) the inspection and the reconditioning processes for the manufacturer. This fee could be a proxy for the remanufacturing cost. To further improve accuracy, this value may also be adjusted by the expected cost associated with the specific warranty offer.

4.4 Discussion

In his seminal paper, Akerlof demonstrates that the lemons problem can be so detrimental that it shuts down trade activities in the secondary market completely (Akerlof, 1970). Hendel and Lizzeri, (2002) later argue that part of the used product trade can survive the lemons problem because there will always be consumers who want to sell off used products for replacement purchases of new ones. Even in that case, however, the emergence of the lemons problem remains highly undesired for the secondary market. In a recent research, Huang et al. (2016) propose that the strategies of Testing and Remanufacturing can be effective solutions to the lemons problem, and the paper further provides guidance on how manufacturers of different products should optimally choose from these options. Our paper empirically studies these strategies given their significant value in the market. One potential of our research is to find practical evidence to support the theoretical results and enhance their validity. We choose the markets of used automobiles for our pursuit as they have long been haunted by the lemons problem. Moreover, the car manufacturers have developed and widely adopted CPO programs to improve the resale value of used vehicles in the existence of the lemons problem. These programs share similar characteristics with the Testing and Remanufacturing strategies of interest because they enable the manufacturers to actively interfere with the qualities of products in the resale. The CPO programs typically include qualification criteria, and sequential inspection and reconditioning, along with additional warranty, based on the vehicle criteria; and both the qualification and vehicle criteria are set by the individual manufacturer. Therefore, the used vehicle context provides a rich discussion ground for our study.

It is very interesting to observe the following in practice: Although the structures of the CPO programs are similar, the actual specifications of the qualification and vehicle criteria vary significantly across manufacturers. Therefore, another potential contribution of this paper is to provide insights on the incentives of manufacturers for making different choices in the details of the CPO programs. Building on that, we can also generate concrete suggestions on instructing the optimal designs of the CPO programs and offer strong theoretical support for informed decision making. For example, the results can provide guidance on whether manufacturers of vehicles that are different in their durability, production cost and product reliability should choose less or more strict qualification criteria to properly control the portion of the used vehicles to be resold under CPO for enhancing the overall profitability.

APPENDIX A

PROOFS OF CHAPTER II

Proof of Lemma 2.1

Under the recycling target R and the collection target λ imposed by legislation, the producer solves the following maximization problem:

$$\max_{p,r} = \Pi(p,r;\rho,\delta) = (1-\theta_1)\left(p - g(\rho,\delta) + \lambda(-\frac{1}{2}\beta r^2 + (\alpha+\rho)r)\right),$$

$$\text{subject to: } R \leq r \leq 1, \quad 1-\theta_1 \geq 0, \quad \theta_1 - \theta_2 \geq 0, \quad \theta_2 \geq 0, \quad p_u \geq 0.$$

The market clearing condition $1-\theta_1 = \theta_1 - \theta_2$ means $\theta_1 - \theta_2 \geq 0$ is redundant as we keep $1-\theta_1 \geq 0$. Furthermore, consumer θ_2 (by definition) is indifferent between choosing Bn or Bu, i.e., $\delta\theta_2 - p_u = 0$, yielding $\theta_2 = \frac{p_u}{\delta}$. Hence $p_u \geq 0$ is redundant as we retain $\theta_2 \geq 0$. Therefore, the full set of constraints to analyze the problem is $1-r \geq 0$, $r - R \geq 0$, $1-\theta_1 \geq 0$ and $\theta_2 \geq 0$. Substituting the expressions of θ_1 and θ_2 from the main text, the last two constraints can be written as $\frac{1+\delta-p}{1+3\delta} \geq 0$ and $\frac{2p-1+\delta}{1+3\delta} \geq 0$, which are equivalent to $1+\delta-p \geq 0$ and $2p-1+\delta \geq 0$ since $1+3\delta \geq 0$. We associate Lagrange multipliers with all the constraints to form the Lagrangian for maximization.

$$\begin{aligned} L = \quad & -\tfrac{1}{1+3\delta}\left(p-(1+\delta)\right)\left(p-g(\rho,\delta)+\lambda(-\tfrac{1}{2}\beta r^2+(\alpha+\rho)r)\right)+\lambda_1(1-r)+\lambda_2(r) \\ & +\lambda_3(1+\delta-p)+\lambda_4(2p+\delta-1). \end{aligned}$$

The Karush-Kuhn-Tucker (KKT) conditions yield the following:

$$0 = \frac{\partial L}{\partial p} = \left(-\frac{1}{1+3\delta}\right)\left(2p - (1+\delta+g(\delta,\rho) - \lambda((\alpha+\rho)r - \frac{1}{2}\beta r^2)\right) - \lambda_3 + 2\lambda_4$$

$$0 = \frac{\partial L}{\partial r} = \left(-\frac{1}{1+3\delta}\right)((\alpha+\rho)-\beta r) - \lambda_1 + \lambda_2$$

There are 9 possible cases (excluding inconsistent cases such as the one with both $1-r=0$ and $r-R=0$).

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
$1-r$	>0	$=0$	$=0$	>0	>0	$=0$	>0	>0	>0
$r-R$	>0	>0	>0	$=0$	$=0$	>0	$=0$	>0	>0
$1+\delta-p$	>0	$=0$	>0	>0	$=0$	>0	>0	$=0$	>0
$2p-(1-\delta)$	>0	>0	$=0$	$=0$	>0	>0	>0	>0	$=0$

We analyze each of them below, and we suppress the arguments of $g(\rho,\delta)$ for brevity.

(1) In this case, $\lambda_1=\lambda_2=\lambda_3=\lambda_4=0$. Substituting them into the first-order conditions, we derive one candidate for the optimal solution to be $r=\frac{\alpha+\rho}{\beta}$ and $p=\frac{1}{2}(1+\delta+g-\lambda\frac{(\alpha+\rho)^2}{2\beta})$. Moreover, the resulting Hessian is negative definite, confirming this pair of values to be a local maximizer.

To ensure the validity of this candidate solution, we need $R\le r=\frac{\alpha+\rho}{\beta}\le 1$ and $\frac{1}{2}(1-\delta)\le p=\frac{1}{2}(1+\delta+g-\lambda\frac{(\alpha+\rho)^2}{2\beta})\le 1+\delta$. Simplifications reduce them to $0\le\alpha+\rho\le\beta$ and $-(1+\delta-g)\le\lambda\frac{(\alpha+\rho)^2}{2\beta}\le(g+2\delta)$. Note that the latter inequality always holds because $\lambda\frac{(\alpha+\rho)^2}{2\beta}$ is the effective unit recycling value at $r=\frac{\alpha+\rho}{\beta}$, which has to be lower than the unit production cost, otherwise it leads to the unreasonable case where the producer can generate a steady profit stream by simply producing and then recycling the products. Therefore, $\lambda\frac{(\alpha+\rho)^2}{2\beta}\le g\le g+2\delta$. Moreover, $1+\delta-g+\lambda\frac{(\alpha+\rho)^2}{2\beta}$ is the unit profit for the producer (accounting for both the production cost and the recycling value), which has to be non-negative to keep the producer in the market, and hence $-(1+\delta-g)\le\lambda\frac{(\alpha+\rho)^2}{2\beta}$.

(2) In this case, $r=1$ and $p=1+\delta$, which lead to zero production and zero profit. This uninteresting case is discarded.

(3) In this case, $r=1$ and $p=\frac{1-\delta}{2}$, with $\lambda_1=\frac{(\alpha+\rho)-\beta}{1+3\delta}$ and $\lambda_4=\frac{-2\delta-g+\lambda((\alpha+\rho)-\frac{1}{2}\beta)}{2(1+3\delta)}$. However, $\lambda_4<0$ because $\lambda(-\frac{1}{2}\beta+(\alpha+\rho))<g<g+2\delta$, with the LHS being

the effective unit recycling value at $r = 1$ that is lower than the unit production cost. Therefore, this candidate solution is invalid and hence discarded.

(4) In this case, $r = R$ and $p = \frac{1-\delta}{2}$, with $\lambda_2 = \frac{(\alpha+\rho)-\beta R}{1+3\delta}$ and $\lambda_4 = \frac{-2\delta-g+\lambda((\alpha+\rho)R-\frac{1}{2}\beta R^2)}{2(1+3\delta)}$. However, similar to Case (3), $\lambda_4 < 0$ and hence this candidate solution is discarded.

(5) In this case, $r = R$ and $p = 1+\delta$, which lead to zero production and zero profit. This uninteresting case is discarded.

(6) In this case, $r = 1$ and $p = \frac{1}{2}(1+\delta+g-\lambda((\alpha+\rho)-\frac{1}{2}\beta))$. To ensure the validity of this candidate solution, we need $\lambda_1 = \frac{\alpha+\rho-\beta}{1+3\delta} \geq 0$ and $\frac{1}{2}(1-\delta) \leq p = \frac{1}{2}(1+\delta+g-\lambda((\alpha+\rho)-\frac{1}{2}\beta)) \leq 1+\delta$, with the latter inequality being satisfied following an argument similar to that in Case (1).

(7) In this case, $r = R$ and $p = \frac{1}{2}(1+\delta+g-\lambda((\alpha+\rho)R-\frac{1}{2}\beta R^2))$. To ensure the validity of this candidate solution, we need $\lambda_2 = \frac{\beta R-(\alpha+\rho)}{1+3\delta} \geq 0$ and $\frac{1}{2}(1-\delta) \leq p = \frac{1}{2}(1+\delta+g-\lambda((\alpha+\rho)R-\frac{1}{2}\beta R^2)) \leq 1+\delta$, with the latter inequality begin satisfied following an argument similar to that in Case (1).

(8) In this case, $p = 1+\delta$, which lead to zero production and zero profit and hence this uninteresting case is discarded.

(9) In this case, $r = \frac{\alpha+\rho}{\beta}$ and $p = \frac{1-\delta}{2}$. However, similar to Case (3), $\lambda_4 = \frac{-2\delta-g+\lambda\frac{(\alpha+\rho)^2}{2\beta}}{2(1+3\delta)} < 0$ and hence this candidate solution is discarded.

Finally, the optimal new product price and recycling level are summarized below.

(i) When $\frac{\alpha+\rho}{\beta} \leq R$	(ii) When $R \leq \frac{\alpha+\rho}{\beta} \leq 1$	(iii) When $1 \leq \frac{\alpha+\rho}{\beta}$
$r^*(\delta,\rho) = R$	$r^*(\delta,\rho) = \frac{\alpha+\rho}{\beta}$	$r^*(\delta,\rho) = 1$
$p^* = \frac{1}{2}(1+\delta+g-\lambda((\alpha+\beta)R-\frac{1}{2}\beta R^2))$	$p^* = \frac{1}{2}(1+\delta+g-\lambda\frac{(\alpha+\rho)^2}{2\beta})$	$p^* = \frac{1}{2}(1+\delta+g-\lambda((\alpha+\beta)-\frac{1}{2}\beta))$

Equivalently, the optimal price is $p^*(\rho,\delta) = \frac{1}{2}(1+\delta+g(\rho,\delta)-\lambda(-\frac{1}{2}\beta(r^*(\rho,\delta))^2 + (\alpha+\rho)r^*(\rho,\delta)))$.

Proof of Proposition 2.2

By backward induction, we study ρ^* and δ^* in three cases, corresponding to the three cases of p^* and r^* in Lemma 1. In solving this problem, we start with a general value of d, and then focus on the case of $d = 0$.

Case(i) When $\frac{\alpha+\rho}{\beta} \leq R$. The producer is faced with the following optimization problem:

$$\max_{\rho,\delta} \Pi(p^*, r^*; \rho, \delta) = \frac{1}{4(1+3\delta)} \left(1 + \delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda((\alpha+\rho)R - \frac{1}{2}\beta R^2)\right)^2,$$

$$\text{subject to:} \quad 0 \leq \delta \leq 1, \quad \rho \geq 0, \quad \alpha + \rho \leq R\beta.$$

We form the Lagrangian of the problem:

$$L_1 = \tfrac{1}{4(1+3\delta)} \left(1 + \delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda((\alpha+\rho)R - \tfrac{1}{2}\beta R^2)\right)^2 + \mu_1(1-\delta) + \mu_2(\delta)$$
$$+\mu_3(R\beta - \alpha - \rho) + \mu_4(\rho).$$

Applying the first-order conditions, we have

$$0 = \frac{\partial L_1}{\partial \rho} = \frac{1}{2(1+3\delta)} \left(1 + \delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda((\alpha+\rho)R - \frac{1}{2}\beta R^2)\right)(-2\tau\rho - d\delta + R\lambda) - \mu_3 + \mu_4,$$
$$0 = \frac{\partial L_1}{\partial \delta} = \frac{1}{4(1+3\delta)^2} \left(1 + \delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda((\alpha+\rho)R - \frac{1}{2}\beta R^2)\right) \times$$
$$\left(-3(1 + \delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda((\alpha+\rho)R - \frac{1}{2}\beta R^2)) + 2(1+3\delta)(1 - d\rho - 2b\delta)\right) - \mu_1 + \mu_2.$$

Note that $(1 + \delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda((\alpha+\rho)R - \frac{1}{2}\beta R^2))$ is the unit profit and hence should be non-negative. There are 3 candidate solutions for ρ^*.

(1) $\rho = \beta R - \alpha$. To ensure $\rho = \beta R - \alpha \geq 0$ and $\mu_3 \geq 0$ for the validity of the candidate solution, the associated constraint is $\beta R - \frac{R\lambda - d\delta}{2\tau} \leq \alpha \leq \beta R$.

(2) $\rho = 0$. To ensure $\mu_4 \geq 0$, the associated constraint is $R\lambda \leq d\delta$.

(3) $\rho = \frac{R\lambda - d\delta}{2\tau}$. The constraints to ensure $\mu_1, \mu_2 \geq 0$ are $d\delta \leq R\lambda$ and $\alpha \leq R\beta - \frac{R\lambda - d\delta}{2\tau}$.

Case(ii) When $R \le \frac{\alpha+\rho}{\beta} \le 1$. The producer is faced with the following optimization problem:

$$\max_{\rho,\delta} \Pi(p^*, r^*; \rho, \delta) = \frac{1}{4(1+3\delta)} \left(1+\delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda \frac{(\alpha+\rho)^2}{2\beta}\right)^2,$$

$$\text{subject to} \quad 0 \le \delta \le 1, \quad \rho \ge 0, \quad \beta R \le \alpha \le \beta.$$

We form the Lagrangian of the problem:

$$\text{Ł}_2 = \frac{1}{4(1+3\delta)} \left(1+\delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda \frac{(\alpha+\rho)^2}{2\beta}\right)^2 + \mu_1(1-\delta) + \mu_2(\delta)$$
$$+\mu_3(\beta - \alpha - \rho) + \mu_4(\rho) + \mu_5(\alpha + \rho - R\beta).$$

Applying the first-order conditions, we have

$$0 = \frac{\partial L_2}{\partial \rho} = \frac{1}{2(1+3\delta)} \left(1+\delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda \frac{(\alpha+\rho)^2}{2\beta}\right) \left(-2\tau\rho - d\delta + \lambda \frac{\alpha+\rho}{\beta}\right) - \mu_3 + \mu_4 + \mu_5,$$
$$0 = \frac{\partial L_2}{\partial \delta} = \frac{1}{4(1+3\delta)^2} \left(1+\delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda \frac{(\alpha+\rho)^2}{2\beta}\right) \times$$
$$\left(-3(1+\delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda \frac{(\alpha+\rho)^2}{2\beta}) + 2(1+3\delta)(1 - d\rho - 2b\delta)\right) - \mu_1 + \mu_2.$$

Note that $(1+\delta - m - \tau\rho^2 - d\rho\delta - b\delta^2 + \lambda \frac{(\alpha+\rho)^2}{2\beta})$ is the unit profit and hence should be non-negative. There are 4 candidate solutions for ρ^*.

(1) $\rho = 0$. The associated constraints to ensure the validity of the candidate solution are $R\beta - \alpha \le \rho = 0 \le \beta - \alpha$ and $\mu_1 \ge 0$, which reduce to $\beta R \le \alpha \le \beta$ and $\frac{\lambda\alpha}{\beta} \le d\delta$.

(2) $\rho = \beta R - \alpha$. The associated constraints are $\rho = \beta R - \alpha \ge 0$ and $\mu_3 \ge 0$, which reduce to $\alpha \le \beta R$ and $2\alpha - R(2\beta\tau - \lambda) \le d\delta$.

(3) $\rho = \beta - \alpha$. The associated constraints are $\rho = \beta - \alpha \ge 0$ and $\mu_2 \ge 0$, which reduce to $\alpha \le \beta$ and $d\delta \le 2\alpha\tau - (2\beta\tau - \lambda)$.

(4) $\rho = \frac{\alpha\lambda - \beta d\beta}{2\beta\tau - 1}$. The associated constraints are $\max[0, R\beta - \alpha] \le \rho \le \beta - \alpha$, which reduce to

- $\alpha \le \beta R$ and $2\alpha\tau - (2\beta\tau - \lambda) \le d\delta \le 2\alpha\tau - R(2\beta\tau - \lambda)$; or
- $\beta R \le \alpha \le \beta$ and $2\alpha\tau - (2\beta\tau - \lambda) \le d\delta \le \frac{\alpha\lambda}{\beta}$.

Case(iii) When $1 \leq \frac{\alpha+\rho}{\beta}$. The producer is faced with the following optimization problem:

$$\max_{\rho,\delta} \Pi(\delta,\rho,p^*,r^*) = \frac{1}{4(1+3\delta)}\left(1+\delta-m-\tau\rho^2-d\rho\delta-b\delta^2+\lambda((\alpha+\rho)-\frac{1}{2}\beta)\right)^2,$$

$$\text{subject to} \quad 0 \leq \delta \leq 1, \quad \rho \geq 0, \quad \alpha+\rho \geq \beta.$$

We form the Lagrangian of the problem:

$$L_3 = \frac{1}{4(1+3\delta)}\left(1+\delta-m-\tau\rho^2-d\rho\delta-b\delta^2+\lambda((\alpha+\rho)-\frac{1}{2}\beta)\right)^2 + \mu_1(1-\delta)+\mu_2(\delta)+\mu_3(\alpha+\rho-\beta)+\mu_4(\rho).$$

Applying the first-order conditions, we have

$$0 = \frac{\partial L_3}{\partial \rho} = \frac{1}{2(1+3\delta)}\left(1+\delta-m-\tau\rho^2-d\rho\delta-b\delta^2+\lambda((\alpha+\rho)-\frac{1}{2}\beta)\right)(-2\tau\rho-d\delta+\lambda)+\mu_3+\mu_4,$$

$$0 = \frac{\partial L_3}{\partial \delta} = \frac{1}{4(1+3\delta)^2}\left(1+\delta-m-\tau\rho^2-d\rho\delta-b\delta^2+\lambda((\alpha+\rho)-\frac{1}{2}\beta)\right)$$
$$\left(-3(1+\delta-m-\tau\rho^2-d\rho\delta-b\delta^2+\lambda((\alpha+\rho)-\frac{1}{2}\beta))+2(1+3\delta)(1-d\rho-2b\delta)\right)-\mu_1+\mu_2.$$

Note that $(1+\delta-m-\tau\rho^2-d\rho\delta-b\delta^2+\lambda((\alpha+\rho)-\frac{1}{2}\beta))$ is the unit profit and hence should be non-negative. There are 3 candidate solutions for ρ^*.

(1) $\rho = 0$. The associated constraints to ensure the validity of the candidate solution are $\beta \leq \alpha$ and $d\delta \geq \lambda$.

(2) $\rho = \beta - \alpha$. The associated constraints are $\alpha \leq \min[\beta, \beta - \frac{\lambda - d\delta}{2\tau}]$.

(3) $\rho = \frac{\lambda - d\delta}{2\tau}$. The associated constraints are

- $\alpha \leq \beta$ and $\beta - \frac{\lambda-d\delta}{2\tau} \leq \alpha$; or
- $\beta \leq \alpha$ and $d\delta \leq \lambda$.

All the candidate solutions can be summarized below.

(i) $\frac{\alpha}{\beta} \leq R$.

	$d\delta \leq 2\alpha\tau-(2\beta\tau-\lambda)$	$2\alpha\tau-(2\beta\tau-\lambda) \leq d\delta \leq 2\alpha\tau - R(2\beta\tau-\lambda)$	$2\alpha\tau - R(2\beta\tau-\lambda) \leq d\delta \leq R\lambda$	$R\lambda \leq d\delta$
$r^* = R$	$\rho = R\beta - \alpha$	$\rho = R\beta - \alpha$	$\rho = \frac{R\lambda - d\delta}{2\tau}$	$\rho = 0$
$r^* = \frac{\alpha+\rho}{\beta}$	$\rho = \beta - \alpha$	$\rho = \frac{\alpha\lambda - d\beta\delta}{2\beta\tau-\lambda}$	$\rho = R\beta - \alpha$	$\rho = R\beta - \alpha$
$r^* = 1$	$\rho = \frac{\lambda - d\delta}{2\tau}$	$\rho = \beta - \alpha$	$\rho = \beta - \alpha$	$\rho = \beta - \alpha$

(ii) $R \leq \frac{\alpha}{\beta} \leq 1$.

	$d\delta \le 2\alpha\tau - (2\beta\tau - \lambda)$	$2\alpha\tau - (2\beta\tau - \lambda) \le d\delta \le \lambda\frac{\alpha}{\beta}$	$\lambda\frac{\alpha}{\beta} \le d\delta$
$r^* = \frac{\alpha+\rho}{\beta}$	$\rho = \beta - \alpha$	$\rho = \frac{\alpha\lambda - d\beta\delta}{2\beta\tau-\lambda}$	$\rho = 0$
$r^* = 1$	$\rho = \frac{\lambda - d\delta}{2\tau}$	$\rho = 0$	$\rho = 0$

(iii) $1 \le \frac{\alpha}{\beta}$.

	$d\delta \le \lambda$	$\lambda \le d\delta$
$r^* = 1$	$\rho = \frac{\lambda - d\delta}{2\tau}$	$\rho = 0$

Next, we need to eliminate the dominated candidate solutions. To this end, we compare the profits resulting from the candidate solutions listed in the same column because they are the valid candidate solutions under the same condition (excluding the first column which simply shows the corresponding recycling level r^*). The optimal solution derived from the comparisons, after an equivalent transformation, is presented below, which we will refer to as the “General Solution” hereafter.

(i) $\frac{\alpha}{\beta} \le R$.

$d\delta \le 2\alpha\tau - (2\beta\tau - \lambda)$	$2\alpha\tau - (2\beta\tau - \lambda) \le d\delta \le 2\alpha\tau - R(2\beta\tau - \lambda)$	$2\alpha\tau - R(2\beta\tau - \lambda) \le d\delta \le R\lambda$	$d\delta \le R\lambda$
$\rho^* = \frac{\lambda - d\delta}{2\tau}$	$\rho^* = \frac{\alpha\lambda - d\delta\beta}{2\beta\tau-\lambda}$	$\rho^* = \frac{R\lambda - d\delta}{2\tau}$	$\rho^* = 0$

(ii) $R \le \frac{\alpha}{\beta} \le 1$.

$d\delta \le 2\alpha\tau - (2\beta\tau - \lambda)$	$2\alpha\tau - (2\beta\tau - \lambda) \le d\delta \le \lambda\frac{\alpha}{\beta}$	$\lambda\frac{\alpha}{\beta} \le d\delta$
$\rho^* = \frac{\lambda - d\delta}{2\tau}$	$\rho^* = \frac{\alpha\lambda - d\delta\beta}{2\beta\tau-\lambda}$	$\rho^* = 0$

(iii) $1 \le \frac{\alpha}{\beta}$.

$d\delta \le \lambda$	$\lambda \le d\delta$
$\rho^* = \frac{\lambda - d\delta}{2\tau}$	$\rho^* = 0$

In the special case where there is no durability-recyclability interaction, i.e., $d = 0$, the General Solution reduces to the following one, presented with the corresponding recycling level and producer profit.

(Ri) When $\alpha \leq R(\beta - \frac{\lambda}{2\tau})$	(Rii) When $R(\beta - \frac{\lambda}{2\tau}) \leq \alpha \leq \beta - \frac{\lambda}{2\tau}$	(Riii) When $\beta - \frac{\lambda}{2\tau} \leq \alpha$
$\rho^* = \frac{R\lambda}{2\tau}$, with $r^* = R$ and $\Pi = \frac{\left(\delta - b\delta^2 + (1-m+\lambda(R\alpha - \frac{2\beta\tau-\lambda}{4\tau}R^2))\right)^2}{4(1+3\delta)}$	$\rho^* = \frac{\alpha\lambda}{2\beta\tau-\lambda}$, with $r^* = \frac{2\alpha\tau}{2\beta\tau-\lambda}$ and $\Pi = \frac{\left(\delta - b\delta^2 + (1-m+\lambda\frac{\alpha^2\tau}{2\beta\tau-1})\right)^2}{4(1+3\delta)}$	$\rho^* = \frac{\lambda}{2\tau}$, with $r^* = 1$ and $\Pi = \frac{\left(\delta - b\delta^2 + (1-m+\lambda(\alpha - \frac{\beta}{2} + \frac{\lambda}{4\tau}))\right)^2}{4(1+3\delta)}$

These results are summarized in Proposition 2.2.

Proof of Proposition 2.3

To prove Proposition 2.3, we start by stating Lemma A.2.

Lemma A.2 *For a given durability δ, the producer's profit at the optimal recyclability choice can be written as*

$$\Pi(\delta) = \frac{(\delta - b\delta^2 + A)^2}{4(1+3\delta)}. \tag{A1}$$

Specifically,

$$A = \begin{cases} 1 - m + \lambda(R\alpha - \frac{2\beta\tau-\lambda}{4\tau}R^2) & \textit{when } \alpha \leq R(\beta - \frac{\lambda}{2\tau}) \\ 1 - m + \lambda\frac{\alpha^2\tau}{2\beta\tau-1} & \textit{when } R(\beta - \frac{\lambda}{2\tau}) \leq \alpha \leq \beta - \frac{\lambda}{2\tau} \\ 1 - m + \lambda(\alpha - \frac{\beta}{2} + \frac{\lambda}{4\tau}) & \textit{when } \beta - \frac{\lambda}{2\tau} \leq \alpha \end{cases}.$$

Proof: The lemma follows from Proposition 1 by rearranging the terms of the profit function.

Based on Lemma 2, the profit function has the form $\Pi(\delta) = \frac{(\delta - b\delta^2 + A)^2}{4(1+3\delta)}$, where A is independent of δ. We solve the first-order condition equation where

$0 = \frac{\partial \Pi}{\partial \delta} = -\frac{\left(A + \delta - b\delta^2\right)\left(-2 + 3A + \delta(-3 + b(4 + 9\delta))\right)}{4(1+3\delta)^2}$, which yields the candidate solutions:

$$\delta_{a,b} = \frac{1 \mp \sqrt{1 + 4Ab}}{2b}, \quad \delta_{c,d} = \frac{(3-4b) + \sqrt{(3-4b)^2 + 3b(2-3A)}}{18b}.$$

Note that $\delta_{a,b} \in \mathbb{R}$ with $\delta_b \geq 0$ and $\delta_a \leq 0$. Moreover, since δ_b can be shown to be a minimizer, both δ_b and δ_a are eliminated as optimal solution. When $\delta_{c,d} \notin \mathbb{R}$, then the profit maximizing solution δ^* can only take the value of 0 or 1, at the boundaries. The optimal solution can be selected by comparing the profits at $\delta = 0$ and $\delta = 1$. When $\delta_{c,d} \in \mathbb{R}$, by pairwise comparisons, we can determine the relative relation between the δ_i's to be $\delta_c \leq \delta_a \leq \delta_d \leq \delta_b$; hence the optimal δ^* can only take the value of 0, 1 or δ_d. The optimal solution can be selected by comparing the profits at these three points and the solution is characterized below, with $\overline{A}(b) \doteq \frac{1}{3}(5 - 13b)$, $\widehat{A'}(b) \doteq \frac{2}{243}(27 + 8b) + \frac{2}{243}\sqrt{\frac{729+972b+432b^2+64b^3}{b}}$ and $\delta_{int} \doteq \delta_d = \frac{(3-4b)+\sqrt{(3-4b)^2+3b(2-3A)}}{18b}$,

(Di) When $0 \leq b < \frac{1}{5}$	(Dii) When $\frac{1}{5} \leq b < \frac{5}{13}$	(Diii) When $\frac{5}{13} \leq b < \frac{3}{4}$	(Div) When $\frac{3}{4} \leq b$
$\delta^* = \begin{cases} 1 & \text{if } A < 1 - b, \\ 0 & \text{otherwise.} \end{cases}$	$\delta^* = \begin{cases} 1 & \text{if } A < \overline{A}(b), \\ \delta_{int} & \text{if } \overline{A}(b) \leq A < \widehat{A'}(b), \\ 0 & \text{otherwise.} \end{cases}$	$\delta^* = \begin{cases} \delta_{int} & \text{if } A < \widehat{A'}(b), \\ 0 & \text{otherwise.} \end{cases}$	$\delta^* = \begin{cases} \delta_{int} & \text{if } A < \frac{2}{3}, \\ 0 & \text{otherwise.} \end{cases}$

These results are summarized in Proposition 2.

Proof of Proposition 2.4

To prove Proposition 2.4, we start by stating Lemma A.3.

Lemma A.3 *When $d \neq 0$, the optimal recyclability choice (and the corresponding optimal recycling level) can be summarized below, with $\delta^1 \doteq \frac{1}{d}(2\alpha\tau - (2\beta\tau - \lambda))$, $\delta^2 \doteq \frac{1}{d}(2\alpha\tau - R(2\beta\tau - \lambda))$, $\delta^3 \doteq \frac{1}{d}(R\lambda)$, $\delta^4 \doteq \frac{1}{d}(\frac{\alpha}{\beta}\lambda)$ and $\delta^5 \doteq \frac{1}{d}(\lambda)$.*

When $d < 0$, and

(i) when $\frac{\alpha}{\beta} \leq R$.

(Ni1) $\delta \leq \delta^2$	*(Ni2)* $\delta^2 \leq \delta \leq \delta^1$	*(Ni3)* $\delta^1 \leq \delta$
$\rho^* = \frac{R\lambda - d\delta}{2\tau}$ $r^* = R$	$\rho^* = \frac{\alpha\lambda - d\beta\delta}{2\beta\tau - \lambda}$ $r^* = \frac{2\alpha\tau - d\delta}{2\beta\tau - \lambda}$	$\rho^* = \frac{\lambda - d\delta}{2\tau}$ $r^* = 1$
$\Pi(\delta) = \Pi_1(\delta)$	$\Pi(\delta) = \Pi_2(\delta)$	$\Pi(\delta) = \Pi_3(\delta)$

(ii) when $R \leq \frac{\alpha}{\beta} \leq 1$.

(Nii1) $\delta \leq \delta^1$	*(Nii2)* $\delta^1 \leq \delta$
$\rho^* = \frac{\alpha\lambda - d\beta\delta}{2\beta\tau - \lambda}$ $r^* = \frac{2\alpha\tau - d\delta}{2\beta\tau - \lambda}$	$\rho^* = \frac{\lambda - d\delta}{2\tau}$ $r^* = 1$
$\Pi(\delta) = \Pi_2(\delta)$	$\Pi(\delta) = \Pi_3(\delta)$

(iii) when $1 \leq \frac{\alpha}{\beta}$.

(Niii1) $\forall\delta$
$\rho^* = \frac{\lambda - d\delta}{2\tau}$ $r^* = 1$
$\Pi(\delta) = \Pi_3(\delta)$.

When $d > 0$, *and*

(i) When $\frac{\alpha}{\beta} \leq R$.

(Pi1) when $\delta \leq \delta^1$	*(Pi2) when* $\delta^1 \leq \delta \leq \delta^2$	*(Pi3) when* $\delta^2 \leq \delta \leq \delta^3$	*(Pi4) when* $\delta^3 \leq \delta$
$\rho^* = \frac{\lambda - d\delta}{2\tau}$ $r^* = 1$	$\rho^* = \frac{\alpha\lambda - d\beta\delta}{2\beta\tau - \lambda}$ $r^* = \frac{2\alpha\tau - d\delta}{2\beta\tau - \lambda}$	$\rho^* = \frac{R\lambda - d\delta}{2\tau}$ $r^* = R$	$\rho^* = 0$ $r^* = R$
$\Pi(\delta) = \Pi_3(\delta)$	$\Pi(\delta) = \Pi_2(\delta)$	$\Pi(\delta) = \Pi_1(\delta)$	$\Pi(\delta) = \Pi_4(\delta)$

(ii) When $R \leq \frac{\alpha}{\beta} \leq 1$.

(Pii1) when $\delta \leq \delta^1$	*(Pii2) when* $\delta^1 \leq \delta \leq \delta^4$	*(Pii3) when* $\delta^4 \leq \delta$
$\rho^* = \frac{\lambda - d\delta}{2\tau}$ $r^* = 1$	$\rho^* = \frac{\alpha\lambda - d\beta\delta}{2\beta\tau - \lambda}$ $r^* = \frac{2\alpha\tau - d\delta}{2\beta\tau - \lambda}$	$\rho^* = 0$ $r^* = \frac{\alpha}{\beta}$
$\Pi(\delta) = \Pi_3(\delta)$	$\Pi(\delta) = \Pi_2(\delta)$	$\Pi(\delta) = \Pi_5(\delta)$

(iii) When $1 \leq \frac{\alpha}{\beta}$.

(Piii1) when $\delta \leq \delta^5$	*(Piii2) when* $\delta^5 \leq \delta$
$\rho^* = \frac{\lambda - d\delta}{2\tau}$ $r^* = 1$	$\rho^* = 0$ $r^* = 1$
$\Pi(\delta) = \Pi_3(\delta)$	$\Pi(\delta) = \Pi_6(\delta)$

Proof: These results can be derived by adapting the General Solution to the cases with $d < 0$ and $d > 0$. The lemma fully characterizes ρ^* for $d \neq 0$, paralleling Proposition 1 for $d = 0$.

Based on Lemma 3, the profit function can be rewritten as

$$\Pi_j(\delta) = \frac{(\delta - b_j\delta^2 + A_j)^2(F_j)^2}{4(1+3\delta)}, \tag{A2}$$

for $j \in \{1,2,3,4,5,6\}$, where A_j's, b_j's and F_j are presented below:

	A_j	b_j	F_j
$j=1$	$\frac{R^2\lambda^2+4(1-m)\tau+4(R\alpha-\frac{R^2\beta}{2})\lambda\tau}{-2dR\lambda+4\tau}$	$\frac{4\tau b-d^2}{4\tau-2dR\lambda}$	$\frac{2\tau-dR\lambda}{2\tau}$
$j=2$	$\frac{\alpha^2\lambda\tau+(1-m)(-\lambda+2\beta\tau)}{-\lambda-d\alpha\lambda+2\beta\tau}$	$\frac{b(2\beta\tau-\lambda)-\frac{1}{2}d^2\beta}{2\beta\tau-\lambda-d\alpha\lambda}$	$\frac{2\beta\tau-\lambda-d\alpha\lambda}{2\beta\tau-\lambda}$
$j=3$	$\frac{\lambda^2+4(1-m)\tau+4\left(\alpha-\frac{\beta}{2}\right)\lambda\tau}{-2d\lambda+4\tau}$	$\frac{4b\tau-d^2}{4\tau-2d\lambda}$	$\frac{2\tau-d\lambda}{2\tau}$
$j=4$	$1-m+(R\alpha-\frac{R^2\beta}{2})\lambda$	b	1
$j=5$	$1-m+\frac{\alpha^2\lambda}{2\beta}$	b	1
$j=6$	$1-m+(\alpha-\frac{\beta}{2})\lambda$	b	1

Since we can unify the profit function into Equation (A2), which has a similar structure as Equation (A1), the solution in Proposition 2 applies. That means for $\Pi(\delta) = \Pi_j(\delta)$, the optimal δ in this case (denoted by δ_j^*) takes the value of $\arg\max_\delta \Pi(\delta)$ as specified in Proposition 2 with $A = A_j$ and $b = b_j$. Then the optimal solution can be identified to be the δ_j^* that yields the highest profit across the different j cases. To be specific,

$$\delta^* = \arg\max_j \left\{\Pi_j(\delta_j^*)\right\}, \text{ where } \begin{cases} j \in \{1,2,3,4\} & \text{when } \frac{\alpha}{\beta} \leq R \\ j \in \{2,3,5\} & \text{when } R \leq \frac{\alpha}{\beta} \leq 1 \\ j \in \{3,6\} & \text{when } 1 \leq \frac{\alpha}{\beta} \end{cases}.$$

Proof of Proposition 2.5

Based on the closed-form solutions of δ^* and ρ^* from Proposition 1–3 and Lemma 3, we can prove that $\frac{\partial \delta^*}{\partial R} \geq 0$, $\frac{\partial \delta^*}{\partial \lambda} \geq 0$, $\frac{\partial \rho^*}{\partial R} \geq 0$ and $\frac{\partial \rho^*}{\partial \lambda} \geq 0$ when $d \leq 0$. Details are omitted for brevity.

Proof of Proposition 2.6

This result is derived from the closed-form solution of δ^* for $d > 0$ from Proposition 3 and its proof, based on which we can calculate $\frac{\partial \delta^*}{\partial R}$. Note that all the thresholds R_{dl} and R_d are in closed-form. They are omitted for brevity.

Proof of Proposition 2.7

This result is derived from the closed-form solution of ρ^* for $d > 0$ from Lemma 3 and its proof, based on which we can calculate $\frac{\partial \rho^*}{\partial R}$. Specifically, $\overline{d} \doteq \sqrt{\frac{6\lambda\tau}{d^2}}$. The thresholds R_r and R_{rr} are also found in closed-form but omitted for brevity.

Proof of Proposition 2.8

This result is derived from the closed-form solution of δ^* for $d > 0$ from Proposition 3 and its proof, based on which we can calculate $\frac{\partial \delta^*}{\partial \lambda}$. Note that the threshold λ_d is found in closed-form but omitted for brevity.

Proof of Proposition 2.9

This result is derived from the closed-form solution of ρ^* for $d > 0$ from Lemma 3 and its proof, based on which we can calculate $\frac{\partial \rho^*}{\partial \lambda}$. The thresholds λ_{rl} and λ_r are found in closed-form but omitted for brevity.

Profitable Recycling and Competition for Cores

In order to elicit returns, the producer and the third parties offer respective buyback options to consumers for the cores. Such buyback options can take various forms including trade-in discounts, coupons, checks or cash. Denote the unit buyback price offered by the producer as p_0 and the one offered by the i-th third parties as p_i (regardless of the product condition). We assume all the n third parties are homogeneous, so as to obtain insights while keeping the analysis tractable.

While the producer is assumed to have a large enough capacity to accept and recycle all the returns that arrive, a third party only has a limited capacity that can accept and recycle a fraction k ($0 \leq k \leq 1$) of all the end-of-life products. When the aggregate third-party capacity covers the whole collection and recycling volume, $k = 1/n$.

We construct a model similar to the one in Arnold (2001) and solve the problem by first looking at the consumers' return strategy. When all the consumers are risk neutral, there exists a symmetric mixed strategy for consumers represented by $\pi = \{\pi_0, \pi_1, \cdots, \pi_n\}$ such that in every attempt to return the core, a consumer chooses the producer and the i-th third party with probabilities π_0 and π_i ($i = 1, \cdots, n$), respectively. Given this strategy, in every period, a portion π_i of the total returns arrive at the i-th third party. Each of these recyclers accept returns up to capacity. Then they start recycling and stop accepting returns during a time period Y, which is assumed to be exponentially distributed with parameter μ and hence $E(Y) = 1/\mu$. Without loss of generality, we assume $\mu = 1$ in the following analysis (the actual value of μ is not a critical assumption). We assume the arrivals of returns follow a Poison process at a rate of $\pi_i q$ where q is the total volume of the cores. Therefore, the period of time that the third party is able to accept returns (i.e., the time period before the returns reach the capacity) is the sum of exponentially distributed random variables (i.e., the time intervals between returns) and hence has a gamma distribution with $E(X) = \frac{kq}{\pi_i q} = \frac{k}{\pi_i}$. The collection (when returns are accepted) and recycling phases form an alternating renewal process. Following standard results from alternating renewal process, the probability that the third party has available capacity to buy back consumer returns will be $\alpha_i = \frac{E(X)}{E(X)+E(Y)} = \frac{k}{k+\pi_i}$ for $i = 1, 2, ..., n$. For the producer, $\alpha_0 = 1$ since it is able to accept any returns that arrive.

For consumers who adopt the strategy $\pi = \{\pi_0, \cdots, \pi_n\}$, the expected payoff is $U = \pi_0(p_0 - s) + \sum_1^n \pi_i(\alpha_i p_i + (1-\alpha_i)U - s)$. In order for $\pi = \{\pi_0, \cdots, \pi_n\}$ to be an equilibrium consumer strategy, it must hold that $U = p_0 - s = \alpha_i(p_i) + (1-\alpha_i)U - s$. Solving it yields: $p_i - p_0 = \frac{s\pi_i}{k}$, where $p_i - p_0$ can be regarded as the price premium the third party has to offer over the producer to compensate the consumers for a possible out-of-capacity situation. Note that π_i, the probability that the i-th third party will be chosen in the equilibrium consumer strategy, increases in the third party's recycling capacity (leading to a lower out-of-capacity probability, i.e., higher service rate) and the price premium, but decreases in the consumers' searching cost.

For the i-th third party, the actual amount of returns that it is able to accept is α_j portion of all the returns that arrive. The third party chooses a buyback price p_i to maximize its profit from buying back and recycling the end-of-life product returns: $\text{Profit}_i = (w - p_i)(\alpha\pi_i q)$. Solving the maximization problem yields $p_i^* = p_0 + \sqrt{s^2 + (w-p_0)s} - s$. Consequently, when the aggregate third party capacity covers the whole collection and recycling volume, the buyback price the producer needs to offer to ensure collection of a λ portion (i.e., $\pi_0 = \lambda$) of end-of-life products for compliance will be $p_\lambda = w - s((2-\lambda)^2 - 1)$.

Proof of Proposition 2.10

When $v(R, 0) > 0$ and $d > 0$, we can solve for the closed-form ρ^* and δ^* that maximizes the producer profit in this case, following a similar procedure as above. Then we can prove that $\frac{\partial \delta^*}{\partial \lambda} \leq 0$ and $\frac{\partial \rho^*}{\partial \lambda} \geq 0$ for $0 \leq \lambda \leq 1$.

Proof of Proposition 2.11

Note that $q(p^*(\rho^*, \delta^*), \delta^*) = \frac{1+\delta-(m+\tau\rho^2+d\rho\delta+b\delta^2)-(\frac{1}{2}\beta R^2+(\alpha+\rho)R)\lambda}{4(1+3\delta)}|_{\rho=\rho^*,\delta=\delta^*}$, with ρ^* and δ^* as specified earlier. Based on the resulting expression of the new production volume, we can calculate $\frac{\partial q(p^*(\rho^*,\delta^*),\delta^*)}{\partial R}$ and $\frac{\partial q(p^*(\rho^*,\delta^*),\delta^*)}{\partial \lambda}$. All the thresholds in the proposition are in closed-form but omitted for brevity.

Details of Calibrated Numerical Study

We first derive the values of $\alpha_j + \rho_j$ and β_j for both the c-Si ($j = 1$) and CIGS ($j = 2$) technologies by using the recycling data. The processing cost is estimated to be $c = \$200$/ton based on recent data (Choi and Fthemakis 2014, Fthenakis and Moskowitz 1999, BIO 2011), and it is comparable for both of the technologies. To convert it into c_1 and c_2 in terms of \$/kW, we use the average weight of 102 kg/kW and 200 kg/kW for the c-Si and CIGS technologies, respectively (Okopol 2007). Next we collect data on the material components of PVPs, as well as the recovery rates and market prices of all the composition elements. Note that the market prices are corresponding to a 100% purity level, which may not always be achieved by the current recycling technologies. Therefore, the actual values of the recovered materials may be lower but these values are good approximations. The table shown in Figure A7 summarizes the data (Cucchiella et al. 2015, BIO 2011), note that it only reflects the recoverable material values but has not yet captured the processing cost.

Materials composition

	Al	Glass	Cd	Cu	Ga	In	Mo	Plastics	Se	Si	Sn	Te	Zn
x-Si (c-si,, p-si, a-si) (% of weight)	17.5	65.8		1				12.8		2.9			
CdTe (% of weight)		96.8	0.08	0.03				3			0.02	0.07	
CIGS (% of weight)		96.9		0.01	0.01	0.01	0.12	3	0.01				0.04
Recycling rates of the material (%)	100	97	98	78	99	75	99	–	80	85	99	80	90
Market prices of the material (\$/kg)	1.00	0.08	0.95	3.69	153.08	417.69	14.62	0.07	32.31	1.17	12.69	59.23	1.12

Figure A7: The material composition of different PVPs.

We can now calculate the recycling levels (r_{m1} and r_{m2}) that only account for the recoverable material values in the following way: For every composition element, multiply its percentage of the total weight by its recovery rate, and then sum over all the elements of the panel. We can also derive the unit recycling material values v_{mj} in the following way: For each element, multiply its percentage of the total weight by the average weight of the panel, then multiply the result by the market price, and sum over all the elements of the panel. Next, let $\alpha_{mj} + \rho_j$ represent the highest marginal recycling value of the product that only accounts for the recoverable material value, given the recyclability of the technology. Then based on $r_{mj} = \min\{1, \max\{\frac{\alpha_{mj}+\rho_j}{\beta_j}, 0\}\}$ and $v_{mj} = -\frac{1}{2}\beta_j r_{mj}^2 + (\alpha_{mj} + \rho_j) r_{mj}^2$, we can calculate $\alpha_{mj} + \rho_j$ and β_j for both the technologies, by $\beta_j = \frac{2v_{mj}}{r_{mj}^2}$ and $\alpha_{mj} + \rho_j = \frac{2v_{mj}}{r_{mj}}$ (since $0 < \frac{\alpha_{mj}+\rho_j}{\beta_j} < 1$). Now we incorporate the processing cost in the estimation. Note that the processing cost applies to all the recycled components of the panel. Therefore, the unit recycling value v_{j0} after accounting for the processing cost (we use the additional subscript "0" for the values in the baseline case without legislation) should be the unit recycling material value net of the processing cost; i.e., $v_{j0} = v_{mj} - c_j$. We assume the processing cost applies in a uniform manner to the recycled components and hence β_j remains unchanged. Substituting the relevant data into the equations, we arrive at the following results: $\beta_1 = 0.08$ and $\beta_2 = 0.112$; $v_{10} = 8.3$ and $v_{20} = 10$. Then we can also solve for r_{j0} and $\alpha_j + \rho_{j0}$ based on $r_{j0} = \min\{1, \max\{0, \frac{\alpha_j+\rho_j}{\beta_j}\}\}$ and $v_j = -\frac{1}{2}\beta_j r_j^2 + (\alpha_j + \rho_j) r_j$. The results are: $r_{10} = 0.455$ and $r_{20} = 0.424$; $\alpha_1 + \rho_1 = 0.0366$ and $\alpha_2 + \rho_2 = 0.0476$.

Next, we show how the X_j values are recovered from the market data. First, we collect data on the current prices of PVPs and the production costs: $p_1 = \$1.75 \times 10^3/\text{kW}$, $p_2 = \$2.1 \times 10^3/\text{kW}$, $g_1 = \$1.05 \times 10^3/\text{kW}$ and $g_2 = \$1.5 \times 10^3/\text{kW}$ (ISET 2010, Reddy 2012). In the baseline case where legislation is absent, when consumer types are distributed in the generalized range of $[0, X_j]$, we re-solve our model in a similar way as before and derive $p_j = \frac{1}{2}(X_j(1 + \delta_j) + g_j - \lambda_0 v_{j0})$. Therefore, $X_j = \frac{2p_j - g_j + \lambda_0 v_{j0}}{1+\delta_j}$, and calculations give $X_1 = 1.26 \times 10^3$ and $X_2 = 1.43 \times 10^3$.

Next, based on the generalization of our model (with X_j), the producer profit in the baseline case is $\Pi_{j0} = \frac{(X(1+\delta_j) - g_j + \lambda_0 v_{j0})^2}{4X_j(1+\delta_j)}$, whereas the profit in the legislated case will be $\Pi_j = \frac{(X(1+\delta_j) - g_j + \lambda v_j)^2}{4X_j(1+\delta_j)}$ with $r_j = \max\{R, r_{j0}\}$ and $v_j = -\frac{1}{2}\beta_j (r_j)^2 + (\alpha_j + \rho_j) r_j$

where R and λ are the legislative recycling and collection targets, respectively. Then $\Delta\Pi_j = \frac{\Pi_{j0}-\Pi_j}{\Pi_{j0}}$. Figure 4 shows how the regions defined by $\min\{\Delta\Pi_1, \Delta\Pi_2\}$ shift as we vary the processing cost from the benchmark value \$200/ton to \$185/ton (as shown by the dashed lines moving downwards).

APPENDIX B

PROOFS OF CHAPTER III

Proof of Proposition 3.6

Depending on their type θ, each consumer self-selects into adopting one of the non-dominated strategies. Accordingly, the market will be divided into segments of consumers choosing different strategies. However, the market segmentation outcomes cannot be determined upfront, because they depend on the prices, which in return are determined by the manufacturer based on the market segment sizes. To solve this problem, we first exhaust all the possible segmentation outcomes. Then for each of these cases, we find the corresponding optimal prices that would lead to that particular segmentation outcome while maximizing the manufacturer's profit.

Note that $V_{NN}[\theta] - V_{NP}[\theta]$, $V_{NP}[\theta] - V_{NH}[\theta]$ and $V_{NH}[\theta] - V_{LL}[\theta]$ are all increasing functions of θ, therefore, consumers in the NN, NP, NH and LL segments have decreasing θ values. We proceed with the analysis by distinguishing two cases.

Case I: When $\delta(1 + \frac{1}{2}s) > 1$.

In this case $V_{NP}[\theta] - V_{PP}[\theta]$ and $V_{PP}[\theta] - V_{NH}[\theta]$ are also increasing functions of θ, so the θ value of consumers in the PP segment lies between those in the NP and NH segments. Depending on the new and used product prices, all the possible market segmentation outcomes are as follows (segments are shown in decreasing order of θ):

(i) NN, NP, PP, NH, LL, II; or

(ii) NN, NP, PP, LL, II; or

(iii) NN, PP, NH, LL, II; or

(iv) NN, PP, LL, II.

We demonstrate the solution process for Subcase (i). For the market to be segmented as in this case, it means $\exists\theta_1^{Ts\delta1}, \theta_2^{Ts\delta1}, \theta_3^{Ts\delta1}, \theta_4^{Ts\delta1}, \theta_5^{Ts\delta1}$ such that a consumer of type θ chooses (1) NN, for $\theta \in (\theta_1^{Ts\delta1}, 1)$; (2) NP, for $\theta \in (\theta_2^{Ts\delta1}, \theta_1^{Ts\delta1}]$; (3) PP, for $\theta \in (\theta_3^{Ts\delta1}, \theta_2^{Ts\delta1}]$; (4) NH, for $\theta \in (\theta_4^{Ts\delta1}, \theta_3^{Ts\delta1}]$; (5) LL, for $\theta \in [\theta_5^{Ts\delta1}, \theta_4^{Ts\delta1}]$; (5) II, for $\theta \in (0, \theta_5^{Ts\delta1}]$.

As a result, the segment sizes of NN, NP, PP, NH, LL and II will be $sgNN = 1 - \theta_1^{Ts\delta1}$, $sgNP = \theta_1^{Ts\delta1} - \theta_2^{Ts\delta1}$, $sgPP = \theta_2^{Ts\delta1} - \theta_3^{Ts\delta1}$, $sgNH = \theta_3^{Ts\delta1} - \theta_4^{Ts\delta1}$, $sgLL = \theta_4^{Ts\delta1} - \theta_5^{Ts\delta1}$ and $sgII = \theta_5^{Ts\delta1}$, respectively.

For the used product trades, there are three associated prices, p_p, p_l and p_u. p_p and p_l are the prices for reselling peaches and lemons, repectively; and p_u is now the acquisition price for the manufacturer to acquire the used units from the consumers. Theoretically, the manufacturer sets p_p and p_l while p_u is endogenously determined by the market such that supply and demand of used products are balanced. Specifically, the market clearing conditions are:

$$sgNN(\alpha) = sgPP, \tag{2}$$

$$sgNN(1-\alpha) + sgNP\frac{1-\alpha}{1+\alpha} = sgLL. \tag{3}$$

Satisfying these conditions to ensure both peaches and lemons are cleared from the market imposes two constraints, so effectively the manufacturer can only set one of the three used product price. Since it is mathematically equivalent to choose any one of the three used product prices as the decision variable for the manufacturer, we choose p_p as the decision variable for the manufacturer. Then the other two prices (i.e., p_l and p_u) will be determined by (i) the proportional relation between lemons and peaches, and (ii) the demand and supply of used products are always balanced; i.e., p_l and p_u can be solved from Equation (2) &(3). The manufacturer profit that comes from the trade of used products will be $\Pi_{used}^{Ts\delta1} = (sgPP)p_p + (sgLL)p_l - (sgNN + sgNP\frac{1-\alpha}{1+\alpha})p_u$, with the first two terms showing the sales revenue from peaches and lemons, while the last one summarizing the total cost to acquire all the used items.

On the other hand, the manufacturer profit that comes from selling new products will be $\Pi^{Ts\delta 1}_{new} = sgNN(p_t - c) + sgNP(\frac{1-\alpha}{1+\alpha}(p_t - c) + \frac{\alpha}{1+\alpha}(p - c)) + sgNH\frac{1}{2}(p - c)$, because in every period in expectation, the following consumers will be buying a new product with trade-in and generate a profit margin of $(p_t - c)$ for the manufacturer: (i) the entire NN segment, and (ii) $\frac{1-\alpha}{1+\alpha}$ fraction of the NP segment; and the following consumers will be buying a new product without trade-in and generate a profit margin of $(p-c)$ for the manufacturer: (i) $\frac{\alpha}{1+\alpha}$ fraction of the NP segment, and (ii) the entire NH segment.

Combining all from the above, the manufacturer solves the following maximization problem

$$\max_{p, p_t, p_p} \Pi^{Ts\delta 1} = \Pi^{Ts\delta 1}_{new} + \Pi^{Ts\delta 1}_{used}$$

subject to $sgNN, sgNP, sgPP, sgNH, sgLL, sgII \geq 0,\ p - p_t \geq 0$.

After substituting the previous results of p_l, p_u and all the segment sizes into the equation, we apply the standard Lagragian approach to solve this constrained optimization problem for the manufacturer profit $\Pi^{Ts\delta 1}$ that is maximized at $p^{Ts\delta 1}$, $p_t^{Ts\delta 1}$ and $p_p^{Ts\delta 1}$, with the corresponding $p_u^{Ts\delta 1}$ and $p_l^{Ts\delta 1}$.

Other subcases are solved in a similar manner. After solving each one of them, we compare the respective optimal profits and identify the highest one. Then the subcase to which the highest profit belongs will be the final optimal solution. The results are shown as in the proposition.

Case II: When $\delta(1 + \frac{1}{2}s) \leq 1$.

In this case, following similar argument as in Case I above, consumers in the PP segment have the higher θ value than the NP segment in this case. Hence, all the possible market segmentation outcomes are

(i) NN, PP, NP, NH, LL, II; or

(ii) NN, PP, NP, LL, II; or

(iii) NN, PP, NH, LL, II; or

(iv) NN, PP, LL, II.

Then the problem is solved following similar procedure as demonstrated above.

Proof of Proposition 3.7

Following similar argument as in the Proof of Proposition 3.6, we first exhaust all the possible market segmentation outcomes as shown below.

Case I: When $\delta(1 + \frac{1}{2}s) > 1$.

(i) NN, NP, NH, RR, II; or

(ii) NN, NP, RR, II; or

(iii) NN, NH, RR, II; or

(iv) NN, RR, II.

Then we identify the final optimal solution by comparing the optimal profit from each possible case. following a similar solution procedure as in the Testing case, except for two differences, which we demonstrate using Subcase (i) as an example.

The first difference is that now with the Remanufacturing strategy, the market clearing conditions change from that presented by Equation (2) &(3) in the Testing case to the following:

$$sgNN + sgNP\frac{1-\alpha}{1+\alpha} = sgRR. \tag{4}$$

The manufacturer will set the remanufactured product price p_r while the used product price p_u will be endogenously determined by the market based on the market clearing condition in Equation (4).

The second difference is that, the manufacturer's profit component from the used products will be $\Pi^{Rs\delta 1}_{reman} = sgRR(p_r) - (\alpha sgNN + sgNP\frac{1-\alpha}{1+\alpha})(us) - (sgNN +$

$sgNP\frac{1-\alpha}{1+\alpha})p_u$, with the first term showing the sales revenue, the second term being the cost of remanufacturing incurred to the lemons that will be resold, and the last term summarizing the total cost of acquiring all the used items.

The manufacturer profit that comes from selling new products will be the same as in the Testing case: $\Pi_{new}^{Rs\delta 1} = sgNN(p_t - c) + sgNP(\frac{1-\alpha}{1+\alpha}(p_t - c) + \frac{\alpha}{1+\alpha}(p - c)) + sgNH\frac{1}{2}(p - c)$.

In this case, the manufacturer solves the following maximization problem

$$\max_{p,p_t,p_r} \Pi^{Rs\delta 1} = \Pi_{new}^{Rs\delta 1} + \Pi_{reman}^{Rs\delta 1},$$

subject to $sgNN, sgNP, sgNH, sgRR, sgII \geq 0,\ p - p_t \geq 0$.

The entire problem is solved similar to the Testing case above, the final optimal solution is presented in the proposition.

Proof of Proposition 3.10

Solving for the optimal solution for the manufacturer with the quantity choice is similar to the case where the quantity choice is absent, except for two differences. The first one that is the market clearing constraints (Equation (2) & (3)) now becomes

$$sgNN(\alpha) = sgPP + x^{TestQ} \tag{5}$$

$$sgNN(1-\alpha) + sgNP\frac{1-\alpha}{1+\alpha} = sgLL + y^{TestQ} \tag{6}$$

The other difference is that the manufacturer is solving the profit maximization problem with the additional decision variables x^{TestQ} and y^{TestQ}

$$\max_{p,p_t,p_p,x^{TestQ},y^{TestQ}} \Pi^{TsQ\delta 1} = \Pi_{new}^{TsQ\delta 1} + \Pi_{used}^{TsQ\delta 1}$$

subject to $sgNN, sgNP, sgPP, sgNH, sgLL, sgII \geq 0,\ p - p_t \geq 0, 0 \leq x \leq sgNN(\alpha)$, $0 \leq y \leq sgNN(1-\alpha) + sgNP\frac{1-\alpha}{1+\alpha}$, with the last two constraints ensuring that the manufacturer does not discard more peaches or lemons than it has on hand.

Incorporating these two changes and then following similar solution procedure as demonstrated above yields the optimal solution presented in the proposition.

Proof of Proposition 3.11

Solving this problem is similar to the case of the Remanufacturing strategy without the quantity choice, whose result presented in Proposition 3.7, with three differences. First, the market clearing condition, with the quantity choice, changes from Equation (4) to

$$sgNN + \frac{1-\alpha}{1+\alpha} sgNP = sgRR + x^{RQ} + y^{RQ}.$$

In addition, while the composition of the manufacturer profit from selling new products is the same as before (i.e., $\Pi_{new}^{Rs\delta 1} = \Pi_{new}^{Rs\delta Q1}$), the one that comes from selling remanufactured products now becomes $\Pi_{reman}^{Rs\delta Q1} = sgNN(p_r) - ((1-\alpha)sgNN + sgNP\frac{1-\alpha}{1+\alpha} - y)(us) - (sgNN + sgNP\frac{1-\alpha}{\alpha})(p_u)$, to account for that the discarded lemons do not incur remanufacturing cost although all the acquired used products (eventually discarded or not) incur the unit acquisition cost p_u.

Finally, the profit maximization problem for the manufacturer now has embedded with two additional decision variables:

$$\max_{p, p_t, p_r, x^{RQ}, y^{RQ}} = \Pi_{new}^{Rs\delta Q1} + \Pi_{reman}^{Rs\delta Q1},$$

subject to $sgNN, sgNP, sgNH, sgRR, sgII \geq 0$, $p - p_t \geq 0$, $0 \leq x \leq (\alpha)sgNN$, $0 \leq y \leq sgNN(1-\alpha) + sgNP\frac{1-\alpha}{1+\alpha}$. Then we solve the problem following similar procedure as discussed above.

REFERENCES

Agrawal, V., M. Ferguson, and G. Souza. 2008 Trade-in rebates for price discrimination or product recovery. Working paper, Kelly School of Business, Indiana University, Bloomington, IN.

Agrawal, V., M. Ferguson, L. B. Toktay, V. Thomas. 2012. Is Leasing Greener than Selling? 58(3), pp. 523–533. *Management Science,*

Agrawal, V., D. Lee. 2015. The Effect of Sourcing Policies on a Supplier's Sustainable Practices. Georgetown University, Working Paper.

Agrawal, V., S. Kavadias, L. B. Toktay. 2015. The Limits of Planned Obsolescence for Conspicuous Durable Goods. *Manufacturing & Service Operations Management*, Forthcoming.

Akerlof G. A. 1970. The market for "lemons": Quality uncertainty and the market mechanism. *The Quarterly Journal of Economics,* 84(3), pp. 488–500.

Alev, I., V. Agrawal, A. Atasu. 2014. Extended Producer Responsibility, Secondary Market, and Export Restrictions. Georgia Institute of Technology, Working Paper.

Anderson S.P. and V. A. Ginsburgh. 1994. Price discrimination via second-hand markets, European Economic Review, 38(1), pp. 23–44.

Apple, 2015. http://www.reddit.com/r/apple/comments/2f092z/hopefully my last lightning cable/, accessed June, 2015.

Arnold, M. 2001. Costly Search, Capacity Constraints, and Bertrand Equilibrium Price Dispersions. *International Economic Review*, 41(1), pp. 117–132.

Atasu, A., V. D. R. Guide Jr, L. N. Van Wassenhove. 2008. Product Reuse Economics in Closed-Loop Supply Chain Research. *Production and Operations Management*, 17, pp. 483-496.

Atasu, A., L. N. Van Wassenhove. 2010. Environmental Legislation on Product Take-Back and Recovery. In *Closed Loop Supply Chains: New Developments to Improve the Sustainability of Business Practices*, Ferguson M. and Souza G. (Eds.), CRC Press, pp. 23–38.

Atasu, A., L. N. Van Wassenhove. 2011. An Operations Perspective on Product Take-Back Legislation for E-Waste: Theory, Practice, and Research Needs. *Production and Operations Management*, 21(3), pp. 407–422.

Atasu, A., L. N. Van Wassenhove, M. Sarvary. 2009. Efficient Take-Back Legislation. *Production and Operations Management*, 18(3), pp. 243–258.

Atasu, A., R. Subramanian. 2012. Extended Producer Responsibility for E-Waste: Individual or Collective Responsibility. *Production and Operations Management*, 21(6), pp. 1042–1059.

Atasu, A., G. Souza. 2012. How Does Product Recovery Affect Quality Choice? *Production and Operations Management*, 22(4), pp. 991–1010.

Atasu, A., O. Ozdemir, L. N. Van Wassenhove. 2012. Stakeholder Perspectives under Take-Back Legislation. *Production and Operations Management*, 22(2), pp. 382–396.

Beisou, M, L. N. Van Wassenhove. 2015. Closed-Loop Supply Chains for Photovoltaic Panels: A Case-Based Approach. *Journal of Industrial Ecology*, Early View.

Battery University. 2015. How to Recycle Batteries. http://batteryuniversity.com/learn/, accessed June, 2015.

BIO Intelligence Service. 2011. Study on Photovoltaic Panels. http://ec.europa.eu/environment/waste/weee/pdf/Study%20on%20PVs%20Bio%20final.pdf, accessed June, 2015.

Bloomberg New Energy Finance (BNEF). 2013. Bloomberg New Energy Finance's Analysis of EBIT Margins of Solar Manufacturers in Q2.

Bonnington, C. 2014. Our E-Waste Problem Is Ridiculous, and Gadget Makers Arent Helping. http://www.wired.com/2014/12/product-design-and-recycling/, accessed March, 2015.

Bulow, J. 1982. Durable-goods Monopolists. *The Journal of Political Economy,* 90(2), pp. 314–332.

Bulow, J. 1986. An Economic Theory of Planned Obsolescence. *Quarterly Journal of Economics*, 101(4), pp. 729–749.

Callcott, P., M. Walls. 2002. Can Downstream Waste Disposal Policies Encourage Upstream "Design for Environment"? *American Economics Review: Paper and Proceedings,* 90(2), pp. 233–237.

Chamama, J., M. Cohen, R. Lobel, G. Perakis. 2015. Consumer Subsidies with a Strategic Supplier: Commitment vs. Flexibility. Massachusetts Institute of Technology, Working Paper.

Chambers, C., P. Kouvelis, J. Semple. 2006. Quality-Based Competition, Profitability, and Variable Costs. *Management Science*, 52(12), pp. 1884–1895.

Chen, C. 2001. Design for the Environment: A Quality-Based Model for Green Product Development. *Management Science*, 47(2), pp. 250–263.

Choi, J. P. 1994. Network Externality, Compatibility Choice, and Planned Obsolescence. *The Journal of Industrial Economics*, 2, pp. 167–182.

Choi, J. K., V. Fthenakis, 2014. Crystalline Silicon Photovoltaic Recycling Planning: *Macro and Micro Perspectives. Journal of Clean Production*, 66, pp. 443-449.

Cohen, M., R. Lobel, G. Perakis. 2015. The Impact of Demand Uncertainty on Consumer Subsidies for Green Technology Adoption. *Management Science*, Forthcoming.

Coker, A. 2015. Personal communications, Hannah Solar LLC, Atlanta, GA.

Coase, R. H. 1972. Durability and Monopoly. *Journal of Law and Economics*, 15(1), pp. 143–149.

Cyccguekka, F, I. D'Adamo, R. Rosa, 2015. End-of-Life of Used Photovoltaic Modules: A Financial Analysis Renewable and Sustainable Energy Reviews, 47, pp. 552–561.

Debo, L. G., L. B. Toktay, L. N. Van Wassenhove. 2005. Market Segmentation and Product Technology Selection for Remanufacturable Products. *Management Science,* 51(8), pp. 1193-1205.

DeCroix, G. A. 2006. Optimal Policy for a Multiechelon Inventory System with Remanufacturing. *Operations*

Research, 54(3), pp. 532–543.

Desai, P., D. Purohit. 1998. Leasing and Selling: Optimal Marketing Strategies for A Durable Goods Firm. *Management Science*, 44(11), pp. 19–34.

Department for Business Innovation & Skills. 2012. The Waste Electrical and Electronic Equipment (WEEE) Directive - Recast Update, https://www.aham.org/index.php?ht=a/GetDocumentAction/i/61297, accessed April, 2015.

De Brito, M. P., R. Dekker. 2004. A Framework for Reverse Logistics. In Reverse Logistics, Dekker, R, M. Fleischmann, K. Inderfurth, L. N. Van Wassenhove (Eds.), Springer Berlin Heidelberg, pp. 3–27.

Dinan, T. M. 1993. Economic Efficiency Effects of Alternative Policies for Reducing Waste Disposal. *Journal of Environmental Economics Management,* 25, pp. 242–256.

Drake, D. 2012. Carbon Tariffs: Effects in Settings with Technology Choice and Foreign Comparative Advan*tage*. Harvard Business School, Working Paper.

Ebay, 2015. http://www.ebay.com/sch/i.html? from=R40& sacat=0& nkw=solar%20panels& dcat=41981 &rt=nc&LH ItemCondition=3000& trksid=p2045573.m1684, accessed September, 2015.

Eichner, T., R. Pething. 2001. Product Design and Efficient Management of Recycling and Waste Treatment. *Journal of Environmental Economics Management*, 41, pp. 109–134.

Eichner, T., M. Runkel. 2003. Efficient Management of Product Durability and Recyclability under Utilitar*ian* and Chichilnisky Preferences. *Journal of Economics*, 80(1), pp. 43–75.

Esenduran, G., A. Atasu, L. N. Van Wassenhove. 2015. Valuable E-Waste: Implications for Extended Producer Responsibility. Working Paper.

Esenduran, G., E. Kemahlioglu-Ziya, J. M. Swaminathan, 2014, Take-Back Legislation: Consequences for Remanufacturing and Environment. *Decision Sciences*, Forthcoming.

Esenduran, G. and E. Kemahlioglu-Ziya. 2015. A Comparison of Product Take-Back Compliance Schemes. *Production and Operations Management*, 24(1), pp. 71–88.

Esteban, S. and M. Shum, 2007. Durable-goods oligopoly with secondary markets: the case of automobiles. *The RAND Journal of Economics*, 38(2), pp.332-354.

Europa-Environment. 2010. Waste Electrical and Electronic Equipment. http://europa.eu/legislation summaries/environment/waste management/l21210 en.htm, accessed April, 2015.

Europa-Environment. 2012. On Waste Electrical and Electronic Equipment (WEEE) (recast). http://eur-lex. europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:en:PDF, accessed December 2014.

Ferrer G., and Whybark D. C. 2001. Material planning for a remanufacturing facility. *Production and Operations Management*. 10(2), pp. 112–124.

Ferguson M. and L. B. Toktay. 2006. The effect of competition on recovery strategies. *Production and Operations*

Management 15(3), pp. 351–368.

Ferguson, M., V. D. R. Guide Jr, G. C. Souza. 2006. Supply Chain Coordination for False Failure Returns. *Manufacturing and Service Operations Management,* 8(4), pp. 376-393.

Ferguson, Mark E., and Gilvan C. Souza (Eds.) Closed-loop Supply Chains: New Developments to Improve the Sustainability of Business Practices. CRC Press, 2010.

Fleischmann, M., P. Beullens, J. M. Bloemhof-Ruwaard, and L. N. Va Wassenhove. 2001. The Impact of Product Recovery on Logistics Network Design. *Production and Operations Management*, 10, pp. 156- 173.

Fraunhofer ISE, 2014. Photovoltaics Report, http://www.webcitation.org/6SFRTUaBS, accessed June, 2015.

Fthenakis, V. M., P. D. Moskowitz, 1999. The Value and Feasibility of Proactive Recycling. *AIP Conference Proceedings,* 462(332).

Fullerton, D., W. Wu. 1998. Policies for Green Design. *Journal of Environmental Economics Management*, 36, pp. 131–148.

Gavazza, A., Lizzeri, A. and Roketskiy, N., 2014. A quantitative analysis of the used-car market. *The American Economic Review,* 104(11), pp.3668-3700.

GBI Research, 2011. Thin Film Photovoltaic PV Cells Market Analysis to 2020 CIGS Copper Indium Gallium Diselenide to Emerge as the Major Technology by 2020. http://www.gbiresearch.com/report- store/market-reports/archive/thin-film-photovoltaic-pv-cells-market-analysis-to-2020-cigs-copper- indium-gallium-diselenide-to-emerge-as-the-major-technolo, accessed June 2015.

Gui L., A. Atasu, O. Ergun, L. B. Toktay. 2015. Design Incentives under Collective Extended Producer Responsibility: A Network Perspective. Georgia Institute of Technology, Working Paper.

Guide, V.D.R. Jr, G. Souza, L. N. Van Wassenhove, J. D. Blackburn. 2006. Time Value of Commercial Product Returns *Management Science,* 52(8), pp. 1200-1214.

Guide, V. D. R. Jr, L. N. Van Wassenhove. 2007. OR FORUMThe Evolution of Closed-Loop Supply Chain Research. *Operations Research*, 57(1), pp. 10–18.

Haroon, Sol. 2015. Personal communications, Pursuit Engineering, Atlanta, GA.

Heese H. S., Cattani K., Ferrer G., Gilland W., and Roth A. V. 2005. Competitive advantage through take-back of used products. *European Journal of Operational Research* 164(1), pp. 143–157.

Hendel, I., A. Lizzeri. 1999a. Adverse Selection in Durable Goods Markets. *American Economic Review*, 89(5), pp. 1097–1115.

Hendel, I., A. Lizzeri. 1999. Interfering with Secondary Markets. *Rand Journal of Economics*, 30(1), pp. 1–21.

HP, 2009. HP Introduces Z Line of Efficient PC's, http://cleantechauthority.com/hp-introduces-z-line-of- efficient-pcs/, accessed April 2015.

Huang, S., Y. Yang, K. Anderson. 2001. A Theory of Finitely Durable Goods Monopoly with Used-Goods Market and Transaction Costs Management Science, 47(11), pp. 1515–1532.

Huang X., A. Atasu, L. B. Toktay. 2016. Lemons, Trade-Ins, and Remanufacturing. Georgia Institute of Technology, Working Paper.

International Solar Electric Technology, 2010. Competitiveness of Ink-Base Thin Film Photovoltaics. http://www.isetinc.com/wp-content/uploads/2012/03/tech white paper4.pdf, accessed June, 2015.

Islegen, O., S. J. Reichelstein. 2011. Carbon capture by fossil fuel power plants: An economic analysis. *Management Science*, 57(1), pp. 21–39.

Jacobs, B. W., R. Subramanian, 2011. Sharing Responsibility for Product Recovery Across the Supply Chain, *Production and Operations Management,* 21(1), pp. 85–100.

Jordan, D. C., S. R. Kurtz. 2012. Photovoltaic Degradation Rates: An Analytical Review. *Progress in Photovoltaics: Research and Applications*, 21(1), pp. 12–29.

Kalkanci, B., E. Ang, E. Plambeck. 2015. Strategic Disclosure of Social and Environmental Impacts in a Supply Chain. Forthcoming in Environmentally Responsible Supply Chains, Atasu, A. (Ed.), Springer.

Karakayali, I., T. Boyaci, V. Verter, L. N. Van Wassenhove. 2015. On the Incorporation of Remanufacturing in Recovery Targets. McGill University, Working Paper.

Kerr W. and Ryan C. 2001. Eco-efficiency from remanufacturing: A case study of photocopier remanufacturing at Fuji Xerox. *Journal of Cleaner Production*. 9, pp. 75–81

Kim, K. 1989. Trade-in Used goods and Durability Choice. *International Economic Journal,* pp. 53–63.

Kim, K., D. Chhajed. 2002. Product Design with Multiple Quality-Type Attributes. *Management Science*, 48(11), pp. 1502–1511.

Knut S., Institut fur Okologie und Politik. Study on The Development of a Take Back and Recovery System for Photovoltaic Products.

Kraft, T., Y. Zheng, F. Erhun, 2013. The NGO's Dilemma: How to Influence Firms to Replace a Potentially Hazardous Substance *Manufacturing & Service Operations Management*, 15(4), pp. 649–669.

Kraft, T., G. Raz. 2015. Compete or Collaborate: Examining Manufacturers' Replacement Strategies for a Substance of Concern. University of Virginia, Working Paper.

Krass, D., T. Nedorezov, A. Ovchinnikov. 2013. Environmental Taxes and the Choice of Green Technology. *Production and Operations Management*, 22(5), pp. 1035–1055.

Krishnan, V., W. Zhu. 2006. Designing a Family of Development-Intensive Products. *Management Science*, 52(6), pp. 813–825.

Lacourbe, P., C. H. Loch, S., Kavadias. 2009. Product Positioning in a Two-Dimensional Market Space *Production and Operations Management,* 18(3), pp. 315–332.

Langrova, V. 2002. Comparative Analysis of EPR Programs for Small Consumer Batteries: Case Study of the Netherlands, Switzerland and Sweden. IIIEE Report, 9. The International Institute for Industrial Environmental Economics, IIIEE, Lund University.

Lee, M. 2002. New Generation Regulation? The Case of End-of-Life Vehicles. *European Environmental Law Review,* 11(2), pp. 114–118.

Levinthal D., and Purohit D. 1989. Durable Goods and Product Obsolescence. *Marketing Science 8*(1), pp. 35–56.

Lindhqvist, T. 2000. Extended Producer Responsibility in Cleaner Production. Lund University, Lund.

Misiga, P. 2012. The Emerging EU Resource Efficiency Policy and Closed Loop Supply Chains, International Closed Loop Supply Chain Conference Presentation, Spain.

MRI E-cycle Solution, 2014. CPR Recycling. http://www.mri.com.au/crt-monitor-recycling.shtml, accessed April, 2015.

Mobile Muster, 2015. The Recycling Process, http://www.mobilemuster.com.au/learn-about-recycling/, accessed April 2015.

Ng, E. 2014. Worst Over for Solar Sector, But Margins Stay Slim. http://www.scmp.com/business/china-business/article/1517854/worst-over-solar-sector-margins-stay-slim, accessed June 2015.

Nocke V. and M. Peitz. 2003. Hyperbolic discounting and secondary markets. *Games and Economic Behavior*, 44(1), pp. 77-97.

NovoPolymers, 2015. http://www.novopolymers.com/en/company, accessed March, 2015.

Organization for Economic Cooperation and Development (OECD). 2001. Extended Producer Responsibility: A Guidance Manual for Governments. OECD, Paris, France.

Plambeck, E.L., Q. Wang. 2009. Effects of E-Waste Regulation on New Product Introduction. *Management Science,* 55(3), pp. 333–347.

Porter, R. and P. Sattler. 1999. Patterns of Trade in the Market for Used Durables: Theory and Evidence.

Purohit, D. 1994. What Should You Do When Your Competitors Send in the Clones? *Marketing Science,* 13(4), pp. 392–411.

Raz, G, V., Blass, C, Durehl, 2015. The Effect of Environmental Regulation on DfE Innovation: Assessing Social Cost in Primary and Secondary Market. University of Virginia, Working paper.

Rao, R., O. Nrasimhan, and G. John. 2006. Understanding the role of trade-ins in durable goods

markets: Theory and evidence. *Marketing Science*. 28(5), pp. 950–967.

Ray S., Boyaci, T., abd Aras, N. 2005. Optimal prices and trade-in rebates for durable, remanufacturable products. *Manufacturing & Service Operations Management*. 7(3), pp. 208-228.

Reddy, R. J., 2012. Solar Power Generation: Technology, New Concepts & Policy, CRC Press.

Savaskan, R. C., S. Bhattacharya, L. N. Van Wassenhove. 2004. Closed-Loop Supply Chain Models with Product Remanufacturing. *Management Science*, 50(2), pp. 239–252.

SecondSol, 2015. http://en.secondsol.de/handelsplatz/marktplatz,1847,Photovoltaikmodule.htm, accessed September, 2015.

Scrap Metal Forum, 2012. Computer Price Breakdown, http://www.scrapmetalforum.com/e-waste-grading-identification/11950-computer-price-breakdown.html, accessed April, 2015.

Smink, C. K.,2006. Vehicle Recycling Regulations: Lessons From Denmark. *Journal of Cleaner Production*, 15, pp. 1135–1146.

State of Rhode Island and Providence Plantations Department of Environmen- tal Management, 2013. Electronic Waste Prevention, Reuse and Recycling Act http://www.dem.ri.gov/pubs/regs/regs/waste/ewaste13.pdf, accessed March, 2015.

Subramanian, R., S. Gupta, B. Talbot. 2009. Product Design and Supply Coordination Under Extended Producer Responsibility. *Production and Operations Management,* 18(3), pp. 259–277.

Subramanian, R., R. Subramanyam, N. R. Tereyagoglu. 2016. The Differential Effects of Buyer Safeguards on New and Refurbished Products in an Online Marketplace. Georgia Institute of Technology, Working Paper.

Peterson, J.R. and H. S. Schneider, 2016. Beautiful lemons: Adverse selection in durable-goods markets with sorting. *Management Science*.

Thomas, V. M. 2008. Demand and De dematerialization impacts of second-hand markets. *Journal of Indus- trial Ecology*, 7(2), pp 65–78.

Toktay, L. B., L. M. Wein, S. A. Zenios. 2000. Inventory Management of Remanufacturable Products. *Management science* 46(11), pp. 1412–1426.

Toyasaki, F., T. Boyaci, V. Verter. 2011. An Analysis of Monopolistic and Competitive Take-Back Schemes for WEEE Recycling. *Production and Operations Management,* 20(6), pp. 805–823.

Toffel, M. W. 2003. The Growing Strategic Importance of End-of-Life Product Management. *California Management Review,* 45(3), pp. 102–129.

Turner, R. K., D. Pearce, (Eds.). 1994. The Role of Economic Instruments in Solid Waste Management Policy. Dordrecht: Kluwer Academic Publishers.

The Solar Spark, 2015. Thin Film Solar Cells, http://www.thesolarspark.co.uk/the-science/solar-power/thin-film/, accessed June, 2015.

Ulku, S., G. Schmidt, C. Dimofte. 2012. Consumer Valuation of Modularly Upgradeable Products. *Management Science*, 58(9), pp. 1761–1776.

U.S. EPA. 2013. Non-Hazardous Waste Management Hierarchy. http://www.epa.gov/waste/nonhaz/municipal/hierarchy.htm, accessed June, 2015.

Van Ackere A. and D. Reyniers. 1993. A rational for trade-ins. *Journal of Economics and Business*. 45(1), pp. 1–16.

Van Ackere A. and D. Reyniers. 1995. Trade-ins and introductory offers in a monopoly. *RAND Journal of Economics*. 26(1), pp. 58–74.

Waldman, M. 1996. Durable Goods Pricing When Quality Matters. *Journal of Business*, 69(4), pp. 583–595.

Waldman, M. 2003. Durable goods Theory for Real World Markets. *The Journal of Economic Perspectives*, 17(1), pp. 131–154.