HEC MONTRÉAL
École affiliée à l'Université de Montréal

Promoting Product Recovery Through Implementing EPR Regulation and Performing Green Activities

par
Mostafa Pazoki

Thèse présentée en vue de l'obtention du grade de Ph. D. en administration
(option Sciences de la décision)

Mars 2019

HEC MONTRÉAL
École affiliée à l'Université de Montréal

Cette thèse intitulée :

Promoting Product Recovery Through Implementing EPR Regulation and Performing Green Activities

Présentée par :

Mostafa Pazoki

a été évaluée par un jury composé des personnes suivantes :

Sihem Taboubi
HEC Montréal
Présidente-rapportrice

Georges Zaccour
HEC Montréal
Directeur de recherche

Michèle Breton (HEC Montréal)
Mehmet Gümüş (McGill University)
Membres du jury

Jing Chen
Dalhousie University
Examinatrice externe

Bernard Gauthier
HEC Montréal
Représentant du directeur de HEC Montréal

Résumé

La responsabilité élargie des producteurs (REP) est une approche visant à amener les pollueurs (producteurs, propriétaires de marques, etc.) à internaliser les coûts environnementaux. Cette thèse comprend trois essais sur la conception de réglementations environnementales basées sur une approche de REP, la répartition de la responsabilité de la récupération de produits usés entre les membres de la chaîne logistique et l'analyse des interactions stratégiques et dynamiques entre un régulateur et une entreprise lorsque les deux entités investissent dans l'amélioration du taux de recouvrement.

Dans le premier essai, on considère un organisme de réglementation qui introduit une réglementation de type REP qui s'applique à toute entreprise qui fabrique de nouveaux produits et qui doit s'engager dans le recyclage et/ou la remise à neuf de produits utilisés. L'objectif de cet essai est de doter le planificateur social d'un système d'aide à la décision qui permet de concevoir une réglementation flexible qui permet d'analyser et de comparer un large éventail de possibilités en matière de taxes et de subsides et d'en évaluer les conséquences économiques et environnementales. Parmi les conclusions importantes tirées de cet essai, trois d'entre elles pourraient être soulignées: (i) la forme de la réglementation proposée généralise toutes les autres proposées dans la littérature; (ii) l'objectif de collecte de produits usés– qui est largement utilisé en pratique comme un indicateur de performance environnementale – n'a aucun impact sur la récupération du produit; et (iii)

l'impact économique et environnemental d'une réglementation EPR dépend surtout par la disponibilité des produits usagés à collecter et à reconstruire.

Dans le deuxième essai, l'hypothèse d'une entreprise est assouplie, ce qui pose la question de savoir quel membre de la chaîne d'approvisionnement devrait être tenu responsable de la récupération du produit et des conséquences financières (taxes ou subsides offerts par le régulateur). Pour répondre à cette question, on considère une chaîne d'approvisionnement composée d'un fabricant et d'un détaillant engagés dans un jeu à la Stackelberg. On montre qu'il n'existe pas une réglementation REP qui domine toutes les autres, et qu'en pratique il faudrait tenir en compte les objectifs d'une telle réglementation (cibles de recyclage, de remise à neuf, taxes et subsides). Ceci montre que la conception de règlements REP et de partage de responsabilités doivent être réalisés simultanément. De plus, en analysant les données de trois produits électroniques, il s'est avéré que le type de produit était aussi important que la politique de partage des responsabilités pour déterminer ses bénéfices environnementaux.

Les deux premiers essais se concentrent sur la conception d'une réglementation environnementale et l'attribution de responsabilités aux intervenants dans une chaîne d'approvisionnement, en supposant que les entreprises possèdent déjà les connaissances et les installations pour collecter et remettre à neuf les produits usés. Dans cet essai, on s'intéresse au cas où la municipalité investit dans le développement de centres de collecte et la firme développe des programmes incitatifs (surtout de communication) pour inciter les consommateurs à amener leurs vieux produits aux centres de collecte. On suppose que la municipalité et la firme déterminent indépendamment leurs politiques d'investissement et on détermine un équilibre de Stackelberg en rétroaction. Dans ce jeu, la firme maximise ses profits et la municipalité le bien-être collectif sur un horizon infini. Entre autres résultats, on montre que si le produit est à fort contenu toxique, la firme visera à le réduire si elle pense que la municipalité réduira la pénalité. Cependant, la municipalité a intérêt à élaborer une taxa-

tion croissante en fonction du contenu toxique du produit. Les politiques d'investissement à d'équilibre des deux joueurs sont au deçà de ce qui optimalement souhaitable, ce qui montre l'existence de resquillage.

Mots-clés

Chaîne d'approvisionnement en boucle fermée, Conception de la réglementation environnementale, Responsabilité élargie des producteurs, Politique de partage des responsabilités, Stratégie de prix, Jeu de Stackelberg.

Méthodes de recherche: Analyse numérique, Recherche quantitative.

Abstract

Extended Producer Responsibility (EPR) is an approach to make the polluters (producers, brand owners, etc.) internalize the environmental costs. This thesis includes three essays on designing environmental regulations based on EPR approach, allocating the responsibility of product recovery among the supply chain members, and examining the dynamic interactions of a regulator and a firm where both are investing in boosting the collection rate of past-sold products.

In the first essay, it is assumed that a regulator introduces an EPR regulation for a firm who produces new products, and then collects the used products to remanufacture them. In this paper, the social planner is provided with a decision support system for designing an environmental regulation based on EPR approach. Furthermore, the proposed system makes the social planner capable of analyzing and comparing a wide set of regulations in a single framework. This paper contributes to the literature on environmental regulation design by discovering and investigating the underlying conceptual and functional form of various environmental regulations. Among the important conclusions made in this essay, two of them could be highlighted: (i) the proposed regulation encompasses all the regulations that have been proposed in the literature; (ii) collection target – which is being used widely as an environmental performance criterion in many actual regulations – may not have any impacts on product recovery; and (ii) impact of an environmental regulation is

largely affected by the availability of used products to collect and remanufacture.

In the second essay, the assumption of one firm (or a centralized supply chain) is relaxed, therefore raising the question of which supply chain member should be held responsible for which product recovery process. This topic is referred to as responsibility sharing policy (RSP) in the literature. To tackle this problem, a supply chain consisting of a manufacturer and a retailer who are playing a Stackelberg game are considered. It is shown that the best design for an EPR regulation depends on the allocation of responsibilities to the supply chain members, and the best allocation of these responsibilities also depends on the proposed EPR regulation, which implies that RSP and EPR regulation design must be done synchronously. Moreover, by analyzing the data for three electronic products, it is shown that the type of the product is as important as the responsibility sharing policy in determining the impact of the proposed regulation (defined target rates) on the environmental performance of the regulation.

The first two essays concentrate on designing an environmental regulation and allocating the defined responsibilities in a supply chain in a context where the firms already have knowledge and capability to collect and remanufacture. Instead of imposing the regulations and expecting the firm to abide by them, the focus is on a case where the municipality and the producer are investing in those activities that boost the returns. These activities are (i) holding information campaigns and other activities that elevate environmental awareness, and (ii) developing collection infrastructure that provides the customers who intend to return their used products with convenience. For this purpose, a differential game à la Stackelberg is proposed with the social planner acting as the leader who maximizes the social welfare, while the (regulated) firm acting as follower who maximizes its profit. It is shown that the consumers benefit from higher environmental awareness and return convenience. Based on sensitivity analysis, it is obtained that while it is in the best interest of the producer to manufacture a product with more hazardous materials, it may decrease the

amount of such materials if it expects that the municipality to drop the penalty value. The municipality, however, responds to a higher amount of toxic materials in the product by increasing the penalty, whereas it decreases the penalty for greener products. Equilibrium investment policies are below what is socially desirable, which shows that each player is free riding the other one.

Keywords

Closed Loop Supply Chain, Environmental Regulation Design, Extended Producer Responsibility, Responsibility Sharing Policy, Pricing Strategy, Stackelberg Game.

Research methods: Quantitative research. Numerical analysis,

Contents

List of Tables

List of Figures

List of acronyms

ELV End-of-life vehicle

EPR Extended producer responsibility

PhD Doctorat

HJB Hamilton-Jacobi-Bellman

HEC Hautes études commerciales

IR Independent manufacturer

RSP Responsibility sharing policy

SP Social planner

TBL Triple bottom line

WEEE Waste electrical and electronic equipment

BER Being Environmentally Responsible

To my incredible parents,

To my one and only love,

And to my amazing sister and brother,

for their endless and unconditional care, love and support.

Acknowledgements

I would like to express my special appreciation and thanks to my supervisor, Prof. Georges Zaccour, for his excellent guidance, continuous support, and commitment which had a great impact on my work.

Many thanks to HEC Montréal and my supervisor for providing me with the financial aide to go through the long PhD journey.

I wholeheartedly appreciate my committee members, Prof. Michèle Breton and Mehmet Gümüş for accepting to serve on my thesis committee, and for their time to provide me with valuable feedback.

I would like to extend my gratitude to all my friends at GERAD for their help and support. In addition, I would like to acknowledge with much appreciation the staff of GERAD.

Preface

This thesis is created based on three research articles. The list of published, submitted and on-preparation articles is provided below:

Pazoki, M., & Zaccour, G. (2019). A mechanism to promote product recovery and environmental performance. *European Journal of Operational Research, 274*(2), 601-614

Pazoki, M., & Zaccour, G. (October 2018). Extended producer responsibility: regulation design and responsibility sharing policies for a supply chain, Technical report, Les Cahiers du GERAD G–2018–78, GERAD, HEC Montréal, Canada.

Pazoki, M. Dynamic Strategic Interactions between a Municipality and a Firm in the Presence of an Extended Producer Responsibility Regulation, Working paper.

General Introduction

Extended Producer Responsibility (EPR) as an approach to design environmental regulations is introduced in 90's. The goal was to improve the performance of the environmental regulations by shifting the burden of product recovery completely or partially from municipalities to producers (Lindhqvist, 2000). The End-of-Life Vehicle Directive (ELV) and the Waste Electrical and Electronic Equipment Directive (WEEE) are famous examples of such environmental laws. Although the environmental regulations have been in place in different forms for approximately 50 years, the discussion around the impact of pollution on the planet and the efficiency of current environmental regulations have been heated recently. According to World Health Organization, 7 million people die every year as the result of polluted air (World Health Organization, 2018). During year 2016, 7.6% of all deaths was associated with ambient air pollution.[1] Water and soil pollution, which are partially caused by inappropriate dumping and landfilling, are also other important types of pollution that endanger many species. The need to establish new environmental regulations as well as improving the existing ones motivated this comprehensive research on the performance of EPR-based regulations.

Before proceeding with the contents of this thesis, the general research theme needs to be positioned within the context of product recovery. Product recovery, and specifically

[1] WHO (2018/07/06).
Retrieved from: http://apps.who.int/gho/data/node.main.BODAMBIENTAIRDTHS?lang=en

remanufacturing, is performed by the firms for three main reasons: profitability, social responsibility, and environmental regulations.

Profitability is one of the most important driving forces of product recovery. Remanufacturing uses the most part of the material and energy already consumed to produce the products at the first place, and therefore costs much less than producing from new materials. According to Ferguson et al. (2016), remanufacturing PCs and printers of HP and IBM cost less than 10% of brand new product, it is 80% cheaper to refill a cartridge instead of manufacturing a new one, and the remanufacturing cost for IT networking industries accounts for 5-20% of costs of new equipment. Low cost makes remanufacturing a profitable practice that accounts for billions of dollars of revenue per year (Lund, 1998).

Social responsibilities, as declared in triple bottom line (TBL) framework, is another driving force to green practices, including remanufacturing. Social responsibility concerns the impact of firm's business on the community. One sort of these impacts is the pollution generated as the result of production. Although fair and beneficial practices involving stakeholders are emphasized, empirical researches suggest that green practices performed by the manufacturers in societies with high environmental awareness finally lead to higher revenue. For example, the level of greenness associated to each product is affecting the purchase intention similar to functional attributes (Montoro et al., 2006). The empirical findings generally suggest that the more the buyers are involved with environment, the higher is the probability that they purchase green products (Schuhwerk and Lefkoff-Hagius, 1995). Schwepker and Cornwell (1991) shows the significance of attitude toward ecologically conscious living and perception of pollution in willingness to buy a product with green packaging. Ultimately, analyzing the data obtained from an extensive survey conducted in Seoul, South Korea, shows that green marketing positively affects product and corporate image, which are significant factors in buying intentions (Ko et al., 2013). All these researches that apply to green products, do also apply to remanufactured products as the greener version of the original products. Thus, although named as a different driving force of product recovery, respecting social responsibility indeed creates revenue in the long-term.

The third factor that pushes for product recovery is the presence of environmental regulations, particularly where recycling and remanufacturing are not profitable and the environmental consequences of production and product disposition are severe. The general theme of this research concerns environmental regulation as a tool to promote product recovery. More specifically, we address the problem of designing and improving the EPR-based environmental regulations. With numerous environmental regulations being practiced, we discuss how these regulations are related, how the regulator can design a new regulation or improve the existing one, how the burden of product recovery should be distributed among the supply chain members, and what happens when municipalities and producers are both involved in green activities.

This thesis is composed of three essays surrounding the main idea of improving the social and environmental performance of EPR-based environmental regulations. Having discussed the position of this thesis in the context of product recovery and environmental regulations, each essay is briefly introduced.

There are several EPR-based environmental regulations all around the world. Some are penalizing disposition of the used products (Webster and Mitra, 2007), while the others are offering incentive for recycling or remanufacturing (Atasu et al., 2009; Yenipazarli, 2016). While some of them consider minimum rates for product recovery (Esenduran et al., 2016, 2017), the others reward any product recovery effort above a certain threshold and penalize any shortcomings (Wang et al., 2015). However, it is not presently clear which regulation is suitable for which market, and if one regulation can be replaced by another one. To address these questions, we need to obtain the underlying concepts of the EPR-based environmental regulations in order to find a common ground among numerous and different regulatory approaches. For this purpose, the first paper is presented.

In the first paper, we propose a general framework for EPR-based environmental regulations that can imitate a wide variety of regulations currently enacted all around the globe. We intend to follow two managerial goals: (i) to assess the current EPR regulations in terms of environmental performance, and (ii) to provide the regulator with a decision support system for designing and evaluating different regulations. Apart from the general managerial goals, we have one other goal in mind which is to investigate the impact of past-production (available products to return and recover) on the success of an environmental regulation. We consider a firm who is producing and distributing a product and its remanufactured version. Firstly, we provide the social planner with a set of guidelines on how to manipulate the target rates and target-based incentives to improve environmental performance. Secondly, we compare three well-known environmental protection regulations which are designed with different approaches to show how the proposed functional form can capture the essence of various environmental regulations. Finally, we show the significance of taking the past-production into account, as product availability – also known as supply constraint – can entirely change the impact of the target rates in the regulation.

The first step of the research was involved with the design of an EPR-based regulation. However, looking into how these regulations have been implemented in different regions, we realized that there is no unanimous way to enforce them. This problem is caused by the ambiguity of the term *producer(s)* in the definition of Extended Producer Responsibility. For instance in Canada, the definition of producer in EPR regulations varies across provinces. While in Manitoba and Quebec only the first importers or brand owners of oil, filters and containers are targeted by EPR, Alberta holds all producers and users responsible.[2] The EPR regulations for batteries in the US and Sweden are other examples of

[2]Extended Producer Responsibility: current status, challenges and perspectives, Quebec's Ministry of Sustainable Development, the Environment and the Fight Against Climate Change, source:

policies in which only the manufacturer is responsible for collecting the products (Tojo et al., 2003). Therefore, while some regulators only consider the manufacturer as the producer, others may hold the whole supply chain members responsible for product recovery. This problem is addressed in the second paper.

The second paper steps beyond the regulation design scope by considering the receiver of the regulation not a firm, but a decentralized supply chain (Cheng et al., 2017; Jacobs and Subramanian, 2012). In this sense, a new question emerges which is how to allocate physical and financial responsibilities defined by a regulation to the supply chain members. As alluded to before, this topic – which is referred to as responsibility sharing policy (RSP) – has invited controversies as the definitions of producer and polluter differ from one jurisdiction to another (See the second paper for more details). To tackle this issue, a supply chain consisting of a manufacturer and a retailer is studied. To study the RSP problem in the supply chain, 4 scenarios based on different allocations of product recovery responsibilities are defined and a set of possible environmental performance indicators are investigated for each scenario. On the one hand, the results suggest that the design of regulation depends on the proposed responsibility sharing policy. On the other hand, it is shown that the best responsibility sharing scheme may depend on the imposed regulation. Thus, we conclude that design of regulation and allocation of responsibilities need to be done simultaneously to achieve the best environmental outcome. Furthermore, we prove that distributing financial responsibilities does not impact the environmental outcome if the manufacturer is in charge of collection and remanufacturing. Finally, analyzing the real data from three electronic products shows that the relative impact of responsibility sharing policy on the environmental effect of target rates is as considerable as the type of product.

In the first two papers of this thesis, the focus has been on designing a regulation to

http://www.assnat.qc.ca/en/deputes/melancon-isabelle-16779/coordonnees.html, March 2008.

push for more product recovery and less pollution, and then on allocating the product recovery responsibilities. Both studies are conducted from a social planner's point of view, who is dealing with profit maximizing firm(s), and intends to improve environmental performance and/or social welfare. However, one important point which is missing in the first two papers as well as many other research studies in the respective literature is that how the firm is going to increase product recovery to satisfy the requirements and fulfil obligations. To tackle this problem, the producers and the municipalities can both invest in those activities that increase collection by encouraging the former customers to bring their end-of-life or end-of-use products back, so that part of the value of the products could be recovered or they could be disposed of environmentally safe.

In the third paper, we investigate the dynamic interactions between a firm and a municipality where both are involved in the activities that increase collection rate. Data suggest that improving collection rate depends on three main factors which are environmental awareness, return convenience and size of refund. While the customers react to the current size of refund to bring back their products, improvement of the other two factors does not happen over night; continuous investment to develop collection capacity and to improve product return convenience as well as educating the community about the hazards of product landfill and benefits of product recovery are required. Therefore, a dynamic model is needed to tackle the problem of dynamic investing in those activities. The third paper concerns the addressed problem without considering the refund size. In other words, the third paper catches the dynamic interactions between a social welfare maximizing regulator and a profit maximizing producer where both players invest in boosting collection rate and an EPR regulation is in place.

To achieve this goal, and to account for gradual improvement in environmental awareness and return convenience, a feedback Stackelberg differential game is proposed with the municipality as the leader and the producer as the follower. As alluded to before, data show the importance of return convenience and environmental awareness in collection rate. Return convenience is improved by developing collection infrastructures that provide the community with convenient product return methods. Elevating environmental awareness is achieved by holding regular information campaigns and inform the community about the benefits of recycling and hazards of unsafe product disposition. These two factors require continuous investment for improvement, and therefore their level is defined as a state variable in the model. To decide on the type of municipality and producer's participation, we consider the fact that before introduction of EPR concept, municipalities were in charge of product collection. Therefore, it is safe to assume that they have the collection infrastructure and also legal authority to expand the collection network within residential areas. Thus, investing in infrastructure development is left to the municipality whereas the producer is in charge of holding information campaigns to elevate community's environmental awareness.

Among the numerous important conclusions made in this paper three of them can be highlighted, the first two of which are concluded from sensitivity analysis. First, there is a threshold for the disposition pollution – the value which is determined by the amount of toxic materials in the product – below which the regulator decreases the penalty to increase social welfare. That brings us to the second highlight which states that the producer benefits from producing a product with more toxic materials, as it invites more investment from the municipality and consequently the collection rate increases and the penalty paid by the producer decreases. Therefore, the producer exploits the municipality to reduce its own cost. However, back to the first point, the producer reduces the disposition pollution if it expects that the regulator reduces the penalty, given that the disposition pollution level drops below the addressed threshold. Finally, it is proved that the consumers benefit from higher environmental awareness and more developed collection infrastructure.

Bibliography

Atasu, A., Van Wassenhove, L. N., & Sarvary, M. (2009). Efficient take-back legislation. *Production and Operations Management, 18*(3), 243-258.

Cheng, J., Li, B., Gong, B., Cheng, M., & Xu, L. (2017). The optimal power structure of environmental protection responsibilities transfer in remanufacturing supply chain. *Journal of Cleaner Production, 153*, 558-569.

Esenduran, G., E. Kemahlıoğlu-Ziya, J.M. Swaminathan. (2016). Take-Back Legislation: Consequences for Remanufacturing and Environment. *Decision Sciences. 47*(2), 219-256.

Esenduran, G., Kemahlıoğlu-Ziya, E., & Swaminathan, J. M. (2017). Impact of Take-Back Regulation on the Remanufacturing Industry. *Production and Operations Management, 26*(5), 924-944.

Ferguson, M., Souza, G. C., & Toktay, L. B. (2016). Examples of Existing Protable Practices in Product Take-Back and Recovery. In Closed-Loop Supply Chains (pp. 162-177). Auerbach Publications.

Jacobs, B. W., & Subramanian, R. (2012). Sharing responsibility for product recovery across the supply chain. *Production and Operations Management, 21*(1), 85-100.

Ko, E., Hwang, Y. K., & Kim, E. Y. (2013). Green marketing functions in building corporate image in the retail setting. Journal of Business Research, 66(10), 1709-1715.

Lindhqvist, Thomas. (2000). Extended Producer Responsibility in Cleaner Production. IIIEE Dissertations 2000:2. Lund: IIIEE, Lund University.

Lund, R. (1998). Remanufacturing: An American resource Proceedings of the fifth international congress for environmentally conscious design and manufacturing on 16–17 June 1998. *Rochester, RY: Rochester Institute of Technology*.

Montoro Rios, F. J., Luque Martinez, T., Fuentes Moreno, F., & Cañadas Soriano, P. (2006). Improving attitudes toward brands with environmental associations: an experimental approach. Journal of Consumer Marketing, 23(1), 26-33.

Schwepker Jr, C. H., & Cornwell, T. B. (1991). An examination of ecologically concerned consumers and their intention to purchase ecologically packaged products. Journal of Public Policy & Marketing, 77-101.

Schuhwerk, M. E., & Lefkoff-Hagius, R. (1995). Green or non-green? Does type of appeal matter when advertising a green product?. Journal of advertising, 24(2), 45-54.

Tojo, N., Lindhqvist, T., & Davis, G. (2003). EPR programme implementation: Institutional and structural factors. Proceedings of OECD Seminar on EPR: EPR Programme Implementation and Assessment. Part 2: Assessing EPR Policies and Programmes.

Wang, W., Zhang, Y., Zhang, K., Bai, T., & Shang, J. (2015). Reward–penalty mechanism for closed-loop supply chains under responsibility-sharing and different power structures. *International Journal of Production Economics, 170*, 178-190.

Webster, S., & Mitra, S. (2007). Competitive strategy in remanufacturing and the impact of take-back laws. *Journal of Operations Management, 25*(6), 1123-1140.

Greenwood, M. (2018, January 5). WHO: 7 million people a year die from air pollution. Retrieved from: https://thehill.com/policy/healthcare/385781-who-7-million-people-a-year-die-from-air-pollution.

Yenipazarli, A. (2016). Managing new and remanufactured products to mitigate environmental damage under emissions regulation. *European Journal of Operational Research, 249*(1), 117-130.

Chapter 1

A Mechanism to Promote Product Recovery and Environmental Performance

Abstract

To address the problem of the effectiveness and efficiency of environmental protection regulations, we propose a general functional form for regulations to provide a decision support system for social planners designing new regulations. Thanks to the proposed functional form, we are able to compare a variety of different regulations within a single framework. It is shown that how the values of subsidies and penalties in several environmental regulations should be set to minimize the environmental impact of production or to maximize product recovery. Further, this paper presents a set of guidelines on how to modify target rates and incentives to improve certain environmental goals. Finally, it is proved that the amount of past production (available product for collection and/or reman-

ufacturing, which is also referred to as supply constraint) modifies the impact of target rates and incentives on environmental performance.

Keywords: Manufacturing; Collection; Environmental protection regulations; Regulation design.

1.1 Introduction

Producing with raw (or new) materials requires resource mining, consumes a considerable amount of energy and results in waste being discarded into nature, and therefore, is responsible for various environmental problems including air pollution and severe damage to water and soil resources (Guide and Srivastava, 1998; Assavapokee and Wongthatsanekorn, 2012; Yenipazarli, 2016). Product recovery by manufacturers is one option to reduce environmental damage, and firms do it whenever it is profitable. The academic and popular literature is teeming with examples showing that remanufacturing is indeed profitable in some sectors and contexts, with the total benefit climbing to billions of dollars.[1] When firms do not implement a product recovery program and do not internalize the associated environmental cost, regulation becomes justified. In the context of product recovery, extended producer responsibility (EPR) is a generic term used to describe governmental regulations passed to achieve product sustainability. The End-of-Life Vehicle Directive (ELV) and the Waste Electrical and Electronic Equipment Directive (WEEE) are famous examples of such environmental laws.

Generally speaking, government regulations can be classified either as command-

[1]For the US, see *Remanufactured Goods: An Overview of the U.S. and Global Industries, Markets, and Trades*, US International Trade Commission, USITC publication, Oct 2012. For the UK, see *Remanufacturing: Towards a Resource Efficient Economy*, The All-Party Parliamentary Sustainable Resource Group, March 2014.

and-control regulations or carrot-and-stick regulations. Minimum (or target) recovery level and/or remanufacturing level are examples of command-and-control regulations that have often been considered in the literature (Esenduran and Kemahlıoğlu-Ziya, 2015; Esenduran et al., 2016, 2017). Subsidies and taxes are examples of carrot-and-stick regulations. Given a set of possible environmental regulations, a regulator needs to know which one to select and how to modify it in order to achieve its specific environmental goals. In this paper, we introduce a flexible environmental regulation function that (i) mimics a variety of existing regulations; (ii) covers most important recovery activities; and (iii) makes it possible to investigate the impact of target rates and incentives on some environmental performance indicators.

Not only should the proposed functional form be flexible enough to embed a variety of existing regulations, but it should also cover the most important recovery activities. Inclusion of product reclamation (also referred to as reuse and remanufacturing) in addition to collection and recycling in regulations has been attracting more attention in practice and in the literature. Europe's WEEE directive[2,3] and the EPR regulation in Quebec[4,5] (Canada) are only two among numerous examples that tend to enforce product reuse. Generally speaking, reuse is an important waste prevention activity to be targeted in legislation (Esenduran et al., 2016, 2017; Yenipazarli, 2016). When product reuse/remanufacturing

[2]The WEEE directive is a development of waste management and waste prevention programs. In the latest version of this directive, *waste* is defined as the products that are discarded, are required to be discarded or are intended to be discarded. In this sense, waste management programs involve all activities relating to the proper treatment of waste. Waste prevention programs target all green activities from product design to the point just before the product is discarded. According to Article (29) of the Waste Framework Directive 2008/98/EC, the member states are required to establish appropriate waste prevention programs along with benchmarks, measures, targets, and information channels.

[3]Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE), *Official Journal of European Union,* 24.7.2012.

[4]Quebec's ministry of sustainable development, environment and parks also emphasizes that product reclamation is the most desirable option.

[5]*Extended Producer Responsibility: Current Status, Challenges and Perspectives*, Ministère du Développement durable, de l'Environnement et des Parcs, March 2008.

regulations are implemented, firms are pushed towards offering two types of products to the market, namely brand-new and remanufactured (or refurbished). In this sense, the remanufacturing decision is complicated by product cannibalization and the availability of products for remanufacturing, which would be a fraction of the products previously produced. Thus, to gain a better understanding of regulation design that is one step closer to real life, the proposed functional form should include product remanufacturing, and the model should allow for consideration of cannibalization and product availability.

To sum up, our research objective is to provide a decision support system for the regulator to

1. design a new EPR regulation,
2. study several existing EPR regulations in a single framework, and
3. investigate the impacts of cannibalization and past production on regulation design decisions.

Flexibility inherent in the functional form of the regulation function made it possible to study the impact of target rates and incentives. We found that while the impact of the target rate is not the same for collection and remanufacturing, increasing the remanufacturing target rate may yield a negative environmental impact. Finally, by conducting rigorous analytical analyses, we realized the importance of considering past production decisions when designing an environmental regulation.

1.1.1 Related studies

Closed-loop supply chains have received considerable attention from researchers in the last two decades or so. In this section, our aim is to position our work with respect to contributions whose objectives are directly related to ours.

To reduce the amount of energy consumed in processing products and also to release less toxic material in nature, used products should be acquired and prepared for appropriate disposal. The acquired products can be used in producing the new products (De Giovanni et al., 2016), remanufactured and sold as imperfect substitutes of brand-new products (Atasu et al., 2008; Bernard, 2011; Abbey et al., 2015; Esenduran et al., 2016; Abbey et al., 2017), or recycled (De Giovanni and Zaccour, 2014).

Due to the high environmental stakes involved in this process, several regulations have been developed in various industries to target the collection, recycling, and remanufacturing processes. These laws act as mechanisms that transfer variable amounts of money between the firm and the social planner. These mechanisms can be performance-based (Webster and Mitra, 2007; Özdemir et al., 2012; Liu et al., 2015; Yenipazarli, 2016) or use a command-and-control approach (Bernard, 2011; Assavapokee and Wongthatsanekorn, 2012; Esenduran et al., 2016, 2017). The performance-based mechanisms may be based on penalties (Webster and Mitra, 2007; Özdemir et al., 2012; Yenipazarli, 2016), rewards (Atasu et al., 2009) or rewards and penalties (Liu et al., 2015).

By setting a minimum mandate level or by looking at taxation, numerous papers have studied the impact of tax values, tax discounts, and minimum mandate levels. Esenduran et al. (2016) study the minimum mandate levels for collection and remanufacturing, assuming that the manufacturer is responsible for both actions and that the new and remanufactured products are vertically differentiated. Esenduran et al. (2017) extend Esenduran et al. (2016) by assuming that remanufacturing can also be done by an independent remanufacturer (IR), and conclude that imposing a minimum mandate level on collection may reduce remanufacturing, despite the result found under the market setting of Esenduran et al. (2016). However, not every state sets minimum mandate level. Yenipazarli (2016) studies the carbon emission tax where manufacturing is taxed but a discount is offered for remanufacturing. Deriving the conditions under which this law can reduce total emissions, the paper concludes that imposing tax and boosting remanufacturing are not always a win-win game. Furthermore, Webster and Mitra (2007) show that not only can the take-back law result in more profit for the original equipment manufacturer (OEM) and the independent remanufacturer, but it may also reduce the tax burden on society. All in all, many papers have analyzed specific regulations in terms of firm profitability, social welfare, and environmental impact. However, to the best of our knowledge, the link between these different regulations has not been studied in the literature.

What sets this paper apart from the literature is that the proposed general functional form of the regulation in our paper is defined for the purposes of providing social planners with a framework with which they can study different regulations, improve the performance of existing ones, and design new ones. In this sense, this work differs from the literature, as the reviewed studies consider an existing regulation, or suggest a new one and analyze it, whereas our goal is not to propose a regulation, but to propose a general framework for use as a decision support system for regulators. This way, social planners are not constrained to select a specific form and can benefit from a wide range of possibilities to regulate the market.

The rest of the paper is organized as follows. Our assumptions are discussed and the model is presented and solved in Section 3.2. Section 1.3 is devoted to analyzing the model in order to address the research questions. We conclude in Section 3.5 by summarizing the contributions, recapitulating the important conclusions, and presenting directions for future research.

1.2 Model

The manufacturer has the capacity to produce a good with new materials as well as to produce products from previously sold units. In our model, the manufacturer is an agent, or

Table 1.1 – Notation for parameters and decision variables

Notation	Description
U_{N1}	Customer's utility in period 1
U_{N2}	Customer's utility in period 2 for new products
U_R	Customer's utility in period 2 for remanufactured products
p_{N1}	Selling price of new products in period 1
p_{N2}	Selling price of new products in period 2
p_R	Selling price of remanufactured products in period 2
p_A	Acquisition price
q_{N1}	Demand for new products in period 1
q_{N2}	Demand for new products in period 2
q_R	Demand for remanufactured products in period 2
q_A	Quantity of acquired products at the end of period 1
c_R	Unit remanufacturing cost
c_N	Unit manufacturing cost
t	Transportation cost or competition intensity
ρ	Value discount factor for remanufactured products
α	Acquisition coefficient
δ	Proportion of returnable used products in period 2

set of agents, involved in production, pricing, and acquisition decisions, and consequently, it can also be seen as a centralized supply chain. Table 1.1 summarizes the notation used in the paper.

The sequence of events is as follows: (i) The social planner (SP) moves first and announces its regulatory policy (stage 0). (ii) In period 1, the firm decides on the price p_{N1} of the good it produces using new materials (to simplify, from now on, we shall refer to such products as new products). (iii) In period 2, the firm acquires a quantity of previously sold products (q_A, where $q_A \leq \delta q_{N1}$, with $\delta \in (0,1)$) by setting the acquisition price (p_A) and decides on the price of the remanufactured products (p_R) (the price of the new products in period 2 (p_{N2}) will be realized upon determining the price of the remanufactured products. Details will be provided later in this paper) (iv) The firm pays (receives) the penalty (reward) to (from) the social planner. In this framework, the production-remanufacturing cycle is captured by introducing a two-period model, which is standard in the literature (see, e.g., Majumder and Groenevelt, 2001; Ferrer and Swaminathan, 2006; Ferguson and Toktay, 2006; De Giovanni and Zaccour, 2014). The main purpose of considering such a setting is to capture the impact of supply constraint on regulation design decisions. Further, we assume that the new and remanufactured products available in period 2 are partially substitutable, and that consumers are aware of the difference between the two products. This means that some degree of cannibalization will eventually take place, a factor that has been considered a deterrent for firms to practice remanufacturing (Abbey et al., 2015). Intuitively, the cannibalization intensity will depend on customer preference and on the firm's pricing strategy (Ferguson and Toktay, 2006).

There are four main components to our model, namely, the demand functions, the acquisition function, the supply constraint, and the regulation function, which we now explain in detail.

Demand functions: Legislation and profitability are not the only reasons to practice product recovery. The environmental hazards involved in landfilling, the detrimental impact of greenhouse gases on the earth and the species living there, and the harm to the ecosystem of overusing virgin materials have all resulted in social awareness about green and sustainable production. Consumers who consider these issues when deciding whether to buy a product are called green customers, and are addressed in various ways in the literature (Atasu et al., 2008; Yenipazarli, 2016). To account for consumers' preferences for the two available products in period 2, we use a Hotelling-type model as in, e.g., Wu (2013). Consumers are uniformly distributed on the interval $[0,1]$, with the new product being located at 1 and the remanufactured product at 0. Assuming full coverage of the market[6], which makes it possible to capture cannibalization, we obtain the following

[6]For discussion on partial market coverage, see Appendix 1.5.4

demand functions:

$$q_R = \frac{\rho - p_R}{t}, \tag{1.1}$$

$$q_{N1} = 1 - p_{N1}, \tag{1.2}$$

$$q_{N2} = \frac{1 - p_{N2}}{t}, \tag{1.3}$$

where $p_{N2} = 1 + \rho - t - p_R$ and $t \in (0,1)$ measures the degree of substitutability between the two products (in period 2). This way, the price of the new products in the second period will be realized upon deciding on the price of the remanufactured products. The details of the derivation of these demand functions are provided in Appendix 1.5.1.

Remark 1. *It is generally assumed that the horizontally differentiated products have the same production cost. However, in this paper we do not have one product with different designs, but rather two products, where the production cost of one is smaller than the other. In the closed-loop supply chain and remanufacturing literature, the remanufactured products cost less to produce as they need less material and also less production time.*[7]

Remark 2. *If the assumption of full market coverage is relaxed, the firm faces two separate markets wherein it is the monopolist. In this case, no cannibalization happens and remanufacturing is profitable. Since we intend to address cannibalization as one of the important reasons for producers avoiding remanufacturing, only the full market coverage is studied in this paper.*

Acquisition function: To ensure that (at least some of) the used products are returned, the firm must offer an incentive to the end users or the collection centers. This incentive, to which we will refer to as *acquisition price*, can be seen as part of a waste prevention program whose objective is recycling and reusing old products before they are disposed

[7]We would like to thank one reviewer for pointing out this remark.

of in nature. Considering the marginal cost of collection as an increasing function of the operation scale is addressed by Ferguson and Toktay (2006), and Bulmuş et al. (2014). They argue that since acquiring more used products means having to make greater efforts to reach more customers, the unit acquisition cost (incentive) is volume dependent. As in Bulmuş et al. (2014), we consider the acquired quantity as a linear function of the acquisition price, such that $q_A = \alpha p_A$. Consequently, the total acquisition cost is $p_A q_A = \alpha p_A^2$, which is a convex increasing function of the acquisition price.

Supply constraint: The supply of used products to collect and remanufacture is limited by (a proportion of) the quantity of new product sold to the market in the first period (Majumder and Groenevelt, 2001; Ferguson and Toktay, 2006; Atasu et al., 2008; Yenipazarli, 2016). Several reasons for this assumption are discussed in the literature. In this paper, we specifically consider this constraint to assess the impact of past production on regulation decisions.

Regulation function: We retain the following regulation function, which appears as a cost in the manufacturer's objective:

$$f(q_{N1}, q_A, q_R) = \theta_A(\pi_A q_{N1} - q_A) + \theta_R(\pi_R q_A - q_R),$$

where π_A is the target collection level, π_R is the target remanufacturing level, θ_A is the per-unit tax/subsidy for deviating from the collection target, and θ_R is the per-unit tax/subsidy for deviating from the remanufacturing target.

The proposed function has two desirable properties. First, it considers the three processes involved in the firm's operations, namely, manufacturing, remanufacturing and collection. To see this, rewrite $f(q_{N1}, q_A, q_R)$ as follows:

$$f(q_{N1}, q_A, q_R) = \pi_A \theta_A q_{N1} + (\pi_R \theta_R - \theta_A) q_A - \theta_R q_R, \tag{1.4}$$

where $\pi_A \theta_A$ represents the manufacturing tax value, and $(\pi_R \theta_R - \theta_A)$ and θ_R represent the SP's valuation of collection and remanufacturing, respectively. This means that the regulator has enough tools to impact all actions taken by the firm by providing the right incentives, be they rewards or penalties.

Second, the proposed function is flexible, as it allows the regulator to consider different policies. Once we have the results in the general case, it will suffice to set parameter values to assess the impact of, e.g., not taxing new products in the first period. In this way, we can consider and contrast different scenarios related to the three aforementioned processes.

As stated before, an important feature of the proposed function is that it encompasses many of the rules that have been proposed in the literature. We illustrate this statement with few examples.

Webster and Mitra (2007) study a recovery regulation in which any firm that does not buy back and take care of the products acquired by the municipality must pay a penalty for each unit not bought back. In this sense, they introduce a penalty-based mechanism. They present the penalizing function as $c_d(\delta q - q_R)$ where c_d is the per-unit penalty, q is the first-period production quantity, δ is the minimum collection level, and q_R is the proportion of acquired products that is bought and remanufactured by the remanufacturer. It suffices to set $\pi_A \theta_A = \delta c_d$ and $\theta_R = c_d$ and $\theta_A = \pi_R \theta_R$ in (1.4) to recover the addressed penalizing regulation.

Atasu et al. (2009) study the subsidy for collection and recycling defined by σrc, where σ is the per-unit tax subsidy, c is the proportion of collected products, and r is the ratio of recycled products to collected products. In that paper, collection and recycling are two different activities, and it is not clear what happens to products that are collected but not recycled. The firm receives subsidies only for the products that are recycled. Setting $\theta_R = \sigma$ and $\pi_A \theta_A = \pi_R = 0$ turns function f into a reward-based mechanism where acquisition is not rewarded but remanufacturing is. Therefore, our proposed mechanism can imitate a tax-subsidy rule, in a way that is close to what is presented in Atasu et al. (2009).

Yenipazarli (2016) defines a carbon emission tax on new and remanufactured products

Table 1.2 – Regulations addressed in the general form

Regulation	Original Function	Regulatory Parameters
Buy-back	$c_d(\delta q_{N1} - q_R)$	$\pi_A\theta_A = \delta c_d$, $\theta_R = c_d$,$\theta_A = \pi_R\theta_R$
Remanufacturing subsidy	σrc	$\theta_R = \sigma$, $\pi_A\theta_A = \pi_R = 0$
Carbon emission tax	$t(q_{N1} + q_{N2} + \alpha q_R)$	$t = \pi_A\theta_A$, $\theta_A = \pi_R\theta_R$, $(1-\alpha)t = \theta_R$

where the remanufactured products are taxed less. As stated in the title, the author considers a penalty-based mechanism. The tax function in that paper is $t(x+\alpha y)$ where t is the per-unit tax, x is the quantity of new products, y is the quantity of remanufactured products and α is the tax discount for remanufactured products, resulting from remanufacturing's lower environmental impact, as compared to producing new products. Our proposed function can be transformed to $t(x+\alpha y)$ by the following substitutions: $t = \pi_A\theta_A$, $\theta_A = \pi_R\theta_R$ and $(1-\alpha)t = \theta_R$.

The regulations which are discussed above are summarized in Table 1.2.

In the next subsection, we present the model and the closed-form solutions.

1.2.1 Firm's optimization problem

The firm's profit function is given by

$$\Pi = q_{N1}(p_{N1} - c_N) + q_{N2}(p_{N2} - c_N) + q_R(p_R - c_R) - q_A p_A - f(q_{N1}, q_A, q_R). \qquad (1.5)$$

Recycling may be costly or profitable. For the sake of simplicity and without loss of generality, assume that the benefit of recycling compensates for its cost. The constraints on acquisition and remanufacturing are as follows:

$$\text{Supply Constraint} : q_A \leq \delta q_{N1}, \qquad (1.6)$$

$$\text{Remanufacturing Constraint} : q_R \leq q_A. \qquad (1.7)$$

Substituting in (1.5) for the quantities by their values from (1.1)-(1.3), we obtain the following optimization problem:

$$\begin{aligned}\max_{p_{N1},p_R,p_A} \Pi &= (1-p_{N1})(p_{N1}-c_N)+\frac{1}{t}(1-p_{N2})(p_{N2}-c_N)+\frac{1}{t}(\rho-p_R)(p_R-c_R) \\ &\quad -\alpha p_A^2-\theta_A(\pi_A(1-p_{N1})-\alpha p_A)-\theta_R(\pi_R\alpha p_A-\frac{1}{t}(\rho-p_R)),\end{aligned} \tag{1.8}$$

$$\begin{aligned}&\text{subject to :} \\ \text{Supply Constraint} &: \alpha p_A+\delta p_{N1}\le\delta, &(1.9)\\ \text{Remanufacturing Constraint} &: (\rho-p_R)/t\le\alpha p_A, &(1.10)\\ \text{Full Market Coverage} &: p_{N2}=1+\rho-t-p_R. &(1.11)\end{aligned}$$

Note that because of our assumption of full market coverage, p_{N2} is not a decision variable.

1.2.2 Firm's reaction function

To solve the optimization problem in (1.8)-(1.11), introduce the Lagrangian

$$\begin{aligned}L(p_{N1},p_R,p_A,\lambda,\eta) &= (1-p_{N1})(p_{N1}-c_N)+\frac{1}{t}(1-p_{N2})(p_{N2}-c_N)+\frac{1}{t}(\rho-p_R)(p_R-c_R) \\ &\quad -\alpha p_A^2-\theta_A(\pi_A(1-p_{N1})-\alpha p_A)-\theta_R(\pi_R\alpha p_A-\frac{1}{t}(\rho-p_R)) \\ &\quad +\lambda(\delta-\alpha p_A-\delta p_{N1})+\frac{\eta}{t}(p_R+\alpha t p_A-\rho),\end{aligned}$$

Table 1.3 – Primary conditions for feasible solution regions

Region	Conditions	Implications
BY	$q_R < q_A < \delta q_{N1}$	Partial acquisition and partial remanufacturing
BX	$q_R = q_A < \delta q_{N1}$	Partial acquisition and full remanufacturing
AY	$q_R < q_A = \delta q_{N1}$	Full acquisition and partial remanufacturing
AX	$q_R = q_A = \delta q_{N1}$	Full acquisition and full remanufacturing

where λ and η are the Lagrange multipliers appended to the acquisition and remanufacturing constraint, respectively. The first-order optimality conditions are given by

$$\frac{\partial L}{\partial p_{N1}} = 0 \Leftrightarrow p_{N1} = \frac{c_N + 1 + \theta_A \pi_A - \delta\lambda}{2}, \tag{1.12}$$

$$\frac{\partial L}{\partial p_R} = 0 \Leftrightarrow p_R = \frac{1 + 3\rho - 2t - c_N + c_R + \eta - \theta_R}{4}, \tag{1.13}$$

$$\frac{\partial L}{\partial p_A} = 0 \Leftrightarrow p_A = \frac{\theta_A - \pi\theta_R - \lambda + \eta}{2}, \tag{1.14}$$

$$\lambda \geq 0, \quad (\delta - \alpha p_A - \delta p_{N1}) \geq 0, \quad \lambda\,(\delta - \alpha p_A - \delta p_{N1}) = 0, \tag{1.15}$$

$$\eta \geq 0, \quad \frac{1}{t}(p_R + \alpha t p_A - \rho) \geq 0, \quad \frac{\eta}{t}(p_R + \alpha t p_A - \rho) = 0. \tag{1.16}$$

It is easy to verify that the objective function (1.12) is strictly concave in all the firm's decision variables, which are p_{N1}, p_A, and p_R, and that the feasibility set is convex. Consequently, the solution is unique.

As the constraints are easier to interpret when written in terms of quantities rather than in prices, we present the solution in quantities. Further, since each of the two constraints in (1.6)-(1.7) can be binding or not, the solution lies in one of the four regions described in Table 1.3. Region AX represents the case where remanufacturing is highly beneficial, and the firm acquires all available used products and remanufactures all of them. Here, both constraints are binding. In region BY, the firm does not acquire all returnables and does not remanufacture all acquired products. A variety of causes can be given for this case, e.g., a high acquisition cost or a low penalty for not remanufacturing. In region BY, neither constraint is binding. The two other regions, that is, AY and BX, correspond to cases where one of the constraints is binding. Table 1.4 gives the optimal prices in each region, and Table 1.5 specifies the conditions, in terms of parameter values, under which the solution is in a particular region. The computational details are presented in Appendix 1.5.2.

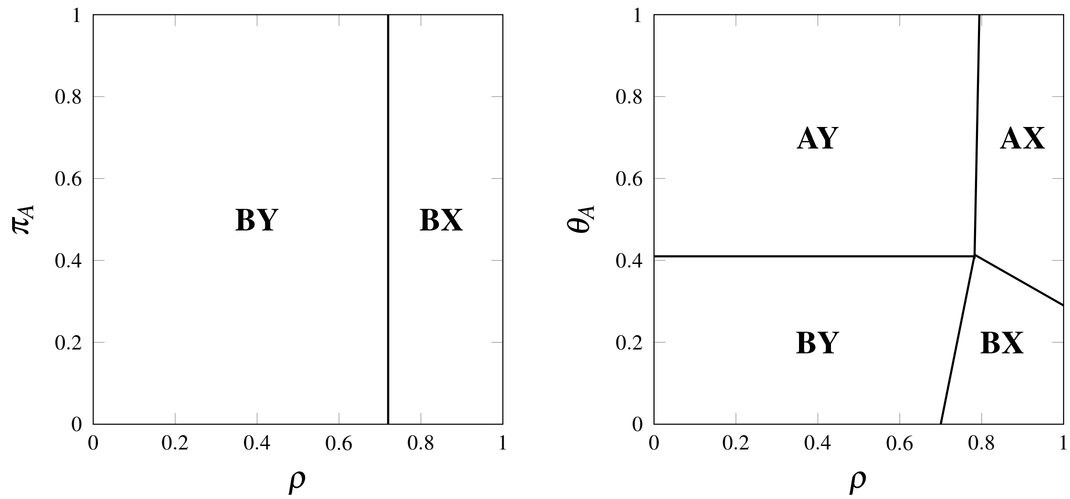
Table 1.4 – Optimal solutions for all regions for the regulated market

Region	p_{N1}	p_R	p_A
BY	$\frac{1+c_N+\pi_A\theta_A}{2}$	$\frac{3\rho-2t+c_R-c_N+1-\theta_R}{4}$	$\frac{\theta_A-\pi_R\theta_R}{2}$
BX	$\frac{1+c_N+\pi_A\theta_A}{2}$	$\frac{\alpha t(3\rho-2t+1-c_N+c_R-\theta_A-\theta_R+\pi_R\theta_R)+2\rho}{2(2\alpha t+1)}$	$\frac{1}{\alpha t}(\rho-p_R^*)$
AY	$1+\frac{c_N+\delta\pi_R\theta_R+\theta_A(\pi_A-\delta)-1}{2(1+\delta^2/\alpha)}$	$\frac{3\rho-2t+c_R-c_N+1-\theta_R}{4}$	$\frac{\delta}{\alpha}(1-p_{N1}^*)$
AX	$1-\frac{1}{\delta t}(\rho-p_R^*)$	$\frac{\delta^2\alpha t(\pi_R\theta_R-\theta_R-c_N+c_R+3\rho-2t+1-\theta_A)+\delta\alpha t(\pi_A\theta_A+c_N-1)+2\delta^2\rho+2\alpha\rho}{2\left(2\delta^2\alpha t+\alpha+\delta^2\right)}$	$\frac{1}{\alpha t}(\rho-p_R^*)$

Table 1.5 – Necessary and sufficient conditions for all regions for the regulated market

Region	Necessary and Sufficient Conditions
BY	$\frac{\rho-1+2t-c_R+c_N+\theta_R}{2\alpha t}+\pi_R\theta_R\leq\theta_A\leq\frac{\alpha\pi_R\theta_R+\delta(1-c_N)}{\alpha+\delta\pi_A}$
BX	$\theta_A\leq min\{\frac{\delta(2\alpha t+1)(1-c_N)-\alpha(\rho+2t-1+c_N-c_R+\theta_R-\pi_R\theta_R)}{\alpha+\delta\pi_A(2\alpha t+1)},\ \frac{\rho-1+2t-c_R+c_N+\theta_R}{2\alpha t}+\pi_R\theta_R\}$
AY	$\theta_A\geq max\{\frac{\alpha\pi_R\theta_R+\delta(1-c_N)}{\alpha+\delta\pi_A},\frac{(1+\delta^2/\alpha)(\rho+\theta_R+c_N-c_R+2t-1)}{2\delta t(\delta-\pi_A)}+\frac{c_N-1+\delta\pi_R\theta_R}{\delta-\pi_A}\}$
AX	$\theta_A\geq\frac{\delta(2\alpha t+1)(1-c_N)-\alpha(\rho+2t-1+c_N-c_R+\theta_R-\pi_R\theta_R)}{\alpha+\delta\pi_A(2\alpha t+1)}$ and $\theta_A\leq\frac{(1+\delta^2/\alpha)(\rho+\theta_R+c_N-c_R+2t-1)}{2\delta t(\delta-\pi_A)}+\frac{c_N-1+\delta\pi_R\theta_R}{\delta-\pi_A}$

From the social planner's point of view, it is interesting to see the impact of each of the key parameters on the policy region wherein the firm would land. For this purpose, we investigate the joint impacts of regulatory parameters for collection and of the value discount factor for remanufactured products (VDF for short).



(a) VDF & collection target for $\theta_A = 0.1$

(b) VDF & collection deviation incentive for $\pi_A = 0.7$

Figure 1.1 – Impact of VDF and of collection regulation parameters on firm's policies

From Figure 1, it can be observed that for $\theta_A = 0.1$, the firm never collects all acquirable products. If remanufactured products are not highly valued relative to new products, the firm remanufactures only a proportion of the collected products. However, intuitively, if the VDF is greater than a certain threshold, the firm finds it profitable to remanufacture as much as possible to maximize its profit. It is interesting to observe that increasing the collection target does not yield more collection if the penalty for not collecting (θ_A) is relatively low. Therefore, it can be concluded that while increasing the collection target rate may reduce the firm's profit margin, it does not necessarily lead to more collection. It can also be observed in the first two rows of Table 1.4 that π_A does not appear in the best pricing policy of the second period.

In Figure 1, all four possible regions are visualized. As expected, high VDF leads to remanufacture-all policy (BY and BX regions). Furthermore, high collection deviation incentive pushes the firm to acquire as many as required (AX and AY regions). The interesting observation is made from the line that separates AX from BX. Even for constant θ_A, a higher VDF makes the firm acquire more to benefit from the high profit margin of remanufacturing (moving from BX to AX). From the latter observation, it can be concluded that the financial reward or penalty for collection transferred between the social planner and the firm can instead be invested in programs to increase environmental awareness, which consequently increases the VDF.

In the next section, the proposed mechanism is employed to gain insight into the impact of the environmental protection laws on the market. Moreover, we will discuss how the social planner can use this mechanism as a toolbox to achieve the goal of efficiently protecting the environment.

1.3 Model analysis

At this point, the proposed mechanism, which mimics several different environmental protection laws, enters the analysis. To start with, we need to define some specific performance criteria. We introduce two performance indicators that are dependent on the state of the remanufacturing industry. Next, to showcase how our regulation function encompasses several existing environmental laws, we compare the mechanisms already discussed in Section 3.2. Lastly, the model is analyzed in terms of design decisions (target rates and deviation incentives) to reveal the impact of past production and provide a decision tool for regulators to improve existing laws or design new ones.

1.3.1 Performance indicators

As alluded to before, the regulator can follow a number of approaches to protect the environment and consider a variety of environmental performance indicators. Popular indicators in the literature and in practice include the collection rate (De Giovanni and Zaccour, 2014), energy consumption (Gutowski et al., 2011; Ovchinnikov et al., 2014), and overall pollution via a life cycle assessment (LCA) (Esenduran et al., 2016). Although the collection rate may represent the amount of products not being landfilled, it does not indicate how implementing the regulation affects production and reuse. It could be the case that a higher collection rate is associated with higher production, which is not environmentally desirable. Moreover, the environmental impact may differ depending on what is done with the collected products. Energy consumption also cannot be an indicative environmental performance metric, since other environmental aspects, such as water and soil pollution, are as important as energy consumption and the release of greenhouse gases into the atmosphere. In this paper, we focus on this last performance indicator and on product recovery.

The WEEE directive in Europe and the EPR directive in Canada suggest that product reclamation (also referred to as reuse and remanufacturing) is preferable to parts harvesting and recycling. Social planners may intend to promote product recovery (in the short term) to help firms build the infrastructure needed to collect, recycle, and reuse products. Therefore, the regulator can promote product recovery without considering the overall environmental impact. In this sense, since remanufacturing is deemed superior to recycling from the regulator's point of view, we define the product recovery performance (PRP) as

$$PRP = q_R + \gamma(q_A - q_R) = (1-\gamma)q_R + \gamma q_A,$$

where $\gamma \leq 1$ denotes the lower environmental benefit of recycling, as compared to remanufacturing. This value handles the (proportional) weight the social planner puts on remanufacturing for political or managerial reasons.

However, if the product recovery industry is well established or if pollution is at a critical level, promoting product recovery is not equivalent to reducing pollution and waste. In such a case, a life cycle assessment (LCA) approach is a good candidate for measuring the regulation's environmental impact. An LCA considers the environmental impact throughout the all possible stages of a product, namely, manufacturing, remanufacturing, landfill, recycling, and usage. Denote by e_m, e_{rm}, e_{rc}, e_d, and e_u the environmental impact of manufacturing, remanufacturing, recycling, landfill, and usage, respectively. The environmental impact function is then as follows:

$$EI = e_m(q_{N1} + q_{N2}) + e_{rm}q_R + e_{rc}(q_A - q_R) + e_d(q_{N1} - q_A) + e_u(q_{N1} + q_{N2} + q_R).$$

Throughout this paper, the terms *environmental performance* and *pollution* refer to the value of the *EI* function and will be used interchangeably.

1.3.2 Special cases

In this section, we revisit some special cases considered in the literature (see Section 3.2), where a variety of real-world contexts have been investigated. Our goal is to show how our regulation function helps generate policies under more constrained rules.

Buy-back

Webster and Mitra (2007) study a problem in which the municipality acquires a proportion of the used products, and if the firm will be penalized for the products not bought back and remanufactured. If the firm does not buy back and remanufacture proportion δ, then it has to pay c_d per unit not acquired and remanufactured. The equivalent parameters are set in accordance to Table 1.2. Let $\pi_R = 1$, $\pi_A = \delta$, and $\theta_A = \theta_R = c_d$. Since offering incentives for remanufacturing beyond δ is not in the nature of the buy-back regulation, we set $\pi_A = \delta$, and the optimal solution for the remanufactured products price in AX is revised to

$$p_R^* = \frac{\pi_A^2\alpha t(3\rho - 2t + 1 - c_N + c_R - \theta_R + \pi_R\theta_R) + \pi_A\alpha t(c_N - 1) + 2\rho(\alpha + \pi_A^2)}{2(\pi_A^2\alpha t + \alpha + \pi_A^2)}.$$

Table 1.6 – Optimal solutions for buy-back legislation

Region	p_{N1}	p_R
BX	$\frac{1+c_N+\delta c_d}{2}$	$\frac{\alpha t(3\rho-2t+1-c_N+c_R-c_d)+2\rho}{2(2\alpha t+1)}$
AX	$1-\frac{1}{\delta t}(\rho-p_R^*)$	$\frac{\delta^2\alpha t(3\rho-2t+1+c_R-c_N)+\delta\alpha t(c_N-1)+2\rho(\alpha+\delta^2)}{2(2\delta^2\alpha t+\alpha+\delta^2)}$

Note that the only difference between this value and the one presented in Table 1.4 is the absence of the term $-\theta_A$ in the numerator, which allows us to conclude that increasing the collection target rate π_A to δ leads to a higher price for remanufactured products, and consequently, fewer remanufactured products. Using the closed-form solutions in Table 1.4, the closed-form solutions for the buy-back regulation are obtained and presented in Table 1.6. Note that by definition, collection has no value until the remanufacturing process is implemented. Therefore, BY and AY do not contain the optimal values. The necessary and sufficient condition for BX to contain the optimal response is

$$c_d \leq c_d^{up} = \frac{\delta(2\alpha t+1)(1-c_N)-\alpha(\rho+2t-1+c_N-c_R)}{\alpha+\delta^2(2\alpha t+1)}. \tag{1.17}$$

Since there is only one inequality to check ($q_R \leq \delta q_{N1}$), there are no minimum terms as there were in Table 1.5. Inequality (1.17) sets an upper bound for the penalty in the buy-back regulation, beyond which all acquirable products would be acquired. If the penalty value is below c_d^{up}, increasing it yields more remanufactured and fewer new products. Intuitively, increasing the penalty value affects production decisions up to c_d^{up}, above which the firm acquires all acquirable products to avoid paying the penalty. Therefore, the price values in Table 1.6 for the AX region are the lower and the upper bounds for the remanufactured and the new products (in the first period), respectively.

In both possible scenarios (BX and AX), all the acquired products are remanufactured. Therefore, the penalty for not collecting is also the penalty for not remanufacturing. If the penalty increases, the firm tries to avoid the penalty by leaving fewer products to collect

Table 1.7 – Optimal solutions for remanufacturing subsidy legislation

Region	p_{N1}	p_R
BX	$\frac{1+c_N}{2}$	$\frac{\alpha t(3\rho-2t+1-c_N+c_R-\sigma)+2\rho}{2(2\alpha t+1)}$
AX	$1-\frac{1}{t}(\rho-p_R^*)$	$\frac{\delta^2\alpha t(3\rho-2t+1-c_N+c_R-\sigma)+\delta\alpha t(c_N-1)+2\rho(\delta^2+\alpha)}{2(2\delta^2\alpha t+\delta^2+\alpha)}$

(reducing first-period production) and by collecting more (which means remanufacturing more), up to the point where all of the acquirable products are acquired and remanufactured (region AX). After this point, the penalty has no impact on the firm's production and collection strategies. This effect shows that a buy-back penalty is appropriate to reduce the production of new products and replacing them by the remanufactured version.

Remanufacturing subsidy

In this section, we define a subsidy model for remanufacturing, similarly to what is considered by Atasu et al. (2009). Setting $\theta_R = \sigma$ and $\pi_A\theta_A = \pi_R = 0$, the proposed regulation function imitates the revised definition of a tax subsidy. Atasu et al. (2009) do not address any specific process choice for the collected products. Therefore, we assume that the firm receives a tax subsidy for remanufacturing the returns. Thus, this is called a remanufacturing subsidy in this paper. Note that since collection is not considered a separate recovery option, the firm remanufactures all collected products. The only place where collection matters is through the constraint $q_R \leq q_A$. Therefore, it is not optimal for the firm to land in the BY or AY regions. Table 1.7 presents the optimal prices for the remanufacturing subsidy case.

Unlike with the buy-back solutions, this regulation affects the prices even if the firm is acquiring all acquirable products. Whether or not the firm acquires all products, higher incentives mean more remanufactured products. Interestingly, the per-unit subsidy for remanufacturing works in a similar way to the per-unit penalty for not remanufacturing in the buy-back regulation; higher values of subsidy and penalty lead to more products being remanufactured if the firm does not acquire all previously sold products. In the remanufacturing subsidy regulation, manufacturing and collection are not directly incentivized, but encouraging collection is embedded in offering incentives for remanufacturing, as all of the collected products are remanufactured in the BX and AX regions.

From Table 1.5, the necessary and sufficient condition for BX is

$$\sigma \leq \sigma^{up} = \frac{\delta(2\alpha t+1)(1-c_N) - \alpha(\rho + 2t - 1 + c_N - c_R)}{\alpha}.$$

Small subsidy values do not affect the first-period price. If the subsidy value is large, the firm will produce more in the first period to have more products to remanufacture in the second period, which is not environmentally desirable. For lower values of the remanufacturing subsidy, however, σ only acts as a discount on the remanufacturing cost, and consequently, encourages the firm to remanufacture more.

Carbon emission tax

Yenipazarli (2016) studies the case where the firm has to pay a tax for producing new and remanufactured products, but less for the latter. The proposed function f transform into the tax function $t(x+\alpha y)$ by doing the following substitutions: $t = \pi_A \theta_A$, $\theta_A = \pi_R \theta_R$, and $(1-\alpha)t = \theta_R$. To avoid confusion in the notations, we denote the per-unit tax by T and the per-unit tax discount by A.

Since collection is not directly addressed in the regulation, the firm collects only for remanufacturing, placing itself in regions BX and AX. The optimal prices for the tax emission problem are given in Table 1.8. The only condition required for partial remanufacturing is

$$T \leq T^{up} = \frac{\delta(2\alpha t+1)(1-c_N) - \alpha(\rho - c_R + c_N - 1 + 2t)}{\delta(2\alpha t+1) + \alpha(1-A)}.$$

Table 1.8 – Optimal solutions for carbon emission tax

Region	p_{N1}	p_R
BX	$\frac{1+c_N+T}{2}$	$\frac{\alpha t(3\rho-2t+1-c_N+c_R-(1-A)T)+2\rho}{2(2\alpha t+1)}$
AX	$1-\frac{1}{\delta t}(\rho-p_R^*)$	$\frac{\delta^2\alpha t(c_R+3\rho-2t+1-(1-A)T-c_N)+\delta\alpha t(T+c_N-1)+2\rho(\delta^2+\alpha)}{2(2\delta^2\alpha t+\delta^2+\alpha)}$

Increasing the production tax T yields more remanufactured and fewer new products if the value of T is smaller than a certain threshold. This outcome is the result of T acting as a cost for manufacturing, which is discounted for remanufacturing, thereby enlarging the profit margin of remanufacturing relative to manufacturing, and consequently, shifting the demand from new to remanufactured products in the second period. However, if T is increased above the threshold, the firm gets to the point where all the acquirable products are collected. In region AX, further increasing the per-unit tax leads to less first-period production, and as a result, to fewer products being available to collect and remanufacture. Consequently, the firm manufactures more new products in the second period to compensate for the unavailability of remanufactured products. Therefore, to guarantee that the firm shifts from producing new to remanufactured products, the value of tax should be set below the addressed threshold.

A represents the tax on remanufactured products, so it is considered an addition to the remanufacturing cost. Intuitively, increasing the remanufacturing cost yields fewer remanufactured products with higher prices, which is not desirable for the regulator. Thus, tax values should be kept low for environmentally desirable outcome.

As a final note, observe that decreasing A pushes T closer to T^{up}. Furthermore, we discussed that to shift production from new to remanufactured products, both A and T should be reduced while $T \leq T^{up}$. Therefore, if production tax T has to be non-zero, there could be a case where the environmentally optimal value for T is T^{up}.

Table 1.9 – Impacts of remanufacturing subsidy, carbon emission tax, and buy-back penalty on manufacturing and remanufacturing

Production Quantities	Subsidy σ		Emission Tax T		Buy-Back Penalty c_d	
	Below	Beyond	Below	Beyond	Below	Beyond
q_R	↗	↗	↗	↘	↗	—
q_{N1}	—	↗	↘	↘	↘	—

Table 1.10 – Distributing subsidies and penalties for production decisions

Regulation	Production Decision Incentives		Results
	New	Remanufactured	
Remanufacturing subsidy	—	σ	Higher quantities
Buy-back	$-\delta c_d$	c_d	More remanufactured products & fewer new products
Carbon emission tax	$-T$	$(1-A)T$	Lower quantities or more remanufactured products & fewer new products

Comparing the remanufacturing subsidy, carbon emission tax, and buy-back

So far, three famous environmental laws have been discussed. In this section, the main conclusions are recapitulated in order to compare these regulations and gain insight into penalties and subsidies. We summarize the discussion in Sections 1.3.2, 1.3.2, and 1.3.2 in Tables 1.9 and 1.10. The terms *Below* and *Beyond* in Table 1.9 imply the threshold that separates the full-collection region AX from the partial-collection region BX. Let T^{up}, c_d^{up}, and σ^{up} be the threshold values for the emission tax, buy-back penalty and per-unit remanufacturing subsidy, respectively.

The results presented in the third column of Table 1.10 (Emission Tax T) agree with the results obtained by Yenipazarli (2016), i.e., there is a threshold for the tax value where the remanufactured quantity will increase and decrease below and above the threshold, while the quantity of new products always decreases in the tax value.

The results extracted from Tables 1.9 and 1.10 are divided into two groups: general and case specific. These are the general results that are applicable for every regulation:

Result 1. *Subsidizing remanufacturing does not necessarily lead to higher production* *quantities.*

The three studied regulations can be interpreted as the regulations that offer rewards for remanufacturing. However, their impact on production is not the same. Thus, we conclude that rewarding remanufacturing does not necessarily yield more remanufacturing.

Result 2. *The impacts of subsidies and penalties on production decisions depend on certain thresholds, defined on the basis of market parameters.*

This result is in line with the literature on environmental regulations. Webster and Mitra (2007) discuss how pricing policies are changed for different intervals of remanufacturing cost. Optimal collection targets and subsidies also change for different ranges of production environmental impact (Atasu et al., 2009). Finally, Yenipazarli (2016) defines thresholds for the value of carbon emission tax where the impact of a tax on pricing strategies and total emissions is different below and above the addressed thresholds. Thus, we confirmed the idea of the existence of thresholds for regulations, which can be obtained by transforming the proposed general form. These thresholds are a by-product of the constraint on returnable products (supply constraint), and showing its effect on regulation design is one of the primary goals of this research.

The following results are specific to the three regulations:

Result 3. *Since the production of new products is a prerequisite for remanufacturing, high subsidy values may result in higher production of new products, which is not environmentally desirable. This result is complementary to Result 1 and disapproves the general intuition about subsidies.*

Result 4. *To shift production from new to remanufactured products, buy-back and carbon tax emission regulations with small penalties should be selected.*

Table 1.11 – Buy-back, remanufacturing subsidy, and carbon emission tax on product recovery and environmental impact

Regulation	Parameter	PRP		EI	
		BX	AX	BX	AX
Buy-back	c_d	$\nearrow$	No impact	$\searrow$	No impact
Remanufacturing subsidy	σ	$\nearrow$	$\nearrow$	$\searrow$	$\nearrow$
Carbon emission tax	A	$\searrow$	$\searrow$	$\searrow$	$\searrow$
	T	$\nearrow$	$\searrow$	$\searrow$	$\searrow$

Result 5. *A large remanufacturing subsidy increases production, a large carbon emission tax deters production, and a large buy-back penalty has no environmental but a negative financial impact. Therefore, the penalty and subsidy values should be small for regulations to be effective.*

The presented results sum up part of the information a regulator needs to know before designing an environmental regulation. Now that the three regulations are compared in terms of their effects on production decisions, we compare them on the basis of the two retained performance indicators. Table 1.11 presents the impact of the regulatory parameter(s) for buy-back, a remanufacturing subsidy, and a carbon emission tax on *PRP* and *EI*. This table can be used by regulators as a guideline to improve the design of existing regulations. Calculation details are presented in Appendix 1.5.3. According to Table 1.11, increasing the tax on manufacturing and remanufacturing decreases the environmental impact (total emissions) whether or not the firm collects all acquirable products. This conclusion is not in accordance with Yenipazarli (2016) where it is claimed that total emissions increase for large tax values, but decreases for small (smaller than a certain threshold) values of T.

Consider three markets regulated by buy-back, remanufacturing subsidy and carbon emission tax regulations, respectively. In Market 1, which is under the buy-back regulation, if $c_d < c_d^{up}$, then increasing the penalty leads to more product recovery and less environmental impact. However, if $c_d > c_d^{up}$, then increasing c_d has no impact on the considered performance indicators. Therefore, the *dominating* value for c_d is c_d^{up}. It is dominating in the sense that if a buy-back regulation is being implemented, c_d^{up} is the only penalty value that optimizes both objective functions (PRP and EI).

In the second market, with the remanufacturing subsidy regulation, the regulator increases σ to promote product recovery and decrease environmental impact. However, beyond σ^{up}, the environmental impact is also increasing. Therefore, a *non-dominated* design is to set $\sigma = \sigma^{up}$ to minimize the environmental impact. It is non-dominated in the sense that there are no other values for the remanufacturing subsidy that yield a higher product recovery and lower environmental impact simultaneously.

The third market is regulated by a carbon emission tax. According to Table 1.11, increasing the tax on remanufacturing reduces product recovery performance and increases environmental impact. However, a *non-dominated* value for tax T is T^{up} to achieve the maximum product recovery performance, meaning that there are no other values for T that outperform T^{up} in both product recovery and environmental impact measures. Remember that T is inversely proportional to A; to achieve a better performance by increasing T^{up}, A needs to be decreased, which will likely have an undesirable environmental impact. Therefore, a balance between A and T is required to find a good design for a carbon emission tax law.

Yenipazarli (2016) introduces the threshold for T below which the total emissions increase in T but it will decrease in T above the threshold. This conclusion is different from the one reached in our paper, namely, that there is a negative relation between environmental impact and the tax value. This difference may have emerged from the fact that the two models are built upon different assumptions.

Thanks to the proposed flexible regulation function, we could imitate a wide variety of

Table 1.12 – Impact of regulatory parameters on product recovery performance

Region	Conditions	Target Rates and Incentives			
		θ_A	θ_R	π_A	π_R
BY	$q_R < q_A < \delta q_{N1}$	$\nearrow$	Undetermined	No impact	$\searrow$
BX	$q_R = q_A < \delta q_{N1}$	$\nearrow$	$\nearrow$	No impact	$\searrow$
AY	$q_R < q_A = \delta q_{N1}$	$\nearrow$	Undetermined	$\searrow$	$\searrow$
AX	$q_R = q_A = \delta q_{N1}$	$\nearrow$	$\nearrow$	$\searrow$	$\searrow$

existing regulations. Using the three sample regulation examples, we showed how social planners can use this function to analyze and improve existing regulations; hence, the first research goal is achieved.

1.3.3 Target levels and incentives

In this section, we address the second research question, concerning regulation design. Regulation design means modifying the target rates and deviation incentives to achieve a certain purpose. To investigate the impact of past production on regulation design decisions, we examine the impact of target rates and incentives on the performance indicators, and if past production appears as an determining parameter, we can conclude that past production indeed affects regulation design decisions. The past production amount is a determining parameter if the impact of target rates and incentives in the BY and BX regions (where $q_A \leq \delta q_{N1}$ is not active) is different from those in the AY and AX regions (where $q_A \leq \delta q_{N1}$ is active). In other words, from the impact of the supply constraint on the impact of target rates and incentives, it can be concluded that past production plays an important role in regulation design.

In terms of product recovery performance, Table 1.12 is presented to illustrate the impact of target rates and incentives in different regions. Detailed calculations are presented in Appendix 1.5.3. The following observations are made from Table 1.12:

Table 1.13 – Impact of regulatory parameters on total environmental impact

Region	Conditions	Target rates and Incentives			
		θ_A	θ_R	π_A	π_R
BY	$q_R < q_A < \delta q_{N1}$	$\searrow$	Undetermined	$\searrow$	$\nearrow$
BX	$q_R = q_A < \delta q_{N1}$	$\searrow$	$\searrow$	$\searrow$	$\nearrow$
AY	$q_R < q_A = \delta q_{N1}$	$\nearrow$	$\searrow$	$\searrow$	$\searrow$
AX	$q_R = q_A = \delta q_{N1}$	$\nearrow$	$\nearrow$	$\searrow$	$\searrow$

1. Increasing the collection incentive and decreasing the remanufacturing target always yield a better product recovery performance.

2. If the firm is not constrained by the past production, the collection target rate has no impact on the product recovery performance. However, if a firm is constrained by past production, increasing the collection target rate will yield less product recovery.

These observations prove the impact of supply constraint on the regulation design decisions if the goal is to promote product recovery. A similar analysis should be performed to address environmental impact, and how supply constraint affects the impact of target rates and incentives on EI.

In terms of environmental impact, Table 1.13 is presented for this purpose. Note that to follow the regulator's point of view, we assume $e_M > e_{RM}$ and $e_D > e_{RC}$. From Table 1.13 we observe the following:

1. If the firm is not constrained by the past production, increasing the collection incentive reduces the environmental impact of production. However, if the firm is constrained by past production, the opposite happens.

2. If the firm is not constrained by the past production, increasing the remanufacturing target rate increases the environmental impact of production. However, if the firm is constrained by past production, the opposite happens.

3. Increasing the collection target rate always results in less pollution (environmental impact).

Thus, there is enough evidence to prove that when designing an EPR regulation, the amount of product available for remanufacturing (supply constraint) should be taken into account. Moreover, Tables 1.12 and 1.13 provide the regulator with guidelines to design a new regulation on the basis of target rates and incentives, either to promote product recovery or to reduce environmental impact. Hence, the second and the third research goals are also achieved.

1.4 Conclusion

In this paper, the problem of EPR regulation design in a (re)manufacturing market was studied. We proposed a general functional form in order to cover a variety of existing regulations. The proposed function revealed the functional commonality between otherwise entirely different rules. Moreover, the flexibility of the proposed function helped us analyze the impact of the past production decisions on how the target rates and deviation incentives affect the market's environmental performance. The research is conducted from the point of view of a social planner who seeks either to design or improve an existing EPR regulation.

One of the main objectives of this paper was to have a flexible mechanism for evaluating a wide variety of regulations in a single framework. Three different regulations were considered for this purpose. The first was the buy-back regulation, under which the firm would be penalized per unit (c_d) not bought back from the collector. The second law was a subsidy program that rewards remanufacturing (σ). The third regulation was a carbon emission tax that penalizes manufacturing and remanufacturing (T) but discounts the penalties for remanufacturing by $1 - A$. A threshold was obtained for each of these parameters beyond which the impact of the respective regulation changes. For each regulation, we concluded that the threshold values for the respective regulatory parameters either minimize the environmental impact or maximize product recovery performance.

Next, we analyzed the model to diagnose the impact of supply constraint on regulation design decisions. We showed that the value of past production can modify or even reverse the impact of target rates and incentives on product recovery performance and environmental impact.

This paper can be extended in several ways. In this research, we considered one firm that has the financial capability and technical infrastructure to remanufacture its own products. However, this may not be the case for mid-size and small companies. In such a case, the firm is under threat by independent remanufacturer(s) that profit from the used products and reduces the sales of brand new products. This scenario is worth studying not only to compare the best mechanisms and policies in a competitive market, but also to see if the competition can partially replace regulations, as some research studies have claimed. Moreover, the introduction of more than one player to the market raises the question of whether coordination outperforms competition in an environmental sense.

The other important aspect to extend this paper is to conduct a social welfare analysis on the impact of the addressed regulatory parameters for social welfare, and consequently, provide a decision support system that considers social welfare instead of environmental performance indicators.

1.5 Appendices

1.5.1 Demand functions

First, we explain the main parameters of the Hotelling-type demand functions. We are assuming that the new product valuation is higher than that of the remanufactured ones. This function captures the horizontal and vertical differentiation of new and remanufactured products. Since $\rho < 1$, more than half the consumers vertically differentiate between the two products. Further, green consumers are also taken into account by distributing consumer preferences over the Hotelling line. Thus, the proposed demand function not only accounts for the lower perceived quality and value of the remanufactured products, but it also considers the segment of the market that prefers greener products. The size of this segment may be simply adjusted in the demand function by defining a proper value for ρ.

The transportation cost t scales the competition intensity between the two products. If t tends to zero, the consumer utility functions tend to $U_{N2} = 1 - p_{N2}$ and $U_R = \rho - p_R$, which are classic utility functions in the remanufacturing market literature. Through an empirical study, Abbey et al. (2017) show that the demand functions derived from $U_{N2} = \delta - p_{N2}$ and $U_R = \delta\theta - p_R$ are sufficiently robust in approximating the new and remanufactured product sales by a monopolist. Replacing θ by ρ and normalizing the market size to 1 ($\delta = 1$), the utility functions turn out to be what the Hotelling model suggests. Moreover, by reducing t, the effect of cannibalization can be lessened. This feature is important to differentiate the extent of cannibalization between commercial and consumer products (Guide and Li, 2010).

In the first period, there is only one product in the market. The normalized demand function for the first period is

$$q_{N1} = 1 - p_{N1}.$$

In the second period, the utilities that a consumer derives from new and remanufactured products are $U_{N2} = 1 - (1-x)t - p_{N2}$ and $U_R = \rho - xt - p_R$, respectively, and x is the position of a consumer on the line. The indifference point is the position of the consumer whose utilities from buying new and remanufactured products are equal, that is,

$$U_{N2} = U_R \Leftrightarrow 1 - (1-x)t - p_{N2} = \rho - xt - p_R \Leftrightarrow x^* = \frac{\rho - 1 + p_{N2} - p_R + t}{2t}.$$

Assuming that the market coverage is full, both utility values at the indifference point must be positive, that is,

$$U_{N2} = 1 - (1-x^*)t - p_{N2} = 1 - (1 - \frac{\rho - 1 + p_{N2} - p_R + t}{2t})t - p_{N2} \geq 0 \Rightarrow$$

$$1 - \frac{t - \rho + 1 - p_{N2} + p_R}{2} - p_{N2} = 1 - t + \rho - p_{N2} - p_R \geq 0 \rightarrow \rho - p_R \geq p_{N2} + t - 1.$$

Therefore, $p_{N2} + p_R \leq \rho - t - 1$ is the condition for full market coverage. Under the full market coverage condition, the quantity demanded for the new product (q_{N2}) is $1 - x^*$ and the quantity demanded for the remanufactured product (q_R) is x^*.

The objective function of the manufacturer has the form

$$\Pi = p_{N2}q_{N2} + p_R q_R + h,$$

where h represents all other costs, which are either linear in in p_{N2} and p_R or independent from them. Assume that the market is fully covered. The Hessian of the objective function in terms of p_{N2} and p_R is given by

$$\begin{pmatrix} \frac{\partial^2 \Pi}{\partial p_{N2}^2} & \frac{\partial^2 \Pi}{\partial p_{N2} \partial p_R} \\ \frac{\partial^2 \Pi}{\partial p_{N2} \partial p_R} & \frac{\partial^2 \Pi}{\partial p_R^2} \end{pmatrix} = \begin{pmatrix} -\frac{1}{t} & \frac{1}{t} \\ \frac{1}{t} & -\frac{1}{t} \end{pmatrix}.$$

On the one hand, observe that the first principal component is negative while the second is zero. Consequently, p_{N2} and p_R are dependent while the objective function is concave. Moreover, the off-diagonal elements are positive, allowing us to conclude that the objective function is jointly increasing in p_{N2} and p_R. Therefore, in order to maximize the concave objective function, we need to jointly increase p_{N2} and p_R. On the other hand, however, we have assumed that the market is fully covered by stipulating an upper bound on the total value of prices: $p_{N2} + p_R \leq \rho + 1 - t$. Thus, any value for p_{N2} and p_R that result in $p_{N2} + p_R < 1 + \rho - t$ is not optimal as we can increase one of them to achieve a higher profit. Hence, assuming full market coverage, the profit is maximized if and only if $p_{N2} + p_R = 1 + \rho - t$. Substituting $p_{N2} = 1 + \rho - t - p_R$ in x^*, which is equal to the demand for the remanufactured products, results in

$$q_R = x^* = \frac{\rho - 1 + p_{N2} - p_R + t}{2t} = \frac{\rho - 1 + (1 + \rho - t - p_R) - p_R + t}{2t} = \frac{\rho - p_R}{t}.$$

Therefore, the demand for new products would be

$$q_{N2} = 1 - x^* = 1 - \frac{\rho - p_R}{t} = \frac{t + p_R - \rho}{t}.$$

From the full market coverage condition we know that $t + p_R - \rho = 1 - p_{N2}$. Therefore, the demand function for the new products is

$$q_{N2} = \frac{1 - p_{N2}}{t}.$$

Therefore, full market coverage results in a situation where the demand function of each product could be represented only by its own price. However, cannibalization is embedded in the inter dependency of price values.

1.5.2 Optimal solutions and conditions in Tables 1.4 and 1.5

To find the optimal solutions and the sufficient conditions in a constrained problem, we applied KKT method and solved the model using Lagrangian multipliers, as is implied in Section 3.2. This way, and assuming interior solutions, we need to solve the following problem:

$$\begin{aligned} Maximize\ L = &(1-p_{N1})(p_{N1}-c_N)+\frac{1}{t}(-\rho+t+p_R)(1+\rho-t-p_R-c_N)+\frac{1}{t}(\rho-p_R)(p_R-c_R) \\ &-\alpha p_A^2-\theta_A(\pi_A(1-p_{N1})-\alpha p_A)-\theta_R(\pi_R\alpha p_A-\frac{1}{t}(\rho-p_R)) \\ &+\lambda\left(\delta-\alpha p_A-\delta p_{N1}\right)+\frac{\eta}{t}\left(p_R+\alpha t p_A-\rho\right), \end{aligned}$$

subject to:

$$\begin{aligned} &\alpha p_A \leq \delta(1-p_{N1}), \\ &(\rho-p_R)/t \leq \alpha p_A, \\ &\lambda(\alpha p_A-\delta(1-p_{N1}))=0, \\ &\eta((\rho-p_R)/t-\alpha p_A)=0, \\ &\lambda \geq 0, \eta \geq 0. \end{aligned}$$

From the first-order optimality conditions, we find

$$\begin{aligned} p_R^* &= \frac{3\rho+1+c_R-c_N-2t-\theta_R+\eta}{4} \\ p_A^* &= \frac{\theta_A-\pi_R\theta_R+\eta-\lambda}{2} \\ p_{N1}^* &= \frac{1+c_N+\pi_A\theta_A-\lambda\delta}{2} \end{aligned}$$

For the BY region, we need to assume $\alpha p_A \leq \delta(1-p_{N1})$ and $(\rho-p_R)/t \leq \alpha p_A$. Therefore, we will have $\lambda=\eta=0$. After finding the optimal solutions, we have to confirm that

$\alpha p_A \leq \delta(1-p_{N1})$ and $(\rho - p_R)/t \leq \alpha p_A$ hold, which results in

$$\frac{\rho - 1 + 2t - c_R + c_N + \theta_R}{2\alpha t} + \pi_R\theta_R \leq \theta_A \leq \frac{\alpha\pi_R\theta_R + \delta(1-c_N)}{\alpha + \delta\pi_A}$$

For the BX region, $\alpha p_A \leq \delta(1-p_{N1})$ and $(\rho - p_R)/t = \alpha p_A$. Therefore, we will have $\lambda = 0$ and η can be any positive value. Replacing η and λ, the optimal values would be

$$p_R^* = \frac{3\rho + 1 + c_R - c_N - 2t - \theta_R + \eta}{4}$$
$$p_A^* = \frac{\theta_A - \pi_R\theta_R + \eta}{2}$$
$$p_{N1}^* = \frac{1 + c_N + \pi_A\theta_A}{2}$$

To find η, we need to confirm $(\rho - p_R)/t = \alpha p_A$. Solving this equation yields

$$\eta^* = \frac{\rho - 1 + c_N - c_R + 2t + \theta_R - 2\alpha t(\theta_A - \pi_R\theta_R)}{2\alpha t + 1}$$

There are two conditions waiting to be confirmed. The first is the positivity of η which yields

$$\theta_A \leq \frac{\rho - 1 + 2t - c_R + c_N + \theta_R}{2\alpha t} + \pi_R\theta_R,$$

and the second one is to make sure that $\alpha p_A \leq \delta(1-p_{N1})$, which yields

$$\theta_A \leq \frac{\delta(2\alpha t + 1)(1-c_N) - \alpha(\rho + 2t - 1 + c_N - c_R + \theta_R - \pi_R\theta_R)}{\alpha + \delta\pi_A(2\alpha t + 1)}.$$

Together, the necessary and sufficient conditions for having the optimal solutions in the region BX are

$$\theta_A \leq Min\Big\{\frac{\delta(2\alpha t + 1)(1-c_N) - \alpha(\rho + 2t - 1 + c_N - c_R + \theta_R - \pi_R\theta_R)}{\alpha + \delta\pi_A(2\alpha t + 1)}, \frac{\rho - 1 + 2t - c_R + c_N + \theta_R}{2\alpha t} + \pi_R\theta_R\Big\}.$$

For the AY region, $\alpha p_A = \delta(1 - p_{N1})$ and $(\rho - p_R)/t \leq \alpha p_A$. Therefore, we will have $\eta = 0$ and λ can be any positive value. Replacing η and λ, the optimal values would be

$$p_R^* = \frac{3\rho + 1 + c_R - c_N - 2t - \theta_R}{4}$$
$$p_A^* = \frac{\theta_A - \pi_R \theta_R - \lambda}{2}$$
$$p_{N1}^* = \frac{1 + c_N + \pi_A \theta_A - \lambda \delta}{2}.$$

To find the optimal value of λ we need to solve $\alpha p_A = \delta(1 - p_{N1})$

$$\lambda^* = \frac{\alpha(\theta_A - \pi_R \theta_R) - \delta(1 - c_N - \pi_A \theta_A)}{\delta^2 + \alpha}.$$

There are two conditions waiting to be confirmed. The fist one is the positivity of λ, which yields

$$\theta_A \geq \frac{\alpha \pi_R \theta_R + \delta(1 - c_N)}{\alpha + \delta \pi_A},$$

and the second is $(\rho - p_R)/t \leq \alpha p_A$, which results in

$$\theta_A \geq \frac{(1 + \delta^2/\alpha)(\rho + \theta_R + c_N - c_R + 2t - 1)}{2\delta t(\delta - \pi_A)} + \frac{c_N - 1 + \delta \pi_R \theta_R}{\delta - \pi_A}.$$

Together, the necessary and sufficient conditions for having the optimal solutions in the region AY are

$$\theta_A \geq \max\left\{\frac{\alpha \pi_R \theta_R + \delta(1 - c_N)}{\alpha + \delta \pi_A}, \frac{(1 + \delta^2/\alpha)(\rho + \theta_R + c_N - c_R + 2t - 1)}{2\delta t(\delta - \pi_A)} + \frac{c_N - 1 + \delta \pi_R \theta_R}{\delta - \pi_A}\right\}.$$

The last region that may contain the optimal solutions is region AX where all acquirable products are acquired and all acquired products are remanufactured. In this sense, both η and λ have to be positive. The optimal solutions for the price values are those presented for the general model. To find the values of η and λ, we solve the linear system of equations $\{\alpha p_A = \delta(1 - p_{N1}), (\rho - p_R)/t = \alpha p_A\}$. The optimal solutions for the Lagrangian multipliers would be

$$\lambda = \frac{\delta(2\alpha t+1)(c_N+\pi_A\theta_A-1)+\alpha(\rho-1+c_N-c_R+\theta_A+\theta_R-\pi_R\theta_R+2t)}{\delta^2+\alpha+2\delta^2\alpha t},$$
$$\eta = \frac{(\delta^2+\alpha)(\rho-1+c_N-c_R+2t+\theta_R)+2\delta\alpha t(c_N+\pi_R\theta_R-1)+2\delta^2\alpha t(\pi_R\theta_R-\theta_A)}{\delta^2+\alpha+2\delta^2\alpha t}.$$

At the last step, we need to make sure that both Lagrangian multipliers are positive:

$$\lambda \geq 0 \rightarrow \theta_A \geq \frac{\delta(2\alpha t+1)(1-c_N)-\alpha(\rho+2t-1+c_N-c_R+\theta_R-\pi_R\theta_R)}{\alpha+\delta\pi_A(2\alpha t+1)},$$
$$\eta \geq 0 \rightarrow \theta_A \leq \frac{(1+\delta^2/\alpha)(\rho+\theta_R+c_N-c_R+2t-1)}{2\delta t(\delta-\pi_A)}+\frac{c_N-1+\delta\pi_R\theta_R}{\delta-\pi_A}.$$

1.5.3 Results in Tables 1.11, 1.12, and 1.13

In this section, C_i denotes a constant value that does not depend on the regulatory parameters. Note that $C_i's$ in two different equations are not equal. To avoid long mathematical terms, we only keep the terms that include the regulatory parameter(s) and show the rest as constants.

First, we show how we constructed Table 1.11. For all considered regulations, only the regions BX and AX may contain the optimal values. Therefore, $PRP = (1-\gamma)q_R+\gamma q_A = q_R = (\rho-p_R)/t$.

For the buy-back regulation and region BX, we have

$$PRP = C_1 + \frac{\alpha c_d}{2(2\alpha t+1)},$$
$$EI = C_1 + \frac{\delta c_d(-e_m-e_d-e_u)}{2} + \frac{\alpha t c_d(-e_m-e_d+e_{rm})}{2(2\alpha t+1)},$$

which show that product recovery and environmental impact are increasing and decreasing functions of c_d, respectively. Note that $e_{rm} \leq e_m$ by definition.

For the buy-back regulation and region AX, c_d is not present in the optimal values. Therefore, having a penalty does not impact the reaction of the firm if it is already collecting all acquirable products and remanufacturing all acquired products.

For the remanufacturing subsidy regulation and region BX, we have

$$PRP = C_1 + \frac{\alpha\sigma}{2(2\alpha t + 1)},$$

$$EI = C_1 + \frac{\alpha\sigma(-e_m - e_d + e_{rm})}{2(2\alpha t + 1)}.$$

The above equations show that product recovery and environmental impact are increasing and decreasing functions of σ, respectively.

For the remanufacturing subsidy regulation and region AX, we have

$$PRP = C_1 + \frac{\delta^2\alpha\sigma}{2(2\delta^2\alpha t + \delta^2 + \alpha)},$$

$$EI = C_1 + \frac{\delta^2\alpha\sigma(e_m/\delta - e_m + e_{rm} + e_d/\delta - e_d + e_u/\delta)}{2(2\delta^2\alpha t + \delta^2 + \alpha)}.$$

Both *PRP* and *EI* are increasing functions of σ, as δ is equal or less than 1.

For the carbon emission tax and region BX, we have

$$PRP = C_1 + \frac{\alpha(1-A)T}{2(2\alpha t + 1)},$$

which is an increasing function of T and a decreasing function of A ($A \leq 1$). The environmental impact function in this region is

$$EI = C_1 + \frac{T(-e_m - e_d - e_u)}{2} + \frac{\alpha T(1-A)(-e_m + e_{rm} - e_d)}{2(2\alpha t + 1)}.$$

Since $e_{rm} \leq e_m$ and $A \leq 1$, the environmental impact function increases in A and decreases in T.

Finally, for carbon emission tax and region AX, we have

$$PRP = C_1 + \frac{\delta\alpha(\delta(1-A)T - T)}{2(2\delta^2\alpha t + \delta^2 + \alpha)},$$

$$EI = C_1 + \frac{\delta\alpha(\delta(1-A)T - T)(e_m/\delta - e_m + e_{rm} + e_d\delta - e_d + e_u/\delta)}{2(2\delta^2\alpha t + \delta^2 + \alpha)}.$$

Since $\delta, A \leq 1$ both *PRP* and *EI* functions are decreasing in A and T.

Now, we proceed by proving the results presented in Table 1.12. For the BY region, we have

$$PRP = C_1 + \frac{(1-\gamma)\theta_R}{4t} + \frac{\alpha\gamma(\theta_A - \pi_R\theta_R)}{2} = C_1 + \frac{\alpha\gamma\theta_A}{2} + \left(\frac{1-\gamma}{4t} - \frac{\alpha\gamma\pi_R}{2}\right)\theta_R.$$

Therefore, in BY, product recovery is an increasing function of θ_A, and a decreasing function of π_R. Since π_A does not appear directly in the *PRP* function, it has no direct impact on product recovery. The impact of a remanufacturing incentive also depends on a set of market parameters.

For the BX region, all acquired products are remanufactured, which means $PRP = q_R = (\rho - p_R)/t$. According to Table 1.4, p_R is an increasing function of θ_R, and a decreasing function of θ_A and π_R. Similarly to the BY region, π_A does not appear in the equation.

For the AY region, we have

$$PRP = C_1 + \frac{(1-\gamma)\theta_R}{4t} + \frac{\delta\gamma\alpha(\delta\theta_A - \pi_A\theta_A - \delta\pi_R\theta_R)}{2(\delta^2+\alpha)} = \frac{\delta\gamma\alpha(\delta - \pi_A)\theta_A}{2(\delta^2+\alpha)} + \left(\frac{1-\gamma}{4t} - \frac{\delta^2\gamma\alpha\pi_R}{2(\delta^2+\alpha)}\right)\theta_R.$$

Therefore, product recovery performance increases in θ_A, and decreases in π_A and π_R. The impact of θ_R on this function depends on a set of market parameters.

Finally, in the AX region, we have $PRP = q_R = (\rho - p_R)/t$. Table 1.4 shows that p_R increases in the target rates and decreases in the incentives. Therefore, *PRP* is an increasing function of θ_A and θ_R, and decreases in π_A and π_R.

The last step is to prove the results reported in Table 1.13. For the BY region we have

$$\begin{aligned} EI &= C_1 + \frac{1}{2}(\alpha\theta_A e_{rc} - \pi_A\theta_A e_m - \alpha\pi_R\theta_R e_{rc} - \pi_A\theta_A e_d + \alpha\pi_R\theta_R e_d - \alpha\theta_A e_d - \pi_A\theta_A e_u) \\ &\quad + \frac{\theta_R}{4t}(e_{rm} - e_m - e_{rc}) \\ &= \frac{\alpha\pi_R\theta_R(e_d - e_{rc})}{2} + \frac{\theta_R(e_{rm} - e_m - e_{rc})}{4t} + \frac{\theta_A(\alpha e_{rc} - \pi_A e_m - \pi_a e_d - \alpha e_d - \pi_A e_u)}{2}. \end{aligned}$$

Therefore, while the impact of θ_R on EI depends on a set of market parameters, the environmental impact function increases in π_R, and decreases in π_A and θ_A.

For the BX region, we calculate

$$EI = C_1 + \frac{\pi_A\theta_A(-e_m - e_d - e_u)}{2} + \frac{\alpha\theta_A(-e_d - e_m + e_{rm})}{2(2\alpha t + 1)} + \frac{\alpha\theta_R(1 - \pi_R)(-e_d - e_m + e_{rm})}{2(2\alpha t + 1)}.$$

Therefore, EI increases in π_R whereas it decreases in θ_R, θ_A, and π_A.

For the AY region, we have

$$\begin{aligned} EI = C_1 + \frac{\theta_R(-e_m + e_{rm} - e_{rc})}{4t} &+ \frac{\delta\alpha\pi_R\theta_R(-e_m - \delta e_{rc} - e_d + \delta e_d - e_u)}{2(\delta^2 + \alpha)} \\ &+ \frac{\alpha\theta_A(\delta - \pi_A)(e_m + \delta e_{rc} + e_d + e_u - \delta e_d)}{2(\delta^2 + \alpha)}, \end{aligned}$$

which is an increasing function of θ_A and decreasing function of θ_R, π_R, and π_A.

Finally, for the AX region,

$$EI = C_1 + C_2(\delta\theta_R(1 - \pi_R) + \theta_A(\delta - \pi_A))(-e_m + e_m/\delta + e_{rm} + e_d/\delta - e_d + e_u/\delta),$$

where $-e_m + e_m/\delta + e_{rm} + e_d/\delta - e_d + e_u/\delta$ is positive. Therefore, EI increases in θ_A and θ_R, and decreases in π_A and π_R.

1.5.4 Partial Market Coverage

This section considers the case where market coverage is not full, and consequently the price on new and remanufactured products in the second period are independent. Where the markets for the new and remanufactured products are separated, there would be two monopoly markets. The demand functions, assuming that there still exists t so that the results of partial market coverage case is comparable with full market coverage case, are:

$$q_{N2} = \frac{1 - p_{N2}}{t},$$

$$q_R = \frac{\rho - p_R}{t}.$$

The firm solves:

$$\begin{aligned}
\max_{p_{N2}, p_{N1}, p_R, p_A} \Pi \quad = \quad & (1 - p_{N1})(p_{N1} - c_N) + \frac{1}{t}(1 - p_{N2})(p_{N2} - c_N) + \frac{1}{t}(\rho - p_R)(p_R - c_R) \\
& -\alpha p_A^2 - \theta_A(\pi_A(1 - p_{N1}) - \alpha p_A) - \theta_R(\pi_R \alpha p_A - \frac{1}{t}(\rho - p_R))
\end{aligned}$$

$$\begin{aligned}
\text{subject to :} & \\
\text{Supply Constraint} \quad : \quad & \alpha p_A + \delta p_{N1} \leq \delta, \\
\text{Remanufacturing Constraint} \quad : \quad & (\rho - p_R)/t \leq \alpha p_A, \\
\text{Full Market Coverage} \quad : \quad & p_{N2} = 1 + \rho - t - p_R.
\end{aligned}$$

Similar to the full market coverage case, 4 regions may contain the optimal solutions of this model: (i) partial collection and partial remanufacturing (S1), (ii) partial collection and full remanufacturing (S2), (iii) full collection and partial remanufacturing (S3), and (iv) full collection and full remanufacturing (S4).

Consequently, the firm solves

$$\begin{aligned}
L(p_{N1}, p_R, p_A, \lambda, \eta) \quad = \quad & (1 - p_{N1})(p_{N1} - c_N) + \frac{1}{t}(1 - p_{N2})(p_{N2} - c_N) + \frac{1}{t}(\rho - p_R)(p_R - c_R) \\
& -\alpha p_A^2 - \theta_A(\pi_A(1 - p_{N1}) - \alpha p_A) - \theta_R(\pi_R \alpha p_A - \frac{1}{t}(\rho - p_R)) \\
& +\lambda\left(\delta - \alpha p_A - \delta p_{N1}\right) + \frac{\eta}{t}\left(p_R + \alpha t p_A - \rho\right),
\end{aligned}$$

where λ and η are the Lagrange multipliers appended to the acquisition and remanufacturing constraint, respectively. The first-order optimality conditions are given by

$$\begin{aligned}
\frac{\partial L}{\partial p_{N1}} &= 0 \Leftrightarrow p_{N1} = \frac{c_N + 1 + \theta_A \pi_A - \delta\lambda}{2}, \\
\frac{\partial L}{\partial p_{N2}} &= 0 \Leftrightarrow p_{N2} = \frac{c_N + 1}{2}, \\
\frac{\partial L}{\partial p_R} &= 0 \Leftrightarrow p_R = \frac{\rho + c_R + \eta - \theta_R}{4}, \\
\frac{\partial L}{\partial p_A} &= 0 \Leftrightarrow p_A = \frac{\theta_A - \pi\theta_R - \lambda + \eta}{2}, \\
\lambda &\geq 0, \quad (\delta - \alpha p_A - \delta p_{N1}) \geq 0, \quad \lambda(\delta - \alpha p_A - \delta p_{N1}) = 0, \\
\eta &\geq 0, \quad \frac{1}{t}(p_R + \alpha t p_A - \rho) \geq 0, \quad \frac{\eta}{t}(p_R + \alpha t p_A - \rho) = 0.
\end{aligned}$$

Solving the model for the addressed four regions, the solutions are presented in Table 1.14. $p_{N2} = \frac{1+c_N}{2}$ is always the case.

Table 1.14 – Optimal solutions for all regions with partial market coverage

Region	p_{N1}	p_R	p_A
BY	$\frac{1+c_N+\pi_A\theta_A}{2}$	$\frac{\rho+c_R-\theta_R}{2}$	$\frac{\theta_A-\pi_R\theta_R}{2}$
BX	$\frac{1+c_N+\pi_A\theta_A}{2}$	$\frac{\alpha t(c_R+\rho-\theta_A+\pi_R\theta_R-\theta_R)+2\rho}{2(\alpha t+1)}$	$\frac{1}{\alpha t}(\rho - p_R^*)$
AY	$1+\frac{\alpha(c_N+\pi_A\theta_A-\delta\theta_A+\delta\pi_R\theta_R)}{2(\delta^2+\alpha)}$	$\frac{\rho+c_R-\theta_R}{2}$	$\frac{\delta}{\alpha}(1-p_{N1}^*)$
AX	$1-\frac{1}{\delta t}(\rho - p_R^*)$	$\frac{\delta^2\alpha t(\rho-\theta_R+c_R-\theta_A+\pi_R\theta_R)+\delta\alpha t(\pi_A\theta_A+c_N-1)+2\delta^2\rho+2\alpha\rho}{2(\delta^2\alpha t+\alpha+\delta^2)}$	$\frac{1}{\alpha t}(\rho - p_R^*)$

To simplify comparing the solutions of full and partial market coverage scenarios, Table 1.4 is repeated here.

Table 1.15 – Optimal solutions for all regions for full market coverage

Region	p_{N1}	p_R	p_A
BY	$\frac{1+c_N+\pi_A\theta_A}{2}$	$\frac{3\rho-2t+c_R-c_N+1-\theta_R}{4}$	$\frac{\theta_A-\pi_R\theta_R}{2}$
BX	$\frac{1+c_N+\pi_A\theta_A}{2}$	$\frac{\alpha t(3\rho-2t+1-c_N+c_R-\theta_A-\theta_R+\pi_R\theta_R)+2\rho}{2(2\alpha t+1)}$	$\frac{1}{\alpha t}(\rho - p_R^*)$
AY	$1+\frac{c_N+\delta\pi_R\theta_R+\theta_A(\pi_A-\delta)-1}{2(1+\delta^2/\alpha)}$	$\frac{3\rho-2t+c_R-c_N+1-\theta_R}{4}$	$\frac{\delta}{\alpha}(1-p_{N1}^*)$
AX	$1-\frac{1}{\delta t}(\rho - p_R^*)$	$\frac{\delta^2\alpha t(\pi_R\theta_R-\theta_R-c_N+c_R+3\rho-2t+1-\theta_A)+\delta\alpha t(\pi_A\theta_A+c_N-1)+2\delta^2\rho+2\alpha\rho}{2(2\delta^2\alpha t+\alpha+\delta^2)}$	$\frac{1}{\alpha t}(\rho - p_R^*)$

Although not the same results, there is a close resemblance between the solutions for full market coverage with those of the partial market coverage. Focusing on the impact of regulatory parameters, the observed similarities include, but not limited to, the followings: (i) increasing θ_R results in lower price for remanufactured products in both market coverage scenarios, (ii) for both market coverage scenarios, higher remanufacturing target rates means higher remanufactured product prices in AX and BX, (iii) higher collection target rate yields higher remanufactured products price, (iv) higher remanufacturing target rate and deviation incentive yield higher new products price in the first period in AY, and (v) higher collection target rate yields higher new products price. Having the exact same regulatory parameter impacts in both market coverage scenarios for p_R, p_A and p_{N1}, the only different is the price of the new products in the second period where the cannibalization effect comes in; if there is no cannibalization, regulation does not affect the price of the new products in the second period.

Bibliography

Abbey, J.D., Blackburn, J.D. & Guide, V.D.R. (2015). Optimal pricing for new and remanufactured products. *Journal of Operations Management, 36*, 130-146.

Abbey, J.D., Kleber, R., Souza, G.C., & Voigt, G. (2017). The role of perceived quality risk in pricing remanufactured products. *Production and Operations Management, 26*(1), 100-115.

Assavapokee, T., & Wongthatsanekorn, W. (2012). Reverse production system infrastructure design for electronic products in the state of Texas. *Computers & Industrial Engineering, 62*(1), 129-140.

Atasu, A., Sarvary, M., & Van Wassenhove, L.N. (2008). Remanufacturing as a Marketing Strategy. *Management Science, 54*(10), 1731-1746.

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

Bernard, S. (2011). Remanufacturing. *Journal of Environmental Economics and Management, 62*(3), 337-351.

Bulmuş, S.C., Zhu, S.X., & Teunter, R.H. (2014). Optimal core acquisition and pricing strategies for hybrid manufacturing and remanufacturing systems. *International Journal of Production Research, 52*(22), 6627-6641.

De Giovanni, P., Reddy, P.V., & Zaccour, G. (2016). Incentive strategies for an optimal recovery program in a closed-loop supply chain. *European Journal of Operational Research, 249*(2), 605-617.

De Giovanni, P., & Zaccour, G. (2014). A two-period game of a closed-loop supply chain. *European Journal of Operational Research, 232*(1), 22-40.

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

Esenduran, G., Kemahlıoğlu-Ziya, E., & Swaminathan, J.M. (2016). Take-Back Legislation: Consequences for Remanufacturing and Environment. *Decision Sciences, 47*(2), 219-256.

Esenduran, G., Kemahlıoğlu-Ziya, E., & Swaminathan, J.M. (2017). Impact of Take-Back Regulation on the Remanufacturing Industry. *Production and Operations Management, 26*(5), 924-944.

Ferguson, M.E., & Toktay, L.B. (2006). The effect of competition on recovery strategies. *Production and Operations Management, 15*(3), 351-368.

Ferrer, G., & Swaminathan, J.M. (2006). Managing new and remanufactured products. *Management Science, 52*(1), 15-26.

Gutowski, T.G., Sahni, S., Boustani, A., & Graves, S.C. (2011). Remanufacturing and energy savings. *Environmental science & technology, 45*(10), 4540-4547.

Guide, V.D.R., & Srivastava, R. (1998). Inventory buffers in recoverable manufacturing. *Journal of Operations Management, 16*(5), 551-568.

Guide Jr, V.D.R. & Li, J. (2010). The potential for cannibalization of new products sales by remanufactured products. *Decision Sciences, 41*(3), 547-572.

Liu, B., Holmbom, M., Segerstedt, A., & Chen, W. (2015). Effects of carbon emission regulations on remanufacturing decisions with limited information of demand distribution. *International Journal of Production Research, 53*(2), 532-548.

Majumder, P., & Groenevelt, H. (2001). Competition in Remanufacturing. *Production and Operations Management, 10*(2), 125-141.

Ovchinnikov, A., Blass, V., & Raz, G. (2014). Economic and environmental assessment of remanufacturing strategies for product + service firms. *Production and Operations Management,* 23(5), 744-761.

Özdemir, Ö., Denizel, M., & Guide, V.D.R. (2012). Recovery decisions of a producer in a legislative disposal fee environment. *European Journal of Operational Research, 216*(2), 293-300.

Webster, S., & Mitra, S. (2007).Competitive strategy in remanufacturing and the impact of take-back laws. *Journal of Operations Management, 25*(6), 1123-1140.

Wu, C.H. (2013). OEM product design in a price competition with remanufactured product. *Omega, 41*(2), 287-298.

Yenipazarli, A. (2016). Managing new and remanufactured products to mitigate environmental damage under emissions regulation. *European Journal of Operational Research, 249*(1), 117-130.

Chapter 2

Extended Producer Responsibility: Regulation Design and Responsibility Sharing Policies for a Supply Chain

Abstract

In this paper, we study the problem of responsibility sharing for product recovery, and its relation to the design of Extended Producer Responsibility (EPR) regulations. By defining several scenarios for responsibility sharing policies, we show that designing an EPR regulation and allocating the responsibilities within the supply chain must be done simultaneously. Furthermore, we prove that sharing the penalties and rewards of collection and remanufacturing with the retailer has no financial or environmental impact if the manufacturer is collecting. However, making the retailer solely responsible to collect results in a higher collection rate, and in more new and fewer remanufactured products. Finally, a numerical analysis is performed for three electronic products to illustrate the use of our

model. This research provides a set of guidelines for regulators seeking to improve environmental standards by designing and implementing EPR regulations.

Keywords: Extended producer responsibility; Responsibility sharing; Closed-loop supply chain; Stackelberg game.

2.1 Introduction

Extended Producer Responsibility (EPR) is a regulatory approach whose aim is to shift the responsibility for managing end-of-use products from municipalities to producers. When defining an EPR, the regulator must (i) design the structure of the regulation and (ii) allocate the responsibilities and financial incentives, if any, to the different parties. This paper incorporates into a single framework both regulation design and responsibility allocation, with the aim of providing regulatory agencies with a tool to guide their policies.

The design part concerns the structure of the regulation itself, which, generally speaking, can take the form of a reward-penalty mechanism (Wang et al., 2015, 2017; Pazoki and Zaccour, 2018; Cheng et al., 2017), or a constraint on minimum product recovery process(es) (Jacobs and Subramanian, 2012). This area of research has attracted a great deal of attention from scholars and practitioners. However, the literature's main focus has been on how to design a regulation, while assuming that a single (centralized) entity will carry out the obligations resulting from that regulation. In other words, the literature does not specifically address how the rewards and penalties should be distributed among the supply chain members when designing the regulation. This distribution is a main concern of this paper.

Allocation of responsibilities is the other focus of EPR. One key aspect of defining an EPR regulation is the definition of *producer(s)*, a point on which the seemingly similar EPR regulations differ and where dispute may emerge. For instance, in 2008 the mayor of New York City, rejected a regulation requiring the manufacturers to collect and recycle 65% (volume-based) of the products they have previously produced. The mayor, Mr. Bloomberg, argued that manufacturers do not have the infrastructure to implement this regulation, and that wholesalers and consumers must also be held accountable. In Canada, EPR is in a similar situation, in that the definition of producer varies across provinces. For instance, in Manitoba and Quebec, only the first importers or brand owners of oil, filters and containers are targeted by EPR, but Alberta holds all producers and users responsible.[1] The EPR regulations for batteries in the US and Sweden are other examples of policies in which only the manufacturer is responsible for collecting the products (Tojo et al., 2003). Therefore, although it has been several years since EPR regulations began appearing, identifying the producer(s) in the value chain remains an administrative challenge (OECD, 2014). Defining who the producers are involves clarifying the responsibilities allocated to supply chain members.

The allocation of responsibilities among supply chain members is referred to as the Responsibility Sharing Policy (RSP). Typically, responsibilities are categorized as physical or financial, with specific definitions being given to each. *Physical responsibility sharing* refers to the distribution of recovery activities such as collection, recycling, and reuse among supply chain members (also referred to as operational responsibility). *Financial responsibility sharing*, then, implies the allocation of collection, recycling, and reuse costs among supply chain members. Jacobs and Subramanian (2012) study the problem of sharing financial responsibilities between a supplier and a manufacturer, where there are mandates for minimum collection and recycling levels. Cheng et al. (2017) decide on which member should collect the products, while both members can be financially in-

[1] *Extended Producer Responsibility: current status, challenges and perspectives*, Quebec's Ministry of Sustainable Development, the Environment and the Fight Against Climate Change, source: http://www.assnat.qc.ca/en/deputes/melancon-isabelle-16779/coordonnees.html, March 2008.

volved in collection and remanufacturing efforts, and where the degree to share financial responsibility is a decision variable of the more powerful member. While the literature on RSP generally focuses on the firm's point of view, the regulator has a different perspective. Its aim is to know who is responsible for what action, and how incentives are to be distributed between the parties. In this paper, we deviate from previous definitions in order to meet the regulator's need and to cope with the potential disputes mentioned above. Throughout this paper, the member who is physically responsible for a certain process will also pay the cost of the process (Chen and Chen, 2017).[2] Furthermore, as in Wang et al. (2015), the allocation of penalties or subsidies defined through regulation will be called financial responsibility sharing. One question that has not been fully addressed in the literature is whether distributing financial responsibilities is the best social option, and whether sharing physical responsibilities is likely to improve or worsen the environmental outcome. In this paper, we also want to address this question.

Our work contributes to the literature by integrating the two focuses of EPR, namely, regulation design and responsibility allocation. Firstly, we study the simultaneous allocation of physical and financial responsibilities in a generic supply chain to figure out which policy serves which regulator's goals. At the same time, this should clarify whether physical and financial responsibility allocations are interrelated. Secondly, we determine how the distribution of responsibilities affects regulation design decisions. In other words, this research reveals if the way in which responsibilities are distributed affects how the regulation performs toward achieving its goal. If we find that there is a relation between RSP and the choice of parameters in EPR regulations, this would be the first research to provide regulators with a complete set of tools for designing regulations and for distributing responsibilities among the supply chain members.

[2]If a certain supply chain member, who collects or remanufactures the products, is not financially responsible for doing so, the distribution of physical responsibilities merely involves delegating them.

In this paper, we consider a supply chain consisting of a manufacturer and a retailer who sells new and remanufactured products to the same market. A performance-based regulation is employed to explore regulation design strategies. To understand and investigate the responsibility sharing policies, we study the regulated supply chain under different scenarios, in which product recovery responsibilities are either centralized or shared between the supply chain members. First, we show that allocation of physical responsibilities and financial incentives should be done in an integrated manner. Subsequently, the underlying relation between the responsibility sharing policy and regulation design is uncovered. Second, we show that transferring all responsibility for collection to the retailer yields higher collection rates and also a lower remanufacturing quantity, which makes it a good strategy to boost material recycling but a bad strategy to promote remanufacturing.

The remainder of this paper is organized as follows. In Section 2.2, the assumptions, RSP scenarios, and their mathematical models are presented. The proposed models are solved and analyzed in Section 2.3. Section 2.4 is devoted to comparing the proposed scenarios in order to address the research questions and obtain valuable insights about EPR design and the RSP problem. While Section 2.4 analyzes the scenarios from an environmental performance perspective, Section 2.5 comments on the financial implications of RSP scenarios and regulatory approaches. Finally, we conclude in Section 2.6.

2.2 Model

In order to address financial and physical responsibility sharing policies, we characterize and contrast the results of four different scenarios. First we introduce the assumptions that are common to all scenarios, and next we define them.

2.2.1 Assumptions

The supply chain is formed of one manufacturer and one retailer. The manufacturer produces a good that comes in two varieties, namely, a new product (N) that is manufactured with new material, and a remanufactured product (R). The manufacturer decides the wholesale price w_i of product i, and the retailer chooses the quantity to order $q_i; i = N, R$. We assume that the game is played à la Stackelberg, with the manufacturer acting as leader (first announcing its wholesale prices) and the retailer as follower. Next, we introduce our main assumptions related to time horizon, prices and quantities, collection rate, EPR regulation, and performance measures. Table 2.1 gives the notation used throughout the paper.

Table 2.1 – Model notation

	Variables
q_N	Quantity of brand new products
q_R	Quantity of remanufactured products
w_N	Wholesale price of brand new products
w_R	Wholesale price of remanufactured products
τ	Collection rate
	Parameters
c_τ	Collection cost coefficient
c_R	Remanufacturing cost per unit of product
c_N	Manufacturing cost per unit of product
π_A	Collection target rate
π_R	Remanufacturing target rate
θ_A	Deviation incentive for collection target
θ_R	Deviation incentive for remanufacturing target
δ	Remanufactured products discount factor
α	Price of selling a collected product to a recycler
ϕ	Manufacturer's share of financial responsibility

Time horizon: We consider a mature market operating at its steady-state value, that is, a situation where the decisions and parameter values do not vary over time. In this sense, manufacturing and remanufacturing are considered at the same time, knowing that the products to collect and remanufactured are produced previously. However, since the new product manufacturing plan do not vary over time, it appears that the production decisions are made simultaneously. A single-period model has often been used in the literature (see, e.g., Jacobs and Subramanian, 2012; and Bulmuş et al., 2014). Although the motivation behind this approach is tractability, we believe that a simple model is able to shed a light on our research questions.

Prices and quantities: The new and remanufactured products are imperfect substitutes, with the customers discounting on their willingness to pay for the remanufactured products. The inverse demand functions are assumed to be linear and given by $p_N = 1 - q_N - \delta q_R$ and $p_R = \delta(1 - q_N - q_R)$. These demand functions (i) capture vertical differentiation between the two products and also consider the outside good option (Debo et al., 2005; Bulmuş et al., 2014; Abbey et al., 2017); (ii) are micro-founded, that is, they are derived from consumer maximization of a quadratic utility; and (iii) are empirically robust (see Abbey et al., 2017).

Collection rate: The chain member who is responsible for collection decides upon the collection rate τ, which is defined as the ratio of collected products to brand new products. τ is realized by implementing product return programs, which include, but not limited to, all activities that mentally and financially encourage the customers to bring back used products instead of discarding them. These activities (which are also known as green activities in the literature) include communicating the merits of product recovery, offering monetary incentive for returning the used products, installing collection points, and advertising the possible ways of returning the products. For a more detailed description of green activities and product recovery programs, see De Giovanni et al. (2016) and De Giovanni and Zaccour (2014). To account for marginal decreasing returns, the cost of these activities is assumed to be convex increasing and given by $C(\tau) = c_\tau \tau^2$, with $c_\tau > 0$. The parameter c_τ is interpreted as collection efficiency and will increase for more expanded collection infrastructures. This assumption is common in the literature on closed-loop supply chains, both for single-period and dynamic models; see, e.g., De Giovanni (2011), De Giovanni et al. (2016), De Giovanni and Zaccour (2014), and Jøorgensen and Zaccour (2003).

EPR regulation: To a large extent, EPR regulation is about collecting (acquiring) and remanufacturing used products. We suppose that regulation takes the following reward/penalty form in the manufacturer's optimization problem:

$$f(q_N, q_R, \tau) = \theta_A q_N(\pi_A - \tau) + \theta_R(\tau \pi_R q_N - q_R). \tag{2.1}$$

The regulation embedded in (2.1), which is proposed in Pazoki and Zaccour (2018), merits three comments. First, collection normally applies to past sold products, and consequently we should expect a lagged sales term in the above function. Given our assumption that the market is at its steady-state value, we are capturing collection by a contemporary term, τq_N. Second, our EPR function mimics a number of established regulations with specific values for target rates and deviation incentives (e.g., take-back, tax incentive, and carbon emission tax). Third, our formulation is very flexible as it allows the regulator to implement high/low targets (i.e., π_A and π_R) combined with high/low incentives (i.e., θ_A and θ_R), leading to a large range of regulatory policies.

Remark 3. *There can be four regulatory approaches for collection and remanufacturing: (i) strictly penalizing (high target rate and high deviation incentive); (ii) strictly rewarding (low target rate and high deviation incentive); (iii) weakly penalizing (high target rate and low deviation incentive); and (iv) weakly rewarding (low target rate and low deviation incentive). The latter can be seen as no regulation since there is a tendency to put both values to zero and subsequently deregulate the market. The terms "weakly rewarding" and "no regulation" are used interchangeably in this paper.*

Performance measures: The role of the regulator is to design an EPR regulation. We do not assign the regulator a specific objective to optimize, but suppose that the regulator has various objectives in mind. We retain the following performance criteria:

Product landfill. Reducing the volume of used products ending up in landfill is a self-defining objective that is of particular interest when the production process involves toxic materials (Atasu et al., 2009).[3] This objective is quantified by $q_D = (1-\tau)q_N$.

Collection rate. This rate is an indicator of the ratio of the materials being reclaimed and saved to the new materials (De Giovanni and Zaccour, 2014). Although τ appears in q_D, distinguishing between the two objectives is of interest in itself, but especially when τ and q_N are not under the control of the same player.

Total energy consumption. This indicator has been proposed in, e.g., Gutowski et al. (2011) and Raz et al. (2017). The assumption is that the environmental impact is measured by energy consumption throughout the product's entire life cycle, which consists of manufacturing (m), remanufacturing (rm), landfill (d), recycling (rc), and usage (u) stages. Denote by e_i the per-unit energy consumption at each stage. Then, the total environmental impact of manufacturing and remanufacturing are $E_m = e_m q_N$, and $E_{rm} = e_{rm} q_R$, respectively. The quantity of recycled products is $\tau q_N - q_R$. Therefore, the environmental impacts of recycling is $E_{rc} = e_{rc}(\tau q_N - q_R)$. Assuming that the product is remanufacturable only once (a pessimistic point of view), the environmental impact of landfilling would be $E_d = e_d((1-\tau)q_N + q_R)$. Finally, at the usage stage, we have $E_u = e_u(q_N + q_R)$. The total environmental

[3]Article 5 of Directive 2012/19/EU of the European Parliament and of the Council on Waste Electrical and Electronic Equipment (WEEE), July 2012, mentions: "Member states shall adopt appropriate measures to minimise the disposal of WEEE...."

impact is then given by $E = E_m + E_{rm} + E_{rc} + E_d + E_u$, that is,

$$E = (e_m + e_d + (e_{rc} - e_d)\,\tau + e_u)\,q_N + (e_{rm} - e_{rc} + e_d + e_u)\,q_R.$$

2.2.2 Scenarios

We introduce and investigate four scenarios defined in terms of how the financial and physical responsibilities are shared between the manufacturer and the retailer. For physical responsibilities, we consider two options. The first, more traditional, option is to hold the manufacturer responsible for collection.[4] In the second one, the retailer is required to collect (and recycle), while the manufacturer is responsible for remanufacturing (Chen et al., 2018).[5] Ultimately, the decision about who should be in charge of collection depends on the regulator's goal as well as on the product type, existing infrastructures, and other preexisting conditions. Financial responsibilities could be designed such that each supply chain member is financially responsible only for its own task, or to have both members being financially responsible for both their actions. This latter case is retained for two reasons: (i) it acts as a benchmark for investigating the impact of financial responsibility sharing policy, and (ii) it allows the regulator to still influence the retailer when collecting is the manufacturer's duty; otherwise, the retailer would not be affected directly by the EPR regulation. A similar approach is adopted in Wang et al. (2015), where one player is responsible for collection while both players pay the penalty or receive the reward.

[4] Depends on the definition of producer in that specific region.

[5] In Article 5 of Directive 2012/19/EU of the European Parliament and of the Council on Waste Electrical and Electronic Equipment (WEEE), July 2012, it is stated that: "...distributors provide for collection....free of charge for the end-users..."

		Physical Responsibility	
		Centralized	Shared
Financial Responsibility	Centralized	mO	rO
	Shared	mP	rP

Figure 2.1 – Scenarios defined based on the sharing of financial and physical responsibilities

As in all considered scenarios, we assume, not unrealistically, that remanufacturing can only be done by the manufacturer, we do not need to highlight it in the labeling of the different scenarios.

Remark 4. *The equilibrium results of each scenario (not in its statement to avoid unduly complicating the notation) will be superscripted with two letters, the first referring to the player in charge of collection, that is, m or r, and the second referring to the financial responsibility, which can either be own responsibility (O) or shared proportionally between the two players* (P)*. The four scenarios, which are depicted in Figure 2.1, are now formally defined.*

Scenario ***mO*****.** The manufacturer is responsible for collection and bears the financial responsibility. The optimization problems of the manufacturer and the retailer are as follows:

$$\begin{aligned}
\max_{w_N, w_R, \tau} \Pi^m &= (w_N - c_N)q_N + (w_R - c_R)q_R - c_\tau \tau^2 - (\pi_A - \tau)q_N\theta_A \\
&\quad -(\tau\pi_R q_N - q_R)\theta_R + \alpha(\tau q_N - q_R), \\
\max_{q_R, q_N} \Pi^r &= (1 - q_N - \delta q_R - w_N)q_N + (\delta(1 - q_N - q_R) - w_R)q_R.
\end{aligned}$$

Scenario *mP*. The manufacturer is in charge of collecting used products, while the financial responsibility is shared between the two members of the supply chain. The optimization problems of the manufacturer and the retailer are as follows:

$$\begin{aligned}
\max_{w_N,w_R,\tau} \Pi^m &= (w_N - c_N)q_N + (w_R - c_R)q_R - \phi((\pi_A - \tau)q_N\theta_A \\
&\quad + (\tau\pi_R q_N - q_R)\theta_R) + \alpha(\tau q_N - q_R) - c_\tau\tau^2, \\
\max_{q_R,q_N} \Pi^r &= (1 - q_N - \delta q_R - w_N)q_N + (\delta(1 - q_N - q_R) - w_R)q_R \\
&\quad - (1-\phi)((\pi_A - \tau)q_N\theta_A + (\tau\pi_R q_N - q_R)\theta_R),
\end{aligned}$$

where $1-\phi$ is the share of the retailer in the financial incentive. The parameter ϕ ($0 < \phi < 1$) is under the regulator's control.

Scenario ***rO*****.** The retailer is responsible for collection and bears the financial responsibility. The optimization problems of the manufacturer and the retailer are as follows:

$$\begin{aligned}
\max_{w_N,w_R} \Pi^m &= (w_N - c_N)q_N + (w_R - c_R)q_R - (\tau\pi_R q_N - q_R)\theta_R, \\
\max_{q_R,q_N,\tau} \Pi^r &= (1 - q_N - \delta q_R - w_N)q_N + (\delta(1 - q_N - q_R) - w_R)q_R \\
&\quad - (\pi_A - \tau)q_N\theta_A + \alpha(\tau q_N - q_R) - c_\tau\tau^2.
\end{aligned}$$

Scenario ***rP*****.** The retailer collects used products, while the financial responsibility is shared between the two members of the supply chain. The optimization problems of the manufacturer and the retailer are as follows:

$$\begin{aligned}
\max_{w_N,w_R} \Pi^m &= (w_N - c_N)q_N + (w_R - c_R)q_R - \phi((\pi_A - \tau)q_N\theta_A \\
&\quad + (\tau\pi_R q_N - q_R)\theta_R), \\
\max_{q_R,q_N,\tau} \Pi^r &= (1 - q_N - \delta q_R - w_N)q_N + (\delta(1 - q_N - q_R) - w_R)q_R - c_\tau\tau^2 \\
&\quad - (1-\phi)((\pi_A - \tau)q_N\theta_A + (\tau\pi_R q_N - q_R)\theta_R) + \alpha(\tau q_N - q_R).
\end{aligned}$$

For all the models presented above, the following constraints must be satisfied:

$$\begin{aligned} \text{Nonnegativitity contraints} &: \quad q_N, \tau, q_R \geq 0, \\ \text{Upper bound on collection rate} &: \quad \tau \leq 1, \\ \text{Upper bound on manufacturing} &: \quad q_N \leq 1, \\ \text{Upper bound on remanufacturing} &: \quad q_R \leq \tau q_N. \end{aligned}$$

These scenarios merit the following comments: (i) Scenario *mO* corresponds to many real-life cases. An illustrative example is the Rethink Tires program in Ontario, Canada, where used tires must be recycled, reused, or disposed of in an environmentally safe way; and the program is wholly funded by the brand owners or first importers.[6] (ii) Scenarios with proportional financial responsibility (*mP* and *rP*) have been considered by Wang et al. (2015), whose study was motivated by the China's need to design an incentive policy for electronic products. Finally, (iii) contrasting two scenarios that differ in only one feature will allow us to isolate and assess the impact of that feature. For instance, contrasting the results of scenarios *mP* and *mO* gives the regulator a measure of the impact of varying financial responsibility on performance criteria.

2.3 Results

We shall (essentially) do the following for each of our scenarios: First, we provide the follower's (retailer's) reaction functions and comment on the strategic relationship between the manufacturer's and the retailer's decisions. Second, we give the equilibrium values, assuming an interior solution. Third, we state the conditions under which the solution is indeed interior. Finally, we comment on (some) corner solutions.

[6]See http://rethinktires.ca/program-participants

Before proceeding to the solutions, we introduce the following notation to simplify the presentation and discussion of the results:

$$\begin{aligned}
\text{Recycling profit} &: \quad A = \alpha + \theta_A - \pi_R \theta_R \\
\text{Retailer's recycling profit} &: \quad A_{rP} = \alpha + (1-\phi)(\theta_A - \pi_R \theta_R) \\
\text{Retailer's recycling profit} &: \quad A_{rO} = \alpha + \theta_A \\
\text{Potential remanufacturing profit} &: \quad L = \delta - 1 + c_N - c_R + \theta_R + \pi_A \theta_A - \alpha.
\end{aligned}$$

Recycling profit (A): If a product is collected but not remanufactured, the supply chain is rewarded[7] by $\theta_A - \pi_R \theta_R$. The collected products must then be recycled, and the recycling profit (or cost) is α. Therefore, $A = \alpha + \theta_A - \pi_R \theta_R$ is the recycling cost/profit for the whole supply chain.

Retailer's recycling profit A_{rP}: This parameter is specific to scenario rP where the retailer collects but the rewards and penalties are distributed between the retailer and the manufacturer by the factor of ϕ. In this sense, while the retailer earns α from recycling the collected product, its share of the regulation reward is $(1-\phi)(\theta_A - \pi_R \theta_R)$. Therefore, $A_{rP} = \alpha + (1-\phi)(\theta_A - \pi_R \theta_R)$. We assume that the regulation on collection is more strict than the regulation on remanufacturing, resulting in $\theta_A > \pi_R \theta_R$. Because the regulation of remanufacturing is not widely defined, and where it is defined, the collection regulation is more strictly enforced, we claim that the addressed assumption is the case in most (if not all) real life cases. Consequently, $A > A_{rP}$ holds, and we assume that it is the case throughout this paper, unless otherwise stated.

Retailer's recycling profit A_{rO}: This parameter shows up in scenario rO, where the retailer is the sole responsible for collection. In this sense, it sells the product for α and pays θ_A less in penalties. Therefore, its gain for recycling the product is $A_{rO} = \alpha + \theta_A$.

[7]Reward is equivalent to not paying the penalty.

Potential remanufacturing profit L**:** If a collected product is remanufactured, the supply chain saves $\theta_R + \pi_A \theta_A$ in penalties (considering that one more unit of remanufactured product means one less unit of new product, and assuming that the collected quantity is not changed). The maximum possible prices for the new and remanufactured products are 1 and δ, while they cost c_N and c_R, respectively. Therefore, the potential gain on a remanufactured product is $\delta - c_R$ and the potential loss of not selling a new product is $1 - c_N$. Furthermore, the profit from recycling is α, which will be lost if a collected product is remanufactured instead of being recycled. Therefore, the potential remanufacturing profit, which consists of the potential gain from remanufacturing, the potential loss caused by cannibalization, and the loss from not recycling the product, would be $L = \delta - 1 + c_N - c_R + \theta_R + \pi_A \theta_A - \alpha$.[8]

Furthermore, let $S = 8c_\tau(1-\delta)$, which represents the attractiveness of the remanufactured product and the collection cost-efficiency. Defining the above parameters brings us to the following conditions: if (i) the consumer discount factor for remanufactured products is low, (ii) collection is not being done cost-efficiently, and (iii) the recycling profit is not large enough, then $A^2 - S < 0$, $2A_{rP}A - S < 0$ and $2A_{rO}A - S < 0$. Given these new secondary parameters, we now characterize the equilibrium in the different scenarios.

Scenario mO**.** Assuming an interior solution, the reaction functions of the retailer are given by

$$q_N(w_R, w_N, \tau) = \frac{1-\delta+w_R-w_N}{2(1-\delta)}, \tag{2.2}$$

$$q_R(w_R, w_N, \tau) = \frac{\delta w_N - w_R}{2\delta(1-\delta)}. \tag{2.3}$$

[8] In the definitions of A, A_{rP}, A_{rO}, and L, it is assumed that the product is already collected. This way, the collection cost is not included in the recycling profit. Since the collection cost function is not linear, the marginal collection cost changes with the amount of production. Therefore, one can interpret the introduced parameters as we have or as the fixed part of the marginal profit or costs, or as potential cost or profit indicators.

The retailer's order for each product is (i) decreasing in the wholesale price of that product, that is, we have strategic substitution; (ii) increasing in the wholesale price of the other product (strategic complementarity); and (iii) independent of the collection rate τ (strategic independence).

The manufacturer, as the leader, takes into account the above reaction functions in its optimization problem. Proposition 1 presents the unique equilibrium values for scenario *mO*.

Proposition 1. *Assuming an interior solution, the unique Stackelberg equilibrium is given by*

$$
\begin{aligned}
w_N^{mO} &= \frac{1+c_N+\pi_A\theta_A}{2}-\frac{A^2|L|}{2(S-A^2)},\\
w_R^{mO} &= \frac{\delta-\theta_R+c_R+\alpha}{2},\\
\tau^{mO} &= \frac{A|L|}{S-A^2},\\
q_N^{mO} &= \frac{2c_\tau|L|}{S-A^2},\\
q_R^{mO} &= \frac{(\delta+\theta_R-\alpha-c_R)}{4\delta}-\frac{2c_\tau|L|}{S-A^2}.
\end{aligned}
$$

Proof. First, we substitute the retailer's reaction functions in the manufacturer's optimization problem. Second, assuming an interior solution, differentiating the profit function with respect to w_R, w_N, and τ, and equating to zero, yields the results. The required condition for the manufacturer's objective function concavity is $S-A^2>0$, which requires costly remanufacturing ($L<0$) □

The results in the above proposition merit the following comments:

1. A stricter remanufacturing regulation means a lower remanufacturing cost $|L|$ and a higher penalty for not remanufacturing for the manufacturer. Therefore, on the

one hand, it reduces w_R^{mO} to encourage the retailer to order more remanufactured products, and on the other hand, it reduces the collection rate and increases w_N^{mO} to shift the demand from new to remanufactured products.

2. A larger collection target rate results in a higher recycling profit (A), and consequently, the manufacturer increases the collection rate to gain more profit from recycling.

3. If the recycling unit profit (α) increases, the recycling profit (A) and the remanufacturing cost ($|L|$) increase. Under this condition, the manufacturer increases the collection rate and the remanufactured products' wholesale price while reducing the new products' wholesale price at the same time, in order to force the retailer to order more new and fewer remanufactured products, and consequently, having more products to recycle.

Proposition 1 assumes an interior solution. In the next proposition, we provide the conditions under which this assumption holds true.

Proposition 2. *Let $J = S - A^2$, and $\Delta = 1 + A(\delta + \theta_R - c_R - \alpha)/2\delta c_\tau$. The required* *conditions for an interior solution are*[9]

$$\pi_A \leq \frac{1}{\theta_A}\left(\frac{-J(\sqrt{\Delta}-1)}{2A} + 1 - \delta + c_R - c_N + \alpha - \theta_R\right),$$
$$\pi_A \geq \frac{1}{\theta_A}\left(\frac{-J}{A} + 1 - \delta + c_R - c_N + \alpha - \theta_R\right),$$
$$\pi_A \geq \frac{1}{\theta_A}\left(\frac{-J(\delta+\theta_R-\alpha-c_R)}{8c_\tau\delta} + 1 - \delta + c_R - c_N + \alpha - \theta_R\right),$$

Proof. See Appendix 2.7.1. □

The interior solution conditions are translated into two lower bounds and one upper bound for the collection target rate. On the lower bounds or below, the manufacturer either stops remanufacturing or it collects all the products (see Appendix 2.7.1). On the upper bound or above, no collected product would be recycled.

To illustrate, we provide a numerical example. Since there are 6 constraints, generally, the feasible region can be divided into a maximum number of 2^6 areas. However, in our case, the maximum number of possible regions is 6 for the following reasons: (i) under a certain set of inputs, none of the curves intersect another one; (ii) the nonnegativity constraint on remanufacturing guarantees an upper bound for the manufacturing constraint; (iii) the upper bound on the remanufacturing constraint guarantees the nonnegativity of the collection rate constraint; (iv) the non-negativity constraints for the manufacturing and the collection rate coincide; and (v) either the non-negativity constraint on remanufacturing guarantees the upper bound on the collection constraint, or vice versa. Therefore, the

[9]These conditions can be rewritten more compactly as

$$\frac{1+\alpha-\delta-\theta_R+c_R-c_N}{\theta_A} - \frac{1}{\theta_A}\max\left\{\frac{J}{A}, \frac{J(\delta+\theta_R-\alpha-c_R)}{8\delta c_\tau}\right\} \leq \pi_A$$
$$\leq \frac{1+\alpha-\delta-\theta_R+c_R-c_N}{\theta_A} - \frac{J}{2A\theta_A}\left(\sqrt{1+\frac{A(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}} - 1\right).$$

However, for interpretation purposes, it is easier to proceed as done in the proposition.

region for an interior solution is built by 2 constraints, and the total number of possible regions is 4. Figure 2.2 depicts the discussed regions. (The numerical values are given in Appendix 2.7.2.)

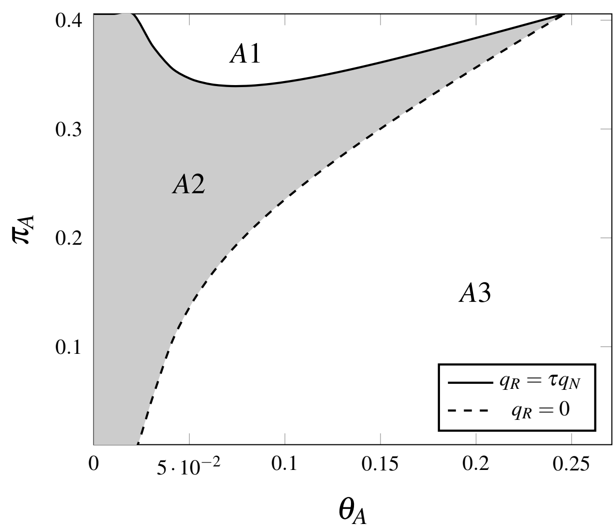


Figure 2.2 – Feasible area for π_A and θ_A in scenario *mO*

Region *A1* denotes the no-recycling region. In other words, all collected products are remanufactured. In region *A2*, the solution is interior, meaning that a proportion of the products is collected and a proportion of the collected products is remanufactured. In region *A3*, however, the manufacturer stops remanufacturing. The area where collection is stopped is positioned beyond the domain, which is determined by the nonnegativity and upper-bound conditions.

Scenario ***mP*****:** In this scenario, the retailer maximizes

$$\begin{aligned}\Pi^r_{mP} &= (1-q_N^{mP}-\delta q_R^{mP}-w_N^{mP})q_N^{mP}+(\delta(1-q_N^{mP}-q_R^{mP})-w_R^{mP})q_R^{mP}\\ &\quad -(1-\phi)((\pi_A-\tau^{mP})q_N^{mP}\theta_A+(\tau^{mP}\pi_R q_N^{mP}-q_R^{mP})\theta_R),\end{aligned}$$

where $1-\phi$ is the proportion of the financial incentive shifted to the retailer. The reaction functions of the retailer are

$$q_N^{mP} = \frac{(1-\phi)(\theta_A(\tau^{mP}-\pi_A)-\theta_R-\pi_R\theta_R\tau^{mP})-w_N^{mP}+w_R^{mP}-\delta+1}{2(1-\delta)}, \quad (2.4)$$

$$q_R^{mP} = \frac{(1-\phi)(\delta\theta_A(\pi_A-\tau^{mP})+\theta_R+\delta\pi_R\theta_R\tau^{mP})-w_R^{mP}+\delta w_N^{mP}}{2\delta(1-\delta)}. \quad (2.5)$$

Like in scenario *mO*, the retailer's orders are increasing in the other product's wholesale price and decreasing in the same product's wholesale price. However, the collection rate is now involved in the retailer's reaction functions; the orders of new and remanufactured products decrease and increase in the collection rate, respectively. Furthermore, comparing (2.4) and (2.5) with (2.2) and (2.3) reveals that by sharing the financial incentives, the regulator has direct control (in addition to indirect control through the manufacturer) over the retailer's reaction functions by the terms $(1-\phi)(\theta_A(\tau^{mP}-\pi_A)-\theta_R-\pi_R\theta_R\tau^{mP})$ and $(1-\phi)(\delta\theta_A(\pi_A-\tau^{mP})+\theta_R+\delta\pi_R\theta_R\tau^{mP})$, for q_N and q_R, respectively. Furthermore, the collection rate has entered the retailer's reaction functions, giving the manufacturer more control over the retailer.

Taking into account the retailer's reaction functions, the manufacturer's total profit is

$$\begin{aligned}\Pi_{mP}^{m} \quad = \quad & (w_N^{mP}-c_N)q_N^{mP}+(w_R^{mP}-c_R)q_R^{mP}-\phi((\pi_A-\tau^{mP})q_N^{mP}\theta_A+(\tau^{mP}\pi_R q_N^{mP}-q_R^{mP})\theta_R) \\ & +\alpha(\tau^{mP}q_N^{mP}-q_R^{mP})-c_\tau(\tau^{mP})^2,\end{aligned}$$

where ϕ is the manufacturer's share of the financial responsibilities.

Proposition 3. *Assuming an interior solution, the unique Stackelberg equilibrium is given* *by*

$$\begin{aligned} w_N^{mP} &= \frac{(1-2\phi)(\theta_A(\tau^{mP}-\pi_A)-\pi_R\theta_R\tau^{mP})+1+c_N-\alpha\tau^{mP}}{2}, \\ w_R^{mP} &= \frac{(1-2\phi)\theta_R+\delta+\alpha+c_R}{2}, \\ \tau^{mP} &= \frac{A|L|}{S-A^2}, \\ q_N^{mP} &= \frac{2c_\tau|L|}{S-A^2}, \\ q_R^{mP} &= \frac{(\delta+\theta_R-\alpha-c_R)}{4\delta}-\frac{2c_\tau|L|}{S-A^2}. \end{aligned}$$

Proof. See the proof for Proposition 1. The necessary and sufficient condition for the manufacturer's objective function concavity is $A^2-S<0$. □

To keep it compact, the equilibrium value for w_N^{mP} is written in terms of τ^{mP}. The equilibrium collection rate in this scenario is the same as in scenario *mO* where the manufacturer is the only one financially responsible for product recovery. Therefore, although the regulator can directly affect the retailer's reaction functions, the transactions between the retailer and the supplier nullify the regulator's control. Thus, the environmental outcome is not changed by sharing the financial incentives if the physical responsibilities are centralized to the manufacturer. The only impact of implementing this scenario is the redistribution of the total profit between the supply chain members.

Since the market outcomes (production, collection, and discarded quantities) are the same for *mO* and *mP*, the same conclusions reached from the corner solutions and sensitivity analysis of *mO* can also be reached for *mP*.

Scenario *rP*: In this scenario, the retailer maximizes

$$\begin{aligned} \Pi_{rP}^{r} &= (1-q_N^{rP}-\delta q_R^{rP}-w_N^{rP})q_N^{rP}+(\delta(1-q_N^{rP}-q_R^{rP})-w_R^{rP})q_R^{rP}-c_\tau(\tau^{rP})^2 \\ &\quad -(1-\phi)((\pi_A-\tau^{rP})q_N^{rP}\theta_A+(\tau^{rP}\pi_R q_N^{rP}-q_R^{rP})\theta_R)+\alpha(\tau^{rP}q_N^{rP}-q_R^{rP}), \end{aligned}$$

and, assuming an interior solution, the best responses of the retailer are

$$q_N^{rP} = \frac{2c_\tau(1-\delta-w_N^{rP}+w_R^{rP}-(1-\phi)(\theta_R+\pi_A\theta_A))}{S/2-A_{rP}^2}, \tag{2.6}$$

$$q_R^{rP} = \frac{\delta-w_R^{rP}+(1-\phi)\theta_R-\alpha}{2\delta} - \frac{2c_\tau(1-\delta-w_N^{rP}+w_R^{rP}-(1-\phi)(\theta_R+\pi_A\theta_A))}{S/2-A_{rP}^2} \tag{2.7}$$

$$\tau^{rP} = \frac{q_N^{rP}A_{rP}}{2c_\tau}. \tag{2.8}$$

Note that since $A_{rO} > A > A_{rP}$ and $S-2A_{rO}A > 0$, we conclude that $S-2A_{rP}^2 > 0$, and consequently, the nonnegativity of q_N^{rP} requires $1-\delta-w_N^{rP}+w_R^{rP}-(1-\phi)(\theta_R+\pi_A\theta_A) > 0$. This term can be interpreted as the potential remanufacturing loss for the retailer. Similarly to the retailer's best response in scenarios *mO* and *mP*, the quantity of new products is increasing in the remanufactured products' wholesale price and is decreasing in its own wholesale price. The exact opposite observations are made for the quantity of remanufactured products. Finally, as expected, a larger retailer's profit for recycling, a more cost-efficient collection, and a higher collection rate are equivalent to more brand new production.

Taking into account the retailer's reaction functions, the manufacturer maximizes

$$\Pi_{rP}^m = (w_N^{rP}-c_N)q_N^{rP} + (w_R^{rP}-c_R)q_R^{rP} - \phi((\pi_A-\tau^{rP})q_N^{rP}\theta_A + (\tau^{rP}\pi_R q_N^{rP} - q_R^{rP})\theta_R).$$

Proposition 4. *Assuming an interior solution, the unique Stackelberg equilibrium is given* *by*

$$
\begin{aligned}
w_N^{rP} &= \frac{(1-2\phi)\theta_R + 2 + \alpha + \delta + c_R - 2(1-\phi)(\theta_R + \pi_A\theta_A)}{2} - \frac{|L|(S - 2A_{rP}^2)}{S - 2A_{rP}A} \\
w_R^{rP} &= \frac{(1-2\phi)\theta_R + \delta - \alpha + c_R}{2}, \\
\tau^{rP} &= \frac{A_{rP}|L|}{S - 2A_{rP}A}, \\
q_N^{rP} &= \frac{2c_\tau|L|}{S - 2A_{rP}A}, \\
q_R^{rP} &= \frac{\delta - \alpha - c_R + \theta_R}{4\delta} - \frac{2c_\tau|L|}{S - 2A_{rP}A}.
\end{aligned}
$$

Proof. See the proof for Proposition 1. In order to guarantee concavity of the manufacturer's problem, condition $S - 2A_{rP}A > 0$ must hold. □

The closed form of w_N^{rP} is too long and complex to be amenable to a qualitative analysis. For $\phi > 1/2$, increasing the remanufacturing deviation incentive θ_R yields a lower w_R^{rP}. However, the impact of the collection target rate does not depend on the value of ϕ; a higher collection target rate means a higher new product wholesale price, and consequently, less brand new production.

The structural forms of q_N^{rP} and τ^{rP} are the same as those in scenarios *mO* and *mP*. However, the term A in q_N^{mO} and τ^{mO} is partially replaced by A_{rP} in q_N^{rP} and τ^{rP}, and that is where the financial responsibility distribution (ϕ) comes in. The impacts of remanufacturing and collection profitability on the collection rate and the quantity of new products are the same as in scenario *mO*. The only factor that has entered the analysis is ϕ, which is an important lever for the regulator. On the one hand, assuming $\theta_A > \pi_R\theta_R$, A_{rP} decreases in ϕ. On the other hand, while the collection rate and the quantity of new product are increasing in A_{rP}, the quantity of remanufactured product is a decreasing function of the retailer's collection profit. Therefore, putting a larger burden of the regulation's financial responsibility on the shoulders of the manufacturer (i.e., increasing ϕ) yields a lower collection rate, fewer new products, and more remanufactured products. Therefore, one way to shift the demand from new to remanufactured products when the retailer is collecting is to give greater financial responsibility to the manufacturer, who is not in charge of collection at all. Otherwise, if $\theta_A < \pi_R \theta_R$, increasing ϕ means more recycling profit for the retailer and less recycling cost for the manufacturer, resulting in more production of the new product, more collection, and less remanufacturing.

The presence of ϕ modifies the conditions for interior solutions, as shown in Proposition 5.

Proposition 5. *Let $J = S - 2A_{rP}A$. In scenario rP, the conditions for interior solutions are*[10]

$$\pi_A \leq \frac{1}{\theta_A}\left(-\frac{J}{2A_{rP}}\left(\sqrt{1+\frac{A_{rP}(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}}-1\right)+\alpha-c_N+c_R-\theta_R+\delta-1\right) \tag{2.9}$$

$$\pi_A \geq \frac{1}{\theta_A}\left(-\frac{J}{A_{rP}}+\alpha-c_N+c_R-\theta_R+\delta-1\right), \tag{2.10}$$

$$\pi_A \geq \frac{1}{\theta_A}\left(-\frac{J(\delta+\theta_R-\alpha-c_R)}{8\delta c_\tau}+\alpha-c_N+c_R-\theta_R+\delta-1\right). \tag{2.11}$$

Proof. See Appendix 2.7.1. □

Similarly to scenario *mO*, there are two lower bounds and one upper bound. If the upper bound is violated, all of the collected products are remanufactured. Otherwise, if the lower bounds do not hold, either no remanufacturing is done (inequality (2.11)) or no

[10] A more compact way of writing the three conditions is

$$\frac{\alpha-c_N+c_R-\theta_R+\delta-1}{\theta_A}-\frac{1}{\theta_A}\max\left\{\frac{J}{A_{rP}},\frac{J(\delta+\theta_R-\alpha-c_R)}{8\delta c_\tau}\right\}\leq\pi_A$$
$$\leq\frac{\alpha-c_N+c_R-\theta_R+\delta-1}{\theta_A}-\frac{J}{2\theta_A A_{rP}}\left(\sqrt{1+\frac{A_{rP}(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}}-1\right).$$

However, for interpretation purposes, it is easier to proceed as done in the proposition.

products are collected (inequality (2.10)). Therefore, we conclude that, while increasing the collection target rate may mean less recycling and/or more remanufacturing, decreasing it means less collection and remanufacturing.

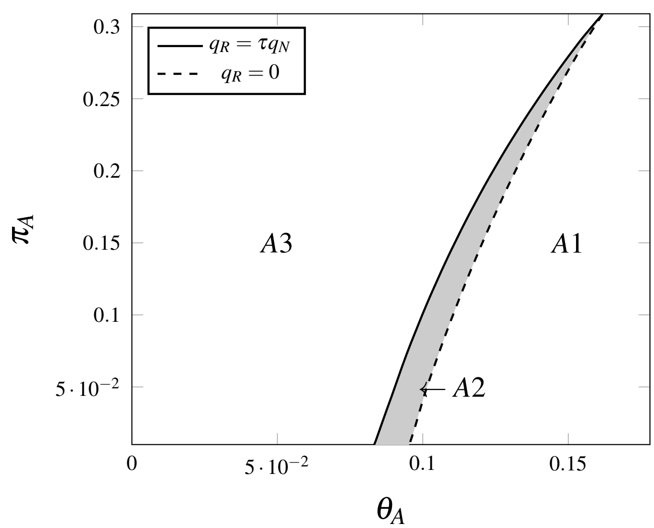


Figure 2.3 – Feasible area for π_A and θ_A in scenario *rP*

The domain of Figure 2.3 is determined for positive new product quantity (and, consequently, positive collection rate). The curve that points to the region where all products are collected is not placed within this domain. Region *A1* denotes the area where there is no remanufacturing. In region *A2*, which is the region of an interior solution, a proportion of the products is collected and remanufactured. Finally, all the collected products will be remanufactured in region *A3*. From Figure 2.3, one can observe that a lower deviation incentive and/or a higher collection target rate pushes for more remanufacturing, while a higher deviation incentive and/or a lower collection target rate deter remanufacturing.

Scenario ***rO*****:** Here, the retailer collects and the manufacturer remanufactures, and each of them is responsible for its own actions. The retailer maximizes

$$\Pi^r_{rO} = (1 - q_N^{rO} - \delta q_R^{rO} - w_N^{rO})q_N^{rO} + (\delta(1 - q_N^{rO} - q_R^{rO}) - w_R^{rO})q_R^{rO} - c_\tau(\tau^{rO})^2 \tag{2.12}$$

$$-(\pi_A - \tau^{rO})q_N^{rO}\theta_A + \alpha(\tau^{rO}q_N^{rO} - q_R^{rO}). \tag{2.13}$$

Assuming an interior solution, the reaction functions of the retailer are given by

$$q_N^{rO} = \frac{2c_\tau(\delta - 1 + w_N^{rO} - w_R^{rO} + \pi_A\theta_A)}{A_{rO}^2 - S/2},$$

$$q_R^{rO} = \frac{A_{rO}^2(\delta - \alpha - w_R^{rO}) - 4c_\tau(\delta w_N^{rO} + \delta\pi_A\theta_A - \alpha - w_R^{rO})}{2\delta A_{rO}^2 - S},$$

$$\tau^{rO} = \frac{A_{rO}(\delta - 1 + w_N^{rO} - w_R^{rO} + \pi_A\theta_A)}{A_{rO}^2 - S/2}.$$

Taking into account the above reaction functions, the manufacturer maximizes

$$\Pi^m_{rO} = (w_N^{rO} - c_N)q_N^{rO} + (w_R^{rO} - c_R)q_R^{rO} - (\tau^{rO}\pi_R q_N^{rO} - q_R^{rO})\theta_R.$$

Proposition 6 characterizes the unique Stackelberg equilibrium.

Proposition 6. *Assuming an interior solution, the unique Stackelberg equilibrium is given by*

$$\begin{aligned}
w_N^{rO} &= \frac{\pi_R\theta_R A_{rO}|L|}{S - 2A_{rO}A} + \frac{1 + c_N - \pi_A\theta_A}{2}, \\
w_R^{rO} &= \frac{\delta + c_R - \alpha - \theta_R}{2}, \\
\tau^{rO} &= \frac{A_{rO}|L|}{S - 2A_{rO}A}, \\
q_N^{rO} &= \frac{2c_\tau|L|}{S - 2A_{rO}A}, \\
q_R^{rO} &= \frac{\delta + \theta_R - c_R - \alpha}{4\delta} - \frac{2c_\tau|L|}{S - 2A_{rO}A}.
\end{aligned}$$

Proof. See the proof for Proposition 1. $S - 2A_{rO}A > 0$ is the necessary and sufficient condition for the concavity of the manufacturer's objective function. □

We make the following observations:

1. If collection is costly and recycling has a low value, ($S - 2A_{rO}A > 0$) this results in less brand new production and collection when the retailer faces a higher collection target rate. A lower quantity of new products on the one hand, and a decreased remanufacturing cost on the other hand, means that a lower quantity of new products will be compensated for by a higher quantity of the remanufactured product.

2. Unlike in scenarios *mO*, *mP*, and *rP*, a higher collection target rate results in a lower wholesale price for new products. Scenario *rO* is the only scenario where the manufacturer is completely disengaged from collection. When the collection target rate increases, the potential remanufacturing cost decreases. Therefore, the retailer orders fewer new products to deal with the collection regulation, and also reduces the collection rate to avoid increasing the collection cost (because the collection cost is a convex increasing function in the collection rate). However, since the total loss for the manufacturer is lower that what it was in the other scenarios where it was involved with collection, it reduces the new product wholesale price to balance the reduced amount of new products ordered.

Since all equilibrium values in Proposition 6 have the same structure as their counterparts in Propositions 1, 3, and 4 (except w_N^{rO}), we do not comment further on these values.

To obtain the equilibrium values in Proposition 6, we assumed an interior solution. The conditions for having such a solution are presented in Proposition 7.

Proposition 7. *Let $J = S - 2A_{rO}A$. The conditions for having an interior solution are*[11]

$$\pi_A \leq \frac{1}{\theta_A}\left(\frac{-J\left(\sqrt{1+\frac{A_{rO}(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}}-1\right)}{2A_{rO}}+1+\alpha-\delta-\theta_R+c_R-c_N\right),$$
$$\pi_A \geq \frac{1}{\theta_A}\left(\frac{-J}{A_{rO}}+1+\alpha-\delta-\theta_R+c_R-c_N\right),$$
$$\pi_A \geq \frac{1}{\theta_A}\left(\frac{-J(\delta+\theta_R-\alpha-c_R)}{8c_\tau\delta}+1+\alpha-\delta-\theta_R+c_R-c_N\right).$$

Proof. See Appendix 2.7.1. □

If we replace A_{rP} by A_{rO}, then the conditions in Proposition 7 would be the same as those in Proposition 5. This change does not alter the conclusions then made about the impact of the cost of remanufacturing and the value of recycling on production quantities and collection rates. Therefore, we conclude that the responsibility sharing policy does not affect the impact of collection target rate on the overall response of the supply chain.

Figure 2.4 is presented to show how modifying the collection target and incentive changes the production and collection policy of the supply chain. The data used to create this graph are given in Appendix 2.7.2.

[11] These conditions can be rewritten more compactly as

$$\frac{1+\alpha-\delta-\theta_R+c_R-c_N}{\theta_A}-\frac{1}{\theta_A}\max\left\{\frac{J}{A_{rO}},\frac{J(\delta+\theta_R-\alpha-c_R)}{8\delta c_\tau}\right\}\leq \pi_A$$
$$\leq \frac{1+\alpha-\delta-\theta_R+c_R-c_N}{\theta_A}-\frac{J}{2\theta_A A_{rO}}\left(\sqrt{1+\frac{A_{rO}(\delta+\theta_R-\alpha-c_R)}{2c_\tau\delta}}-1\right).$$

However, for interpretation purposes, it is easier to proceed as done in the proposition.

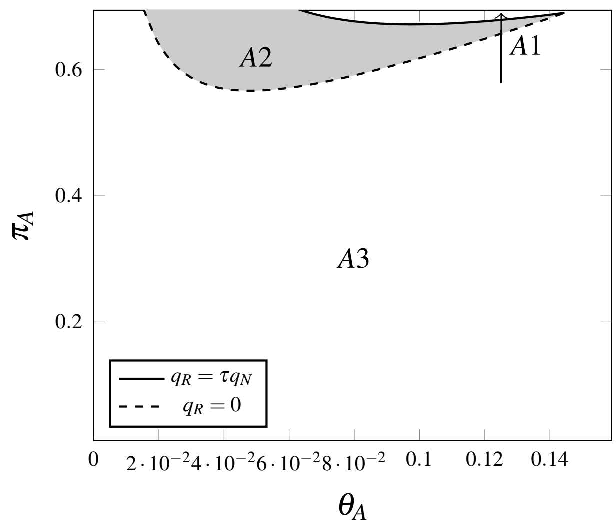


Figure 2.4 – Feasible area for π_A and θ_A in scenario *rO*

The interior solution conditions are $\theta_A \in [0, 0.144]$ and $\pi_A \in [0, 0.694]$. As in Figure 2.3, not all the possible regions are shown as they were positioned beyond the domain of this graph. Region *A1* denotes the area with full remanufacturing. In region *A2*, a proportion of the products is collected and remanufactured (interior solution region). Finally, remanufacturing stops in region *A3*. According to this illustration, decreasing the collection target results in less remanufacturing. Therefore, as was the case for the other scenarios, remanufacturing is controlled without directly targeting remanufacturing.

Table 2.2 summarizes the meaning of each region in Figure 2.4.

Table 2.2 – Meaning of regions in Figure 2.4

Regions	Collection	Remanufacturing
A1	partial	all
A2	partial	partial
A3	partial	none

Having presented the equilibria in all scenarios and their regulatory implications, we now compare them in order to propose guidelines to regulators depending on their specific environmental goal.

2.4 Environmental Performance Analysis

In this section, we look at the environmental performance of each of the considered scenarios. Our objective is to derive insights for EPR regulation design and responsibility sharing policies.

Proposition 8 confirms that decision regarding financial responsibility sharing cannot be made independently from those about physical responsibility sharing. This proposition is based on the conclusions in Section 2.3.

Proposition 8. *If all physical responsibilities are centralized to the manufacturer, sharing financial responsibility does not affect the collection rate or the quantity landfilled. However, this is not the case if the physical responsibilities are distributed.*

Proof. Solutions were already presented in Section 2.3. For the first part of the proposition, all that is needed is to show that the closed-form solutions of q_R, τ, and q_N for the mO and mP scenarios are the same. From Propositions 1 and 3, we have

$$\begin{aligned}
\tau^{mO} &= \tau^{mP} = \frac{A|L|}{S-A^2}, \\
q_N^{mO} &= q_N^{mP} = \frac{2c_\tau|L|}{S-A^2}, \\
q_R^{mO} &= q_R^{mP} = \frac{(\delta+\theta_R-\alpha-c_R)}{4\delta} - \frac{2c_\tau|L|}{S-A^2}.
\end{aligned}$$

Therefore, the production and collection policies are the same under both scenarios. However, as for the second part, from Propositions 4 and 6 we have

$$A_{rO} \neq A_{rP} \longleftrightarrow \frac{A_{rO}|L|}{S-2A_{rO}A} \neq \frac{A_{rP}|L|}{S-2A_{rP}A} \longleftrightarrow \tau^{rO} \neq \tau^{rP},$$
$$A_{rO} \neq A_{rP} \longleftrightarrow \frac{2c_\tau|L|}{S-2A_{rO}A} \neq \frac{2c_\tau|L|}{S-2A_{rP}A} \longleftrightarrow q_N^{rO} \neq q_N^{rP},$$
$$A_{rO} \neq A_{rP} \longleftrightarrow \frac{\delta+\theta_R-c_R-\alpha}{4\delta} - \frac{2c_\tau|L|}{S-2A_{rO}A} \neq \frac{\delta+\theta_R-c_R-\alpha}{4\delta} - \frac{2c_\tau|L|}{S-2A_{rP}A} \longleftrightarrow q_R^{rO} \neq q_R^{rP}.$$

Therefore, the production and collection policies for scenarios rP and rO are the same. □

The next step is to determine the conditions under which a responsibility sharing policy is the best one. Proposition 9 deals with the scenario with the best collection rate.

Proposition 9. *For a low collection cost-efficiency and a low consumer discount factor for remanufactured products, or for a low recycling profit for the member who collects, scenario rO leads to the highest collection rate.*

Proof. See Appendix 2.7.1. □

Therefore, if the regulator aims to maximize the proportion of products collected, the best RSP strategy is to have the retailer collect and to hold it financially responsible to pay the related penalties, if it could not meet the collection rate target. Furthermore, scenario *rO* has the largest new product and the lowest remanufactured product quantities, making it an undesirable RSP policy if the regulator seeks to promote remanufacturing.

Alternatively, if the product contains toxic materials, the quantity landfilled is an important indicator of environmental performance. There could be cases where the collection rate is increased while the quantity landfilled is not reduced. A significant increase in the quantity of the new products is one possible reason for this outcome. Aside from the collection rate and quantity discarded, a regulator may want to reduce the overall energy consumption. However, since there are numerous conditions that put one scenario ahead of the others in terms of the discarded quantity and the total energy consumed, and consequently, it is almost impossible to extract insightful conclusions, we leave this criteria to be discussed through a numerical analysis.

We investigate the case of electronic products because they (i) are generally remanufacturable, (ii) are generally remanufacturable only once, (iii) mostly fall under environmental regulations, and (iv) usually contain toxic materials and are dangerous to landfill. The data for three types of electronic products are available from Esenduran et al. (2016). To consider low, medium, and high energy consumption during the production process, they have selected cell phones, LCD monitors, and refrigerators, respectively. For further details about the data, interested readers may refer to Esenduran et al. (2016). Since the assumptions on the demand function in Esenduran et al. (2016) are slightly different from ours, some adjustments are made to fit the data to our model.

Table 2.3 – Data for numerical analysis

Parameters	Cell Phones	Refrigerators	LCD Monitors
α	$\begin{pmatrix} 1/60 & 1/100 & 1/140 \\ 1/30 & 1/50 & 1/70 \\ 1/20 & 3/100 & 3/140 \end{pmatrix}$	$\begin{pmatrix} 1/60 & 1/120 & 1/180 \\ 1/25 & 1/50 & 1/75 \\ 19/300 & 19/600 & 19/900 \end{pmatrix}$	$\begin{pmatrix} 1/40 & 1/80 & 1/120 \\ 9/200 & 9/400 & 3/200 \\ 13/200 & 13/400 & 13/600 \end{pmatrix}$
c_N	$\begin{pmatrix} 1/4 & 3/20 & 3/28 \\ 5/12 & 1/4 & 5/28 \\ 7/12 & 7/20 & 1/4 \end{pmatrix}$	$\begin{pmatrix} 1/4 & 1/8 & 1/12 \\ 1/2 & 1/4 & 1/6 \\ 3/4 & 3/8 & 1/4 \end{pmatrix}$	$\begin{pmatrix} 1/4 & 1/8 & 1/12 \\ 1/2 & 1/4 & 1/6 \\ 3/4 & 3/8 & 1/4 \end{pmatrix}$
c_R/c_N	0.05, 0.50	0.05, 0.50	0.05, 0.50
θ_R/α	1.1, 1.3, 1.5	1.1, 1.3, 1.5	1.1, 1.3, 1.5
θ_A/θ_R	1.1, 1.3, 1.5	1.1, 1.3, 1.5	1.1, 1.3, 1.5
δ	0.5,..,0.9	0.5,..,0.9	0.5,..,0.9
ϕ	0.2, 0.5, 0.8	0.2, 0.5, 0.8	0.2, 0.5, 0.8
c_τ	0.0089	0.0089	0.0089

The reason to define α and c_N in matrices is that not all 9 values are to be considered for each set of other parameters (i.e., instead of 3 values, we have defined 3 sets of values to adjust the data to our model). For instance, if the values for α are 1/60, 1/100 and 1/140, the corresponding values for high, medium, and low manufacturing costs are 1/4, 3/20 and

3/28, respectively. The reason to consider α and c_N this way was to adjust for variations in prices of each type of electronic products. The value of θ_R/α is selected in such a way that it accounts for low, medium, and high values of remanufacturing penalty relative to the value of collected but not remanufactured products. The higher this ratio is, the higher is the incentive to remanufacture rather than to sell away the collected products. The ratio θ_A/θ_R represents the proportional emphasis on collection over remanufacturing from the regulator's point of view. We selected 1.1, 1.3, and 1.5 to target high, medium, and low values of remanufacturing, respectively.

Table 2.4 – Energy consumption parameters (Esenduran et al., 2016)

Parameter	Cell Phones	Refrigerators	LCD Monitors
e_{rm}/e_m	0.2,0.4	0.2,0.4	0.2,0.4
e_{rc}/e_m	-0.037	-0.01	0.026
e_d/e_m	0.00003	0.00125	0.00011
e_u/e_m	0.575	10.468	0.411
e_m	200	6909	2073

The numerical analysis procedure is as follows. To investigate the impact of the collection target level and for each of set of parameters, the performance indicators are calculated for π_A values ranging from 0.024 to 0.96 with a step of 0.024. The remanufacturing target rate belongs to the set $\{0.2, 0.4, 0.6\}$. To study the impact of the remanufacturing target, the values are reversed. For each set of the input data, the problem is solved and the value of the performance indicator(s) is obtained. We count the total number of times where the performance indicator is increased. At the end, the proportion of the times when increasing the target rate yields a higher value of performance indicator is calculated. In other words, this ratio represents the percentage of the time when increasing the target rate leads to an increase in the respective performance indicator.

The impacts of target rates on uncollected quantities are reported in Tables 2.5 and 2.6.

According to Proposition 8, the quantity of brand new and remanufactured products, and the collection rate are the same for the *mO* and *mP* scenarios. The first two rows in Tables 2.5 to 2.8 numerically confirm this proposition.

Table 2.5 – Impact of collection target rate on uncollected quantity

Scenarios	Cell Phones	Refrigerators	LCD Monitors
mO	%3.41	%7.30	%10.69
mP	%3.41	%7.30	%10.69
rO	%38.53	%35.45	%48.56
rP	%9.97	%6.75	%19.74

Table 2.6 – Impact of remanufacturing target rate on uncollected quantity

Scenarios	Cell Phones	Refrigerators	LCD Monitors
mO	%86.95	%83.82	%78.85
mP	%86.95	%83.82	%78.85
rO	%38.18	%34.99	%47.28
rP	%96.95	%92.05	%92.49

For all three products, the variation of the values within each column is considerable. Thus, it is safe to make the following claims:

Claim 1. *For the three products and in terms of the uncollected quantity, the responsibility sharing policy impacts the way collection and remanufacturing target rates affect the environmental performance indicators.*

In other words, before increasing or decreasing the value of target rates, the imposed responsibility sharing policy should be taken into account. Furthermore, by observing all the values in Table 2.5, it could be concluded that increasing the collection target rate will most likely reduce the quantity of uncollected products. The same conclusion is not true for the remanufacturing target rate.

Tables 2.7 and 2.8 report the proportions of time when increasing the target rates results in an increase in the total energy consumption.

Table 2.7 – Impact of collection target rate on total energy consumption

Scenarios	Cell Phones	Refrigerators	LCD Monitors
mO	%0.00	%0.06	%0.05
mP	%0.00	%0.06	%0.05
rO	%3.37	%6.75	%10.70
rP	%0.04	%1.60	%2.73

Table 2.8 – Impact of remanufacturing target rate on total energy consumption

Scenarios	Cell Phones	Refrigerators	LCD Monitors
mO	%6.72	%0.06	%13.33
mP	%6.72	%0.06	%13.33
rO	%2.81	%5.85	%8.71
rP	%10.18	%3.47	%21.05

According to Tables 2.7 and 2.8, the following claims can be made for the total energy consumption:

Claim 2. *For the three products and in terms of the total energy consumption, the responsibility sharing policy has a significant impact on the effect of collection and remanufacturing target rates.*

Claim 3. *Increasing collection and remanufacturing target rates most likely yields a lower total energy consumption for all responsibility sharing policies.*

Claims 1 to 3 tend to show that the impact of the regulatory parameters on environmental performance depends on the selected responsibility sharing policy, and apparently, the product. Considering these observations, together with Propositions 8 and 9, we confirm the interrelation between physical and financial RSPs on the one hand, and the interrelation between selecting the best RSP and EPR regulation design on the other hand. Thus, we have achieved the main research goals.

Any discussions of regulations from the environmental point of view is not complete unless the supply chain profitability and consumer surplus implications of the regulations are also considered.

2.5 Profitability and Consumer Surplus Implications

Throughout this paper, EPR regulation design and RSP are discussed with the aim of improving environmental performance. However, supply chain profitability and consumer surplus are two other important considerations when designing an environmental regulation or allocating responsibilities among the supply chain members. For this purpose, we present numerical examples under different regulating scenarios. In Sections 2.5.1 and 2.5.2, the impacts of collection and remanufacturing regulations on consumer surplus and profitability are discussed for different responsibility sharing policies.

2.5.1 Collection Regulation

To isolate the impact of the collection regulation, assume that there is no regulation on remanufacturing. To study different levels of regulation, we retain the following four scenarios: (i) strictly rewarding regulation, i.e., high deviation incentive and low target rate ($\theta_A = 0.7$ and $\pi_A = 0.3$); (ii) strictly penalizing regulation, i.e., high deviation incentive and target rate ($\theta_A = 0.7$ and $\pi_A = 0.7$); (iii) weakly rewarding regulation, i.e., low deviation incentive and target rate ($\theta_A = 0.3$ and $\pi_A = 0.3$); and (iv) weakly penalizing regulation, i.e., low deviation incentive and high target rate ($\theta_A = 0.3$ and $\pi_A = 0.7$). For each scenario, the manufacturer's profit, the retailer's profit, and the consumer surplus are calculated under the addressed RSP scenarios. The data used for the examples are presented in Table 2.9.

Table 2.9 – Input data for profitability and consumer surplus implications under a collection regulation

Parameter	c_τ	ϕ	δ	c_R	c_N	α
Value	0.5	0.7	0.85	0.1	0.25	0.05

Table 2.10 reports the values of profit and consumer surplus for all collection regulation and RSP scenarios.

Table 2.10 – Profitability and consumer surplus implications of collection regulations ($\times 10^{-5}$)

Collection Regulation	RSP Scenarios	Manufacturer Profit	Retailer Profit	Consumer Surplus
Strictly rewarding $\pi_A = 0.3$, $\theta_A = 0.7$	mO	4524	2686	1343
	mP	4524	2686	1343
	rO	5211	2666	1729
	rP	4144	2262	1186
Weakly rewarding $\pi_A = 0.3$, $\theta_A = 0.3$	mO	5743	3009	1504
	mP	5743	3009	1504
	rO	5900	2995	1585
	rP	5629	2879	1453
Strictly penalizing $\pi_A = 0.7$, $\theta_A = 0.7$	mO	1240	853	426
	mP	1240	853	426
	rO	1423	856	556
	rP	999	586	293
Weakly penalizing $\pi_A = 0.7$, $\theta_A = 0.3$	mO	3945	2114	1057
	mP	3945	2114	1057
	rO	4027	2081	1102
	rP	3796	1956	987

The following observations can be made from these tables:

1. The profit and surplus values are the same in the *mO* and *mP* scenarios. The difference between the wholesale price values for these scenarios shows that the manufacturer has to adjust the wholesale prices to compensate for the costs incurred to the retailer as the result of sharing the financial responsibilities.

2. The best RSP for the manufacturer and consumers is scenario *rO*. This result sheds light on the discussion between the manufacturers and the regulators on involving the retailers in the after-sale environmental services.

3. A weakly rewarding collection regulation (which can also be seen as no regulation) is the best scenario for the supply chain. It will benefit the supply chain more than a regulation that most probably rewards collection.

4. The best case for the remanufacturer occurs when the retailer is physically and financially in charge of collection, and the collection regulation is a weakly rewarding one. Retailers get the most from a weakly rewarding regulation where the manufacturer is in charge of collection. Finally, the highest consumer surplus is obtained when the retailer is totally responsible for collection and the the regulator has stipulated a strictly rewarding collection regulation.

In the next section, the same analysis is done for a remanufacturing regulation, assuming that a collection regulation is also in place.

2.5.2 Remanufacturing Regulation

In this section, we assume that remanufacturing and collection are both regulated. Using the same procedure, we study the impact of regulating remanufacturing and RSP scenarios on supply chain profitability and on consumer surplus. The same input data as used in Section 2.5.1 is also used here, with the only difference being that the previously varied parameters π_A and θ_A are now assigned a value of 0.5. To study different levels of remanufacturing regulation, four scenarios are defined: (i) a strictly rewarding regulation, i.e., high deviation incentive and low target rate ($\theta_R = 0.6$ and $\pi_R = 0.2$), (ii) a strictly penalizing regulation, i.e., high deviation incentive and target rate ($\theta_R = 0.6$ and $\pi_R = 0.6$), (iii) a weakly rewarding regulation, i.e., low deviation incentive and target rate ($\theta_R = 0.2$ and $\pi_R = 0.2$), and (iv) a weakly penalizing regulation, i.e., low deviation incentive and high target rate ($\theta_R = 0.2$ and $\pi_R = 0.6$). The results are reported in Table 2.11.

Table 2.11 – Profitability and consumer surplus implications of remanufacturing regulations ($\times 10^{-5}$)

Remanufacturing Regulation	RSP Scenarios	Manufacturer Profit	Retailer Profit	Consumer Surplus
Strictly rewarding $\pi_R = 0.2$, $\theta_R = 0.6$	mO	4555	3005	1502
	mP	4555	3005	1502
	rO	4518	2690	1541
	rP	3483	1908	966
Weakly rewarding $\pi_R = 0.2$, $\theta_R = 0.2$	mO	3882	2312	1156
	mP	3882	2312	1156
	rO	4087	2234	1287
	rP	3429	1841	936
Strictly penalizing $\pi_R = 0.6$, $\theta_R = 0.6$	mO	4024	2456	1228
	mP	4024	2456	1228
	rO	4188	2336	1345
	rP	3282	1715	861
Weakly penalizing $\pi_R = 0.6$, $\theta_R = 0.2$	mO	3755	2184	1092
	mP	3775	2184	1092
	rO	3990	2138	1232
	rP	3365	1783	903

The observations made from Table 2.11 have similarities to and differences with those made from Table 2.10. Firstly, the best regulating policy for the consumers and the supply chain is a strictly rewarding remanufacturing regulation. This result is different from what was observed for the collection regulation, where a weakly rewarding regulation on collection best served the supply chain. Consequently, there are different best outcomes for supply chain members and for consumers. Given the input data, the best case for the manufacturer and the retailer is a strictly rewarding regulation where the manufacturer is collecting. The consumers, however, are better off if the retailer is collecting and paying the penalties or receiving the rewards. The main similarity between these results is that the financial outcomes of all stakeholders are equal, even if the financial responsibilities are shared. Furthermore, from the numbers reported in these two tables, it is apparent that the best responsibility sharing policy varies by regulatory approach (the four retained scenarios), and the best regulatory approach also varies according to which responsibility sharing policy is selected. Confirming and analyzing this interrelation was one of the main goals of our research.

In the final section, our research contribution, the main assumptions, and the main takeaways of this research are reviewed.

2.6 Conclusion

In this paper, the responsibility sharing problem is studied for a supply chain that is obliged to collect and remanufacture previously sold products. This paper contributes to the literature by highlighting the underlying relationship between responsibility sharing policy and EPR regulation design. A supply chain consisting of a manufacturer and a retailer is considered, where the manufacturer acts as the leader of the chain and interacts with the retailer through the wholesale price and the physical transfer of new, remanufactured, and returned products. The regulator stipulates a reward-penalty regulation to achieve a specified environmental goal. The reward-penalty regulation is based on target rates and deviation incentives for collection and remanufacturing.

Four scenarios are defined on the basis of physical and financial responsibility sharing policies. On the one hand, we showed that not only is there an interdependence between the selected financial and physical responsibility sharing policies, but also, the choice of the best policy – depending on the performance measure – may be affected by the selected target rates and deviation incentives (i.e., the regulation design). On the other hand, we obtained that the impacts of the target rates and deviation incentives depend on the chosen responsibility sharing policy. Thus, it is concluded that the EPR regulation design and the responsibility sharing policy must be considered simultaneously. Hence, any claim about the impact of any specific EPR regulation is incomplete unless it clarifies which member is responsible for what recovery action and how the incentives are to be distributed among the supply chain members.

Using a numerical example, we showed that, while a regulation that rewards remanufacturing is the best option for the supply chain members, expectedly, they prefer a weak collection regulation. Furthermore, the best RSP for the manufacturer is to have the retailer collect while the manufacturer has nothing to do with its financial consequences. However, the retailer prefers the scenario where the remanufacturer collects, except for the case of a regulation that strictly penalizes collection.

There are several possible ways to extend this paper. This study is built on a set of assumptions, which clearly have an impact on the results, and it would be worthwhile to relax some of them in future investigations. Firstly, we analyzed the scenarios under the conditions that collecting is costly and remanufacturing is not profitable, in order to concentrate on the critical cases where regulating the market is needed. Profitable remanufacturing may change the conclusions entirely. Secondly, we assumed that the market is in its steady state. However, if the remanufacturing market is not at its steady state, the amount of past production may affect the regulation design choices (Pazoki and Zaccour, 2018). Moreover, collection could be done by more than one member of the supply chain.

2.7 Appendices

2.7.1 Proof of Propositions

Proposition 2. The constraints to be satisfied are $0 \le q_R \le \tau q_N$, $0 \le \tau \le 1$, and $0 \le q_N \le 1$. $0 \le p_N \le \delta$ and $0 \le p_R \le \delta$ will be automatically satisfied. Let $A = \theta_A + \alpha - \pi_R\theta_R$, $L = \delta - 1 + \theta_R + \pi_A\theta_A - c_R + c_N - \alpha$, $S = 8c_\tau(1-\delta)$ and $\Delta = 1 + A(\delta + \theta_R - c_R - \alpha)/2\delta c_\tau$. Assuming $J = S - A^2 > 0$, the following conditions are obtained

$$\tau \ge 0 \rightarrow \quad \pi_R\theta_R \le \alpha + \theta_A$$

$$\pi_A \le (1 + \alpha - \delta - \theta_R + c_R - c_N)/\theta_A$$

$$\tau \le 1 \rightarrow \quad \text{conditions for } \tau \ge 0 \text{ and } J \ge A|L|$$

$$\rightarrow \quad \pi_A \ge \left(\frac{-J}{A} + 1 + \alpha - \delta - \theta_R + c_R - c_N\right)/\theta_A$$

$$q_N \ge 0 \rightarrow \quad \text{The same conditions as for } \tau \ge 0$$

$$q_N \le 1 \rightarrow \quad \tau \le 1 \text{ and } J \ge 2c_\tau|L|$$

$$\rightarrow \quad \pi_A \ge \left(\frac{-J}{2c_\tau} + 1 + \alpha - \delta - \theta_R + c_R - c_N\right)/\theta_A$$

$$q_R \ge 0 \rightarrow \quad \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \ge q_N = \frac{2c_\tau|L|}{J}$$

$$\rightarrow \quad \pi_A \ge \left(\frac{-J}{8c_\tau\delta}(\delta + \theta_R - \alpha - c_R) + 1 + \alpha - \delta - \theta_R + c_R - c_N\right)/\theta_A$$

$$q_R \le \tau q_N \rightarrow$$

$$\frac{\delta + \theta_R - \alpha - c_R}{4\delta} \le \frac{2c_\tau|L|(A|L| + J)}{J^2}$$

$$\pi_A \le \left(\frac{-J(\sqrt{\Delta} - 1)}{2A} + 1 - \delta + c_R - c_N + \alpha - \theta_R\right)/\theta_A$$

There are initially 2 upper bounds and 3 lower bounds for π_A. The upper bound found for $q_R \le \tau q_N$ is smaller than that of $\tau \ge 0$, allowing us to conclude that there is only one upper bound resulting from $q_R \leq \tau q_N$. The lower bound obtained for $q_N \leq 1$ is smaller than that of $q_R \geq 0$. Therefore, the maximum of those found for $q_R \geq 0$ and $\tau \leq 1$ is the lower bound for π_A. Therefore, we end up with one upper bound and two lower bounds. $\square$

Proposition 5. Let $A = \alpha + \theta_A - \pi_R\theta_R$, $L = \delta - 1 + \theta_R + \pi_A\theta_A - c_R + c_N - \alpha$, and $A_{rP} = \alpha + (1-\phi)(\theta_A - \pi_R\theta_R)$, and assume $J = S - 2A_{rP}A > 0$. We need to satisfy

$$\begin{aligned}
\tau \geq 0 \rightarrow \quad & (1-\phi)\pi_R\theta_R \leq \alpha + (1-\phi)\theta_A \\
& \pi_A \leq (1 - \delta + \alpha + c_R - c_N - \theta_R)/\theta_A \\
\tau \leq 1 \rightarrow \quad & \text{conditions for } \tau \geq 0 \text{ and } J \leq |L| A_{rP} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{A_{rP}} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A
\end{aligned}$$

$$\begin{aligned}
q_N \geq 0 \rightarrow \quad & \text{same conditions as for } \tau \geq 0 \\
q_N \leq 1 \rightarrow \quad & \text{condition for } \tau \geq 0 \text{ and} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{2c_\tau} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A.
\end{aligned}$$

$$\begin{aligned}
q_R \geq 0 \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \geq q_N = \frac{2c_\tau |L|}{J} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J(\delta + \theta_R - \alpha - c_R)}{8c_\tau\delta} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A \\
q_R \leq \tau q_N \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \leq \frac{2c_\tau |L| (A_{rP}|L| + J)}{J^2} \\
& \pi_A \leq \left(-J\frac{\sqrt{1 + \frac{A_{rP}(\delta + \theta_R - \alpha - c_R)}{2c_\tau\delta}} - 1}{2A_{rP}} + \alpha - c_N + c_R - \theta_R + \delta - 1\right)\theta_A,
\end{aligned}$$

There are initially 2 upper bounds and 3 lower bounds for π_A. The upper bound found for $q_R \leq \tau q_N$ is smaller than that of $\tau \geq 0$, allowing us to conclude that there is only one upper bound resulting from $q_R \leq \tau q_N$. The lower bound obtained for $q_N \leq 1$ is smaller than that of $q_R \geq 0$. Therefore, the maximum of those found for $q_R \geq 0$ and $\tau \leq 1$ is the lower bound for π_A. Therefore, we end up with one upper bound and two lower bounds, as presented in Proposition 5. □

Proposition 7. Let $A = \alpha + \theta_A - \pi_R\theta_R$, $A_{rO} = \alpha + \theta_A$ and $L = \delta - 1 + \theta_R + \pi_A\theta_A - c_R + c_N - \alpha$, and assume $J = S - 2A_{rO}A > 0$. We need to satisfy

$$\begin{aligned}
\tau \geq 0 \rightarrow \quad & (1-\phi)\pi_R\theta_R \leq \alpha + (1-\phi)\theta_A \\
& \pi_A \leq (1 - \delta + \alpha + c_R - c_N - \theta_R)/\theta_A \\
\tau \leq 1 \rightarrow \quad & \text{conditions for } \tau \geq 0 \text{ and } J \leq |L|A_{rO} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{A_{rO}} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A
\end{aligned}$$

$$\begin{aligned}
q_N \geq 0 \rightarrow \quad & \text{same conditions as for } \tau \geq 0 \\
q_N \leq 1 \rightarrow \quad & \text{condition for } \tau \geq 0 \text{ and} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J}{2c_\tau} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A.
\end{aligned}$$

$$\begin{aligned}
q_R \geq 0 \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \geq q_N = \frac{2c_\tau|L|}{J} \\
\rightarrow \quad & \pi_A \geq \left(\frac{-J(\delta + \theta_R - \alpha - c_R)}{8c_\tau\delta} + 1 - \delta + \alpha + c_R - c_N - \theta_R\right)/\theta_A \\
q_R \leq \tau q_N \rightarrow \quad & \frac{\delta + \theta_R - \alpha - c_R}{4\delta} \leq \frac{2c_\tau|L|(A_{rO}|L| + J)}{J^2} \\
& \pi_A \leq \left(-J\frac{\sqrt{1 + \frac{A_{rO}(\delta + \theta_R - \alpha - c_R)}{2c_\tau\delta}} - 1}{2A_{rO}} + \alpha - c_N + c_R - \theta_R + \delta - 1\right)\theta_A,
\end{aligned}$$

There are initially 2 upper bounds and 3 lower bounds for π_A. The upper bound found for $q_R \leq \tau q_N$ is smaller than that of $\tau \geq 0$, allowing us to conclude that there is only one upper bound resulting from $q_R \leq \tau q_N$. The lower bound obtained for $q_N \leq 1$ is smaller than that of $q_R \geq 0$. Therefore, the maximum of those found for $q_R \geq 0$ and $\tau \leq 1$ is the lower bound for π_A. Therefore, we end up with one upper bound and two lower bounds. □

Proposition 9. For the three scenarios (mP is the same as mO), the collection rates are $\tau^{mO} = A|L|/(S-A^2)$, $\tau^{rP} = A_{rP}|L|/(S-2A_{rP}A)$ and $\tau^{rO} = A_{rO}|L|/(S-2A_{rO}A)$. Furthermore, we know that $A_{rO} > A_{rP}$ and $A_{rO} > A$, and we assumed in the article that $\theta_A > \pi_R\theta_R$, which means that the collection regulation is more emphasized than the remanufacturing regulation. Therefore, $A_{rO} > A > A_{rP}$. We have

$$\tau^{rO} > \tau^{rP} \Longleftrightarrow \frac{A_{rO}|L|}{S-2A_{rO}A} > \frac{A_{rP}|L|}{S-2A_{rP}A} \Longleftrightarrow A_{rO}|L|S > A_{rP}|L|S \Longleftrightarrow A_{rO} > A_{rP},$$

and

$$\tau^{rO} > \tau^{mO} \Longleftrightarrow \frac{A_{rO}|L|}{S-2A_{rO}A} > \frac{A|L|}{S-A^2} \Longleftrightarrow A_{rO}A^2 > S(A-A_{rO}),$$

and thus conclude that scenario rO yields the highest collection rate. In a similar way, it is simple to show that q_N^{rO} and q_R^{rO} are the highest and the lowest among the addressed scenarios, respectively. □

2.7.2 Sensitivity Analysis Data

Table 2.12 – Input data for Figures 2.2, 2.3, and 2.4

Parameter	δ	c_R	c_N	c_τ	α	ϕ	π_R	θ_R
Value	0.85	0.1	0.25	0.1	0.1	0.2	0	0

Bibliography

Abbey, J. D., Kleber, R., Souza, G. C., & Voigt, G. (2017). The role of perceived quality risk in pricing remanufactured products. *Production and Operations Management, 26*(1), 100-115.

Atasu, A., Van Wassenhove, L. N., & Sarvary, M. (2009). Efficient take-back legislation. *Production and Operations Management, 18*(3), 243-258.

Bulmuş, S. C., Zhu, S. X., & Teunter, R. H. (2014). Optimal core acquisition and pricing strategies for hybrid manufacturing and remanufacturing systems. *International Journal of Production Research, 52*(22), 6627-6641.

Chen, D., Demirbag, M., Ignatius, J., Marra, M., Sun, D., Zhan, S., & Zhou, C. (2018). Reverse logistics pricing strategy for a green supply chain: A view of customers' environmental awareness. *International Journal of Production Economics*, *Article in Press*, https://doi.org/10.1016/j.ijpe.2018.08.031.

Chen, J. X., & Chen, J. (2017). Supply chain carbon footprinting and responsibility allocation under emission regulations. *Journal of Environmental Management, 188*, 255-267.

Cheng, J., Li, B., Gong, B., Cheng, M., & Xu, L. (2017). The optimal power structure of environmental protection responsibilities transfer in remanufacturing supply chain. *Journal of Cleaner Production, 153*, 558-569.

De Giovanni, P. (2011). Quality improvement vs. advertising support: which strategy works better for a manufacturer?. *European Journal of Operational Research, 208*(2), 119-130.

De Giovanni, P., Reddy, P. V., & Zaccour, G. (2016). Incentive strategies for an optimal recovery program in a closed-loop supply chain. *European Journal of Operational Research, 249*(2), 605-617.

De Giovanni, P., & Zaccour, G. (2014). A two-period game of a closed-loop supply chain. *European Journal of Operational Research, 232*(1), 22-40.

Debo, L. G., Toktay, L. B., & Van Wassenhove, L. N. (2005). Market segmentation and product technology selection for remanufacturable products. *Management Science, 51*(8), 1193-1205.

Esenduran, G., E. Kemahlıoğlu-Ziya, J.M. Swaminathan. (2016). Take-Back Legislation: Consequences for Remanufacturing and Environment. *Decision Sciences. 47*(2), 219-256.

Gutowski, T. G., Sahni, S., Boustani, A., & Graves, S. C. (2011). Remanufacturing and energy savings. *Environmental Science & Technology, 45*(10), 4540-4547.

Jacobs, B. W., & Subramanian, R. (2012). Sharing responsibility for product recovery across the supply chain. *Production and Operations Management, 21*(1), 85-100.

Jørgensen, S., & Zaccour, G. (2003). Channel coordination over time: Incentive equilibria and credibility. *Journal of Economic Dynamics and Control, 27*(5), 801-822.

OECD. 2014. The State of Play on Extended Producer Responsibility (EPR): Opportunities and Challenges. OECD, Tokyo.

Pazoki, M., & Zaccour, G. (2019). A mechanism to promote product recovery and environmental performance. *European Journal of Operational Research, 274*(2), 601-614.

Raz, G., Ovchinnikov, A., & Blass, V. (2017). Economic, environmental, and social impact of remanufacturing in a competitive setting. *IEEE Transactions on Engineering Management, 64*(4), 476-490.

Tojo, N., Lindhqvist, T., & Davis, G. (2003). EPR programme implementation: Institutional and structural factors. Proceedings of OECD Seminar on EPR: EPR Programme Implementation and Assessment. Part 2: Assessing EPR Policies and Programmes.

Wang, W., Zhang, Y., Zhang, K., Bai, T., & Shang, J. (2015). Reward–penalty mechanism for closed-loop supply chains under responsibility-sharing and different power structures. *International Journal of Production Economics, 170*, 178-190.

Wang, W., Fan, L., Ma, P., Zhang, P., & Lu, Z. (2017). Reward-penalty mechanism in a closed-loop supply chain with sequential manufacturers' price competition. *Journal of Cleaner Production, 168*, 118-130.

Chapter 3

Dynamic Strategic Interactions between a Municipality and a Firm in the Presence of an Extended Producer Responsibility Regulation

Abstract

In this exploratory study, we consider an extended producer responsibility (EPR) regulation in the context where a firm can be penalized by a municipality for each uncollected unit of past sold products. A starting point is that the return rate of used products depends on the available infrastructure and environmental awareness of consumers. These two assets can be increased by investing in the infrastructure and in promoting the importance of returning the products instead of throwing them in the garbage. As environmental awareness and infrastructure can only be built through sustained investments over time, we retain a dynamic game model. The game feature is to account the strategic interactions between the manufacturer and the municipality. A feedback Stackelberg equilibrium is sought, with the municipality acting as leader and the manufacturer as follower. In particular, we look at the impact of the two key parameters of the model, namely, the penalty for not collecting a unit of product and its environmental damage cost, on the results.

Keywords: Extended Producer Responsibility; Environmental awareness; Collection Infrastructure; Dynamic Game; Stackelberg Equilibrium.

3.1 Introduction

Extended producer responsibility (EPR) is an environmental regulation requiring, roughly speaking, that firms implement programs to collect their past sold products and recover them. Examples of the product recovery options include, but not limited to, reusing, repairing and recycling. The regulation can take the form of a reward-penalty mechanism (Wang et al., 2015, 2017; Pazoki and Zaccour, 2019), or a constraint on minimum product recovery process(es) (Jacobs and Subramanian, 2012). For an EPR regulation to work, producers and public institutions, e.g., municipalities, need to develop an adequate infrastructure for collection and to engage in some green activities to raise consumer's environmental awareness and participation. One of the most important set of these green activities is holding information campaigns. In an analysis of the data for refillable bottles of wine and liquor, Lindhqvist (2000) finds that the amount of the refund, the convenience of returning a product, and the environmental awareness are the key factors of collection rate. In this exploratory research, we study strategic interactions between a municipality (local government) and a firm in the framework of an EPR-based regulation. The municipality is in charge of building the collection infrastructure and has the power of fining the firm for each uncollected unit. The firm can invest in green activities to raise environmental awareness and consequently the level of participation in its collection program.

A convenient access to collection and recycling programs is somehow a necessary condition for citizens' participation. To illustrate, although the percentage of households having access to at least one recycling program in Canada has increased from 74% in 1994 to 95% in 2007, still around 600,000 of the non-recycling households name lack of access to the programs as one of the main reasons for not recycling. Furthermore, 43% of non-recyclers stated that inconvenience was the most important barrier to recycle (Munro, 2007).

Environmental awareness plays an important role in the realization of the objectives of collection programs, even in the absence of financial incentives (Tojo et al., 2001). A survey conducted in Canada revealed that 82% of the recyclers are motivated by environmental responsibility (Munro, 2007). Promoting the sense of environmental responsibility in addition to informing the communities about the collection and recycling programs are done via information campaigns. An instance of such information campaigns is RBRC (Rechargeable Battery Recycling Corporation) in the US that has launched a public information campaign called *Charge Up to Recycle* program to increase the awareness of consumers about the existence of recycling programs for Ni-Cd batteries and its benefits (OECD, 2001). Similar program is also lunched to expand recycling of batteries in Canada. The literature in operations management and closed-loop supply chain has also considered the role of environmental awareness in the collection process. For instance, Savaskan and Van Wassenhove (2006) exclude financial incentive and concentrate solely on promotional activities as a tool to boost the collection rate. De Giovanni and Zaccour (2013) study the impact of cost-revenue sharing contract on profitability and return rate, with the latter being dependent on some green activities, e.g., communication about recycling programs and symbolic incentives. The same assumptions are made in De Giovanni and Zaccour (2014) to decide about who should take care of the collection of used products, i.e., the manufacturer, the retailer or a third party. Li et al. (2017) recognize the impact of environmental awareness on the collected quantities and suggest the coordination of the formal collection channel and the government to promote environmental awareness. Martinho et al. (2017) confirm the impact of environmental awareness on collection in Portugal. Finally, Expòsito and Velasco (2018) identify three regions in Spain with the highest Waste Management performance and associate their success with several regional plans including the environmental awareness programs funded by the Waste Management Funds.

In this paper, we retain the *collection infrastructure* and *environmental awareness* as the determinants of the return rate. These physical and mental capacities cannot be developed instantly, but require sustainable financial efforts over time. For this intuitive reason, we consider them as state (stock) variables whose evolution over time depends on the investments made by the municipality (in collection infrastructure) and the firm (in environmental awareness). To account for these dynamics and for strategic interactions, we adopt a parsimonious differential game model played over an infinite-planning horizon. The game is played à la Stackelberg with the municipality as leader, moving first by announcing its investment in collection infrastructure. Next, the follower (the producer[1]) reacts by choosing the product's price and investment in green activities. In terms of the dynamic interactions between the municipality and the firm, we seek to address the following questions:

> **Q1:** What are the equilibrium strategies in collection infrastructure and environmental awareness?
>
> **Q2:** How the equilibrium strategies and outcomes are affected by the two key parameters in the model, namely, the penalty for not collecting the used products and

[1]The terms "follower", "manufacturer", "firm' and "producer" are used interchangeably in this paper.

the environmental damage cost (disposition pollution)?

Moreover, the main purpose of such exploratory research is to obtain managerial insights about the possible strategies of the firm and the municipality in order to maximize their own objective functions, namely total profit and social welfare, respectively. Thus, our practical research questions are as follows:

Q3: Where the municipality and the producer are involved in boosting collection rate, is it in the best interest of the municipality to increase the penalty (tax)?

Q4: Where the municipality and the producer are involved in boosting collection rate, is it in the best interest of the producer to make a less polluting product?

The rest of this paper is organized as follows. In Section 3.2, the model is introduced. The Stackelberg equilibrium is characterized in Section 3.3. Section 3.4 discusses the impact of penalty and disposition pollution in the product through sensitivity analysis. Finally, the paper is summarized with presenting the most important insights in Section 3.5.

3.2 Model

We consider an infinite-horizon differential game with the players being a firm (player f) selling a unique product and a municipality (player m) in charge of enforcing collection of past-sold products when they reach their end of useful life. We assume that the demand $q(t)$ for the producer's product is linear and given by $q(t) = 1 - p(t)$, where $p(t)$ is the price at $t \in [0, \infty)$. A linear demand is common in the literature and its use has been typically justified by its tractability and the fact that it can be derived from consumer utility maximization.

When collection of past-sold products is not profitable to the producer, there is a need for some form of public intervention to avoid having these items ending in the landfill. We suppose that the municipality sets a penalty-based collection regulation that requires the producer to pay a constant fine k per unit of uncollected products. Similar versions of this regulation is often referred to as buy-back, take-back or buy-it-back in the literature. The penalty value for not taking back the product can be seen as a tax, where the producer gets a tax refund for the product it collects. We note that this regulation is a special case of the EPR-based regulation discussed in Pazoki and Zaccour (2019).

Returning the product to the producer or to a third party requires some effort from consumer, and (s)he will participate in a product-return program only if (s)he gets some monetary or non-monetary benefits. We focus on non-monetary motivation, namely, being environmentally responsible (BER). We suppose that the two main drivers of collection program's success are environmental awareness and collection infrastructure. Being informed about the merit of returning the product instead of throwing it in the garbage is a necessary condition for BER. Also, the better the collection infrastructures and the more spread they are, the higher the returns. Environmental awareness, denoted by $A(t)$, and return convenience (equivalent to developed collection infrastructure, as addressed before), denoted by $K(t)$, are the two state variables in the game.

Denote by $G(t)$ the green activities conducted at $t \in [0, \infty)$ by the firm to increase environmental awareness, e.g., advertising and communications campaigns about the firm's recycling policies. The cost of such activities is assumed to be convex increasing and taken quadratic for simplicity, that is, $C(G(t)) = c_G G^2(t)$. (This assumption is often made in the dynamic advertising literature, see the surveys in Haung et al. (2012) and Jørgensen and Zaccour (2014).) The evolution of $A(t)$ is governed by the following à la Nerlove-Arrow (Nerlove and Arrow, 1962) linear-differential equation:

$$\dot{A}(t) = G(t) - \psi A(t), \quad A(0) = A_0 > 0, \tag{3.1}$$

where $\psi > 0$ is the decay rate and A_0 is the initial value.

Let $I(t)$ be the efforts made by the municipality at time t to develop and improve collection infrastructure. These efforts include, but are not limited to, setting up new collection centers closer to populated areas, constructing and developing warehouses for collected products, product transportation, monitoring and controlling regularly all these activities, and all efforts associated with executing such development programs. The cost associated with these efforts is convex increasing function of efforts $c_I I^2(t)$. The dynamics of collection capacity is given by the following linear-differential equation:

$$\dot{K}(t) = I(t) - \nu K(t), \quad K(0) = K_0 > 0, \tag{3.2}$$

where ν is the decay rate and K_0 is the initial capacity.

Remark 5. *Here, putting more efforts to increase environmental awareness means investing more in activities such as holding information campaigns. Therefore, by proposing a dynamic strategy for the efforts put on increasing environmental awareness, we indirectly propose a dynamic investing strategy to increase environmental awareness. The same holds for increasing return convenience by putting efforts on developing collection infrastructure and increasing collection capacity. Since the assumed costs functions are strictly increasing in efforts, the terms putting more (less) efforts and investing more (less) are equivalent.*

As discussed before, it is imperative to have appropriate infrastructure that provides convenience to the customers who desire to bring back their used products. Furthermore, it is empirically shown that environmental awareness with convenient returning policies help achieving high collection rates (Tojo et al., 2001). Therefore, we define the collection rate as a linear function of return convenience and environmental awareness at time t, i.e.,

$$\tau(t) = t_A A(t) + t_K K(t), \tag{3.3}$$

such that return convenience and environmental awareness are complimentary in boosting the returns. The positive parameters t_A and t_K scale the impacts of return convenience and environmental awareness on collection rate, which must be in $[0,1]$.

Remark 6. *One may argue that without the infrastructure, a high level of environmental awareness of society cannot incite more, if not any, returns. While this statement is true, we need to be careful about distinguishing the investment in maintaining the collection infrastructure from the investment on developing the collection infrastructure with the goal of elevating convenient returns. For instance, there can be running collection facilities that make return possible. However, increasing the number of such facilities decreases the distance to the households and consequently elevates return convenience.*

Assuming profit maximization behavior, the firm's optimization problem is given by

$$\max_{p(t),G(t)} \Pi_f = \int_0^{\infty} e^{-\rho t}\Big((1-p(t))p(t) - c_G G^2(t) - k(1-p(t))(1-\tau(t))\Big)dt, \tag{3.4}$$

subject to : (3.1) and (3.2),

where $\rho \in (0,1)$ is the discount rate. The first term of the objective function of the producer is the revenue, the second term is the investment in green activities, and the third term is the penalty paid for uncollected products.

The municipality's optimization problem is as follows:

$$\max_{I(t)} \Pi_m = \Pi_f + \int_0^\infty e^{-\rho t}\Bigg(k(1-p(t))(1-\tau(t)) + \frac{(1-p(t))(1-p(t))}{2} - c_I I(t)^2 \\ - \varepsilon(1-\tau(t))(1-p(t))\Bigg)dt, \tag{3.5}$$

subject to : (3.1) and (3.2).

The first part of the social welfare function is the profit of the firm, the second part is the penalty received from the producer, the third term represents consumer surplus, and the fourth term is the cost of developing collection infrastructure to increase return convenience. Finally, the last term, that is, $\varepsilon(1-\tau(t))(1-p(t))$, where ε is a positive parameter, measures the environmental damage cost of product's unsafe disposition. ε represents the amount of toxic materials in the product that can damage the environment if the product is landfilled. That is the reason to use *disposition pollution* as an alternative term to refer to ε. For a more extensive discussion about the value of ε, also called “hazardous waste" in the literature, refer to Atasu et al. (2009).

To recapitulate, by (3.1), (3.2), (3.4) and (3.5), we have defined a two-player infinite-time horizon differential game, with two state variables (A and K) and three control variables, two for the firm (p,G) and one for the municipality (I). The game is played à la Stackelberg with the municipality, as leader, moves first and announces its investment in collection infrastructure. Next, the follower (the producer) reacts by choosing the product's price and investment in elevating environmental awareness. We consider a stationary feedback information structure, that is, the strategies are state-dependant and time-invariant, which is reminiscent to the autonomous nature of the game. Unless it causes an ambiguity, we omit from now on the time argument. Table 3.1 collects the notations used in the paper.

Table 3.1 – Dependent and independent variables under study

Parameters	Description
ε	Monetary value of product disposition's environmental impact
k	Penalty per unit of uncollected product
A	Environmental awareness (state variable)
K	Return convenience (collection infrastructure development, state variable)
G	Effort level to increase environmental awareness
I	Effort level to increase return convenience (collection capacity)
$c_j,\ j \in \{I, G\}$	Coefficients to transform green efforts into costs
$t_j,\ j \in \{A, K\}$	Coefficients to transform green efforts into collection rate
Π_f	Firm's profit
Π_s	Social welfare
τ	Collection rate
p	Price
ψ	Decay rate of environmental awareness
ν	Decay rate of return convenience
t	Time index
ρ	Discount factor

3.3 Equilibrium

In this section, we characterize the feedback Stackelberg equilibrium strategies and outcomes. We start by solving the follower's problem to determine its reaction functions to the investment strategy announced by the leader. The Hamilton-Jacobi-Bellman (HJB) equation of the firm is given by

$$\rho V_f(A,K) = \max_{p,G} \Big\{ (1-p)p - c_G G^2 - k(1-p)(1-t_A A - t_K K) + \frac{\partial V_f(A,K)}{\partial A}(G-\psi A) + \frac{\partial V_f(A,K)}{\partial K}(I-\nu K) \Big\}, \tag{3.6}$$

where V_f is the value function.

Differentiating the right-hand side of the HJB and equating it to zero, we obtain the following firm's reaction functions:

$$p(A,K) = \frac{1+k(1-t_A A - t_K K)}{2}, \tag{3.7}$$

$$G(A,K) = \frac{1}{2c_G}\frac{\partial V_f(A,K)}{\partial A}. \tag{3.8}$$

Few comments can be made regarding these reaction functions. First, the price, which can be rewritten as $\frac{1+k(1-\tau(t))}{2}$, is decreasing both in environmental awareness and in the return convenience, or synonymously in the collection rate. The reason is that when either of these variables increases, the penalty, which is a cost to the producer, is lower, and so is the price. Similarly, for the same reason, the higher the efficiency parameter t_A (respectively t_K) is, the lower is the price. Second, in the absence of an EPR regulation (i.e. when $k=0$), the firm's price is $1/2$, which is the constant monopoly price. Finally, the green activities level is determined by the familiar rule of equating the marginal cost, given by $2c_G G(A,K)$ to its marginal revenue, given by $\frac{\partial V_f}{\partial A}$.

Next, we turn to the leader's problem. The HJB equation of the municipality is given by

$$\begin{aligned}\rho V_m(A,K) = \max_I \Big\{ &(1-p)p - c_G G^2 - c_I I^2 - \frac{(1-p)^2}{2} - \varepsilon(1-t_A A - t_K K)(1-p) \\ &+ \frac{\partial V_m(A,K)}{\partial A}(G-\psi A) + \frac{\partial V_m(A,K)}{\partial K}(I-\nu K)\Big\},\end{aligned} \tag{3.9}$$

where V_m is its value function. Substituting for the follower's reaction functions, the above equation becomes

$$\begin{aligned}\rho V_m(A,K) = \max_I \Big\{ &\left(\frac{3+(k-4\varepsilon)(1-t_A A - t_K K)}{4}\right)\left(\frac{1-k(1-t_A A - t_K K)}{2}\right) \\ &- \frac{1}{4c_G}\left(\frac{\partial V_f}{\partial A}\right)^2 - c_I I^2 + \frac{\partial V_m}{\partial A}\left(\frac{1}{2c_G}\frac{\partial V_f}{\partial A} - \psi A\right) + \frac{\partial V_m}{\partial K}(I-\nu K)\Big\}.\end{aligned} \tag{3.10}$$

Differentiating the right-hand side with respect to I and equating it to zero yields the following optimal decision:

$$I = \frac{1}{2c_I}\frac{\partial V_m}{\partial K}. \tag{3.11}$$

The interpretation is straightforward, i.e., the investment level is chosen such that the marginal cost ($2c_I I$) is equal to the marginal value $\left(\frac{\partial V_m}{\partial K}\right)$.

Given the linear-quadratic structure of the differential game, we make the informed guess that their value functions are quadratic and given by

$$V_m(A,K) = \frac{1}{2}m_1 K^2 + \frac{1}{2}m_2 A^2 + m_3 AK + m_4 K + m_5 A + m_6, \tag{3.12}$$

and

$$V_f(A,K) = \frac{1}{2}f_1 K^2 + \frac{1}{2}f_2 A^2 + f_3 AK + f_4 K + f_5 A + f_6, \tag{3.13}$$

where $m_1,\ldots,m_6$ and $f_1,\ldots,f_6$ are coefficients to be determined. Substituting for V_f and V_m in Equations (3.8) and (3.11), we obtain

$$I = \frac{1}{2c_I}\left(m_1 K + m_3 A + m_4\right), \tag{3.14}$$

$$G = \frac{1}{2c_G}(f_2 A + f_3 K + f_5). \tag{3.15}$$

To find f_1 to f_6 and m_1 to m_6, we apply the undetermined coefficients method (see Haurie et al. (2012)) to compute the 12 coefficients associated to the value functions. The 12 corresponding equations are given in Appendix 3.6. Clearly, this system cannot be solved analytically, and therefore, we proceed numerically.

3.4 Impact of penalty and damage cost

To illustrate the type of insight that can be obtained from our model, first we provide a numerical example. Our model has nine parameters, that is,

Collection rate function parameters	:	t_K, t_A,
Investment cost function parameters	:	c_G, c_I,
Decay rates	:	ψ, ν,
Discount rate	:	ρ,
Environmental damage cost	:	ε,
Penalty per unit of uncollected products	:	k,
Initial state values	:	$A(0), K(0)$.

We arbitrarily set the numerical values as follows:

Table 3.2 – Parameter values for the numerical example

Parameter	t_K	t_A	c_G	c_I	ρ	ψ	ν	ε	k	$A(0)$	$K(0)$
Value	0.5	0.5	1	1	0.05	0.2	0.2	0.2	0.2	0.1	0.1

Solving numerically the 12 equations given in Appendix 3.6 results in 20 sets of solutions, 8 of which are real-valued, and among these 8 sets, only one of them returns the steady-state trajectories. These coefficients are reported in Table 3.3.

Table 3.3 – Value function coefficients in the numerical example

V_m coefficients	m_1	m_2	m_3	m_4	m_5	m_6
	0.0173	0.0173	0.0173	0.2569	0.2569	5.4273
V_f coefficients	f_1	f_2	f_3	f_4	f_5	f_6
	0.0117	0.0117	0.0117	0.1762	0.1762	3.808

The coefficient values reported in Table 3.3 yields:

$$I(t) = 0.0086A(t) + 0.0086K(t) + 0.1284, \tag{3.16}$$

$$G(t) = 0.0058A(t) + 0.0058K(t) + 0.0881. \tag{3.17}$$

Equations (3.16) and (3.17) imply that higher levels of environmental awareness and return convenience encourage the producer and the municipality to put more efforts on increasing environmental awareness and developing collection infrastructures. Substituting (3.16) and (3.17) in (3.1) and (3.2), yields:

$$\dot{K}(t) = 0.0086A(t) - 0.1913K(t) + 0.1284, \tag{3.18}$$

$$\dot{A}(t) = -0.1941A(t) + 0.0058K(t) + 0.0881, \tag{3.19}$$

and solving the system of ordinary linear differential equations (3.18) and (3.19) leads to:

$$A(t) = 0.4784 + J_1 e^{-0.2t} + J_2 e^{-0.1855t}, \tag{3.20}$$

$$K(t) = 0.6927 + 1.4766 J_2 e^{-0.1855t} - J_1 e^{-0.2t}. \tag{3.21}$$

Solving Equations (3.20) and (3.21) for $t = 0$ yields $J_1 = 0.0158$ and $J_2 = -0.3906$, and the steady-state values would be $A_{ss} = 0.4748$ and $K_{ss} = 0.6926$. These state trajectories along with the other dependent parameters are depicted in Figure 3.1.

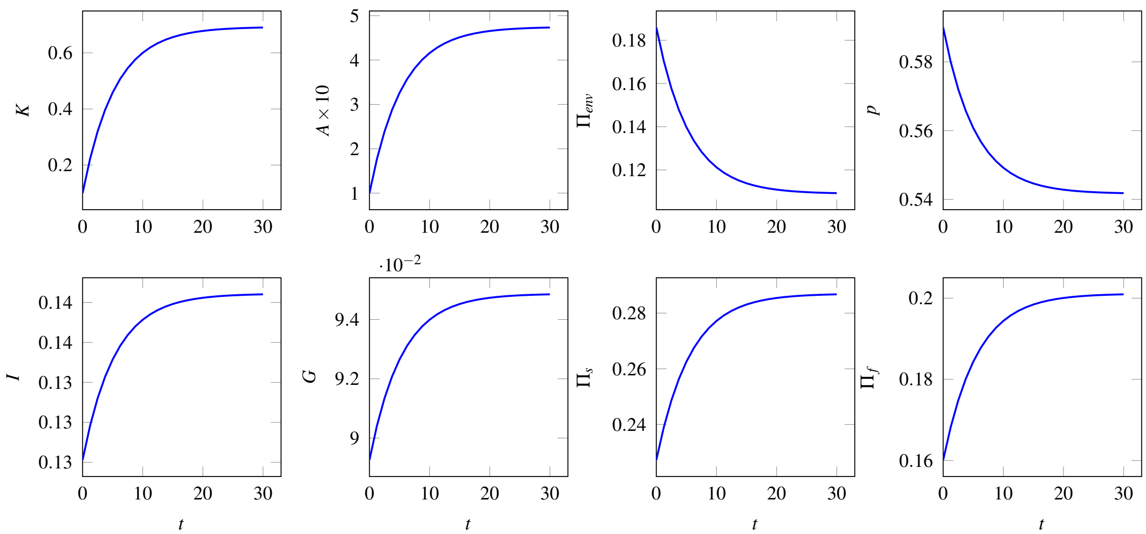


Figure 3.1 – State trajectories and dependent parameters for the numerical example

As the time passes, both producer and municipality invest more on raising environmental awareness and developing collection infrastructure, and consequently return convenience and environmental awareness go up. Furthermore, higher return convenience and environmental awareness lead to higher collection rate and consequently less penalty for the firm. Lower penalty, then, means lower cost for the producer and lower prices are resulted. As the price goes down, the demand increases, and this means more products to dispose. Even though a higher collection rate means a lower proportion of the products are disposed, since the decline in the uncollected products rate $(1-\tau)$ is more than the increase in quantity demanded, the overall environmental impact decreases. Lower prices lead to higher producer's profit and consumer surplus, and together with lower environmental impact, result in higher social welfare.

Although all parameters do have an impact on the equilibrium strategies and outcomes, we believe that the two most important ones in our context are the environmental damage cost ε, and the penalty per unit of uncollected products k. These parameters are determined before starting the game, and they possess strategic values; ε, is determined at the product design stage when the materials to be used in the product are decided, and k is the penalty parameter decided by the municipality at time zero. To assess the impact of ε and k, we keep the other parameter values as given in Table 3.2.

To start with, we set $\varepsilon = 0.1$ and let k vary from 0.05 to 0.3 by 0.05 steps. Next, we increase ε to 0.2 and vary k again as in the previous case. This way, not only we numerically investigate the impact of k on the equilibria, but also we examine the existence correlation between k and ε. Next, we set $k = 0.1$ and let ε vary from 0.05 to 0.3 by steps of 0.05. Finally, we increase k to 0.2 and vary k again as in the previous case for the same addressed reason. When solving for each of the instances, we get multiple solutions for the system of 12 equations. Excluding complex solutions and those not converging to a steady states reduces the number of solutions from 20 to 1. Finally, in each case that one solution yields positive values for investments, price and demand.

Figure 3.2 illustrates the impact of penalty on the market equilibria, and it will be used for providing the municipality with guidelines to increase social welfare.

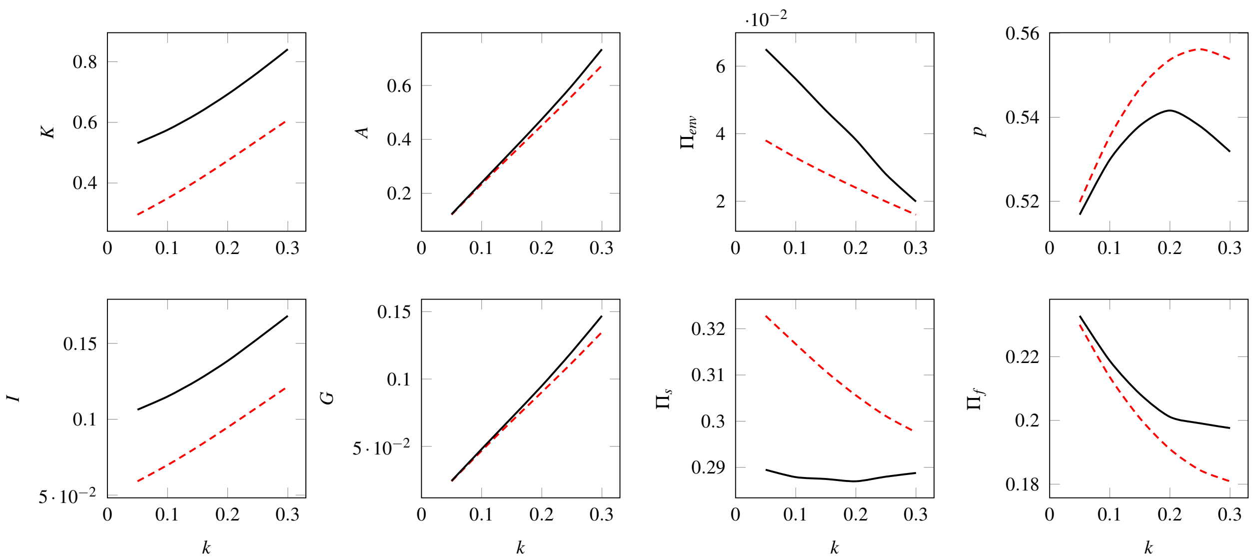


Figure 3.2 – Comparing state trajectories and dependent variables for two values of ε while modifying k. Each line represents a penalty value. $\varepsilon = 0.1$: (- - -) , $\varepsilon = 0.2$: (——)

Figure 3.2 illustrates the impact of penalty on the control and state variables as well as on other market outcomes. Four important observations can be made from Figure 3.2. First, a higher penalty leads to higher investments by both players and consequently higher environmental awareness and return convenience. The reason is that the higher the penalty, the higher the firm's cost and the price, which hurts profits and consumer's surplus. By increasing the investments in collection infrastructure and environmental awareness, the return rate increases, which reduces the tax burden for not collecting. Second, the impact of k on the price is non-monotone. Increasing a low value of k hurts demand, through the additional cost and higher price. When k is already high, increasing it further leads to lower prices. The reason for this unexpected outcome is that a higher k leads to higher investments in collection infrastructure and environmental awareness, which in turn leads to higher return rate and less penalty to pay. This reduces the manufacturer's cost and lowers its price. Third, comparing the two curves obtained for two different values of ε

reveals a positive correlation between k and ε, confirming that the penalty value should be set according to the disposition pollution. Therefore, any product requires its own value of penalty if not collected. Finally, we see that for any given k, a higher ε leads to higher investment in infrastructure, but has almost no impact on the investment in awareness. This can be explain by the fact that ε does not affect, at least directly, the manufacturer's payoff. Therefore, the manufacturer changes the product's design and includes more hazardous materials in order to force the municipality to invest more on collection infrastructures. This way, the manufacturer free rides on the high collection rate resulted from high investments in collection infrastructure to decrease its own price. The higher is k, the lower the manufacturer profits from increasing ε, and the less negative effect it will have on social welfare and environmental impact.

We proceed by investigating the impact of ε on market equilibria. Although valuable insights are obtained from Figure 3.2 by comparing the curves, Figure 3.3 is presented to give more details about the impact of hazardous materials in the product.

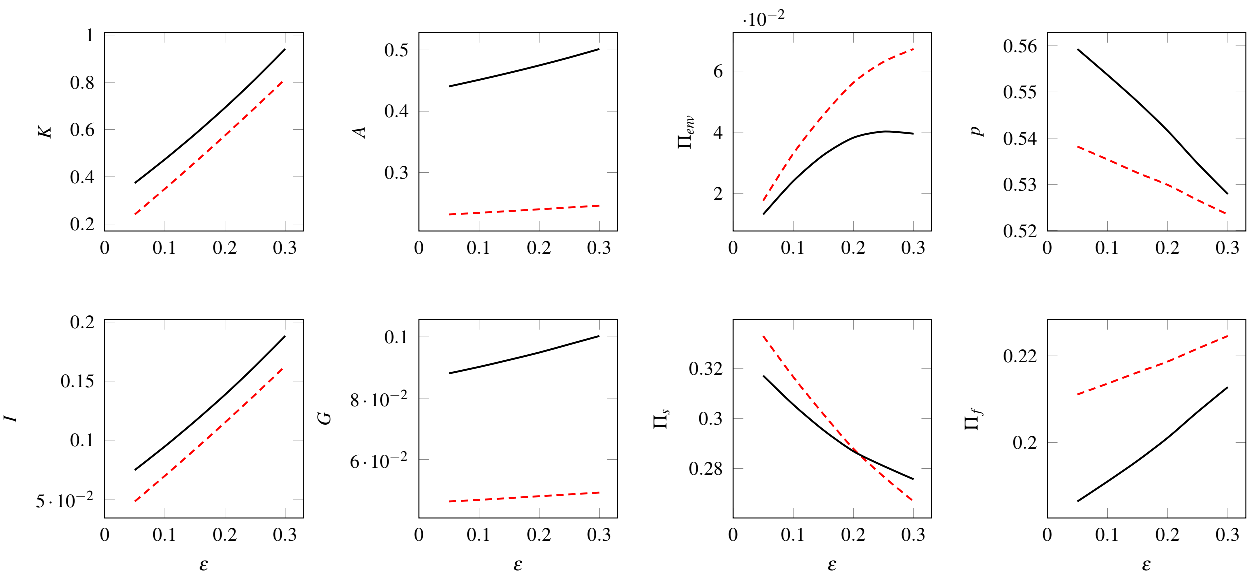


Figure 3.3 – Comparing state trajectories and dependent variables for two values of k while modifying ε. Each line represents a penalty value. $k = 0.1$: (red dashed line), $k = 0.2$: (black solid line)

For higher levels of disposition pollution (ε), the municipality invests more in collection infrastructure and consequently collection rate is driven up. It can be observed that the increase in G is negligible comparing to the increase in I, confirming the comment made for Figure 3.2 about the municipality being exploited by the manufacturer. A lower price caused by higher collection rate and lower paid penalty pushes up the manufacturer's profit and consumer surplus. Therefore, the manufacturer is better off with increasing the amount of toxic materials in the product, given a fixed penalty. However, since social welfare decreases as the result of higher disposition pollution, the municipality can increase the penalty to slow down the reduction in social welfare. This decision can be interpreted from Π_s vs. ε curve in Figure 3.3 where the municipality increases the penalty from 0.1 to 0.2 if ε passes 0.2. By this change in the regulation, negative environmental impact and manufacturer's profit drop. Therefore, it is not in the best interest of the manufacturer to increase ε beyond 0.2 if it is already below that value. Thus, although we have not included ε and k as the decision variables, based on the conducted sensitivity analysis it can be concluded the market equilibrium for ε is not at extreme points.

The next section sums up the research conducted in this paper and important conclusions.

3.5 Conclusion

We considered a two-player differential game in the context of an extended producer responsibility regulation. The municipality has the legislative power to tax the manufacturer for each unit of past sold products which is not collected. The manufacturer invests on raising environmental awareness via information campaigns, and the municipality tries to develop collection infrastructure to provide a more convenient return for the community.

Determining the feedback-Stackelberg equilibrium required solving a system of 12 equations that are highly coupled. As such system does not admit an analytical solution, we solved it numerically and illustrate the results in few instances. We also looked at the impact of varying the two main parameters, namely k and ε, on the market equilibrium strategies and objective functions.

We could prove that higher environmental awareness and return convenience result in a lower price. Since the regulation is a penalizing one based on collected quantity, a lower price means a higher profit for the producer. Therefore, the producer always benefits from higher environmental awareness and collection convenience.

Research question Q1 is addressed in Section 3.3. Based on the observations made from the conducted sensitivity analysis, we address research questions 2 to 4.

> **Q2:** *How the equilibrium strategies and outcomes are affected by the two key parameters in the model, namely, the penalty for uncollected products and the envi-*

ronmental damage cost? A higher penalty and environmental damage cost result in more investments in collection infrastructure and environmental awareness. A higher penalty yields lower environmental impact, and a higher environmental damage cost leads to a lower price and consequently higher consumer surplus and firm's profit, given that the penalty does not change.

Q3: *Where the municipality and the producer are involved in boosting collection rate, is it in the best interest of the municipality to increase the penalty (tax)?* If the amount of toxic materials in the product increases, it can be the case. However, for low values of disposition pollution (lower than certain threshold) the municipality decreases the penalty to increase social welfare.

Q4 *Where the municipality and the producer are involved in boosting collection rate, is it in the best interest of the producer to make a less polluting – greener – product?* The manufacturer always benefits from a product with more toxic materials. It would shift to a greener product only if a drop in the penalty value is anticipated on condition that the manufacturer reduces the disposition pollution below a certain level.

This exploratory study concentrated on participating in green activities under costly collection. If the product contains valuable materials, the producer may benefit from collection, and practices it even without the force of regulation. Furthermore, the other product recovery options such as remanufacturing might significantly change the suggested policies, as on the one hand it brings an opportunity to expand the market by selling less expensive products to the price-sensitive segment of the market, and on the other hand it may cannibalize the sale of the new products. Therefore, considering a variety of product recovery options is an interesting direction to expand this research. Another extension is to consider the case where the penalty is not a given parameter but a control variable of the municipality.

3.6 Appendices

To find the coefficients of the value functions, 12 equations must be solved to find the values of coefficients by identification. Assuming value functions (3.12) and (3.13) for the producer and municipality, the set of equations to solve would be:

$$\rho f_1 = \frac{k^2 t_K^2}{2} + \frac{f_3^2}{2c_G} + 2f_1\left(\frac{m_1}{2c_I} - \nu\right)$$

$$\rho f_2 = \frac{k_2 t_A^2}{2} - \frac{f_2}{2c_G} + \frac{m_3 f_3}{c_I} + 2f_2\left(\frac{f_2}{2c_G} - \nu\right)$$

$$\rho f_3 = \frac{k^2 t_K t_I}{2} + \frac{f_1 m_3}{2c_I} + f_3\left(\frac{m_1}{2c_I} + \frac{f_2}{2c_G} - \nu - \psi\right)$$

$$\rho f_4 = kt_K - \frac{k^2 t_K}{2} + \frac{f_1 m_4}{2c_I} + \frac{f_3 f_5}{2c_G} + f_4\left(\frac{m_1}{2c_I} - \nu\right)$$

$$\rho f_5 = kt_A - \frac{k^2 t_A}{2} + \frac{f_3 m_4}{2c_I} + \frac{f_5 m_3}{2c_I} + f_5\left(\frac{f_2}{2c_G} - \psi\right)$$

$$\rho f_6 = \frac{(1-k)^2}{4} + \frac{f_5}{4c_G} + \frac{f_4 m_4}{2c_I}$$

$$\rho m_1 = -\frac{k^2 t_K^2}{4} + \varepsilon k t_K^2 - \frac{f_2^2}{2c_G} + \frac{m_1^2}{2c_I} + \frac{f_3 m_3}{c_G} + 2m_1\left(\frac{m_1}{2c_I} - \nu\right)$$

$$\rho m_2 = -\frac{k^2 t_A^2}{4} + \varepsilon k t_A^2 - \frac{f_2^2}{2c_G} + \frac{m_3^2}{2c_I} + 2m_2\left(\frac{f_2}{2c_G} - \psi\right)$$

$$\rho m_3 = \varepsilon k t_A t_K - \frac{k^2 t_A t_K}{4} - \frac{f_2 f_3}{2c_G} + \frac{f_3 m_2}{2c_G} + m_3\left(\frac{m_1}{2c_I} + \frac{f_2}{2c_G} - \nu - \psi\right)$$

$$\rho m_4 = \frac{kt_K(1+k)}{4} + \frac{\varepsilon t_K(1-k)}{4} - \frac{\varepsilon k t_K}{2} - \frac{f_3 f_5}{2c_G} + \frac{f_5 m_3}{2c_G} + \frac{f_3 m_5}{2c_G} + m_4\left(\frac{m_1}{2c_I} - \nu\right)$$

$$\rho m_5 = \frac{kt_A(1+k)}{4} + \frac{\varepsilon t_A(1-k)}{2} - \frac{\varepsilon k t_A}{2} - \frac{f_2 f_5}{2c_G} + \frac{m_3 m_4}{2c_I} + \frac{f_5 m_2}{2c_G} + m_5\left(\frac{f_2}{2c_G} - \psi\right)$$

$$\rho m_6 = -\frac{\varepsilon(1-k)}{2} + \frac{3}{4}(1-k^2) - \frac{f_5^2}{4c_G} + \frac{m_4^2}{4c_I} + \frac{f_5 m_5}{2c_G}$$

Bibliography

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

De Giovanni, P., & Zaccour, G. (2013). Cost-Revenue Sharing in a Closed-Loop Supply Chain. *Annals of the International Society of Dynamic Games*, 12, 395-421, Birkhäuser, Boston, MA.

De Giovanni, P. & G. Zaccour. (2014). A two-period game of a closed-loop supply chain. *European Journal of Operational Research*, 232(1), 22-40.

Expòsito, A., & Velasco, F. (2018). Municipal solid-waste recycling market and the European 2020 Horizon Strategy: A regional efficiency analysis in Spain. *Journal of Cleaner Production*, 172, 938-948.

Jacobs, B. W., & Subramanian, R. (2012). Sharing responsibility for product recovery across the supply chain. *Production and Operations Management, 21*(1), 85-100.

Jørgensen, S., & Zaccour, G. (2014). A survey of game-theoretic models of cooperative advertising. *European Journal of Operational Research, 237*(1), 1-14.

Huang, J., Leng, M., & Liang, L. (2012). Recent developments in dynamic advertising research. *European Journal of Operational Research, 220*(3), 591-609.

Haurie, A., Krawczyk, J. B., & Zaccour, G. (2012). *Games and dynamic games (Vol. 1)*. World Scientific Publishing Company.

Li, Y., Xu, F., & Zhao, X. (2017). Governance mechanisms of dual-channel reverse supply chains with informal collection channel. *Journal of cleaner production*, 155, 125-140.

Lindhqvist, T. (2000). Extended Producer Responsibility in Cleaner Production. IIIEE Dissertations 2000:2. Lund: IIIEE, Lund University.

Martinho, G., Magalhães, D., & Pires, A. (2017). Consumer behavior with respect to the consumption and recycling of smartphones and tablets: An exploratory study in Portugal. *Journal of Cleaner Production*, 156, 147-158.

Munro, A. (2007) Recycling by Canadian Households. Catalogue no. 16-001-M, no. 13, Statistics Canada. Available at http://www.statcan.gc.ca/pub/16-001-m/2010013/part-partie1-eng.htm, [Verified 15 April 2018].

Nerlove, M., & Arrow, K. J. (1962). Optimal advertising policy under dynamic conditions. *Economica,* 129-142.

OECD (2001), Extended Producer Responsibility: A Guidance Manual for Governments, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264189867-en. [Verified 15 April 2018].

Pazoki, M., & Zaccour, G. (2019). A mechanism to promote product recovery and environmental performance. *European Journal of Operational Research, 274*(2), 601-614.

Savaskan, R. C., & Van Wassenhove, L. N. (2006). Reverse channel design: the case of competing retailers. *Management Science*, 52(1), 1-14.

Tojo, N., Lindhqvist, T., & Davis, G.A., EPR Programme Implementation: Institutional and Structural Factors. OECD Seminar on Extended Producer Responsibility, 13-14 December, 2001, OECD Headquarters, Paris, France.

Wang, W., Zhang, Y., Zhang, K., Bai, T., & Shang, J. (2015). Reward–penalty mechanism for closed-loop supply chains under responsibility-sharing and different power structures. *International Journal of Production Economics, 170*, 178-190.

Wang, W., Fan, L., Ma, P., Zhang, P., & Lu, Z. (2017). Reward-penalty mechanism in a closed-loop supply chain with sequential manufacturers' price competition. *Journal of Cleaner Production, 168*, 118-130.

General Conclusion

Production activities have environmental consequences, which is also called pollution. To reduce or omit production-caused pollution, environmental regulations have been in place. Extended Producer Responsibility (EPR) is a regulating concept seeking to partially or wholly hold the producer responsible to reduce the pollution resulted from its production process. Depending on the product, the market, and their structure, these regulations have different impacts on pollution and also on the financial outcome of production for the producer and for the consumers. In this thesis, we concentrate on the environmental regulations, designed based on EPR approach for the products which are recyclable, probably remanufacturable, and relatively have short life cycle. The activities that reduce the production-caused pollution, then, are to collect the products for recycling or remanufacturing, and they are to be done mainly by the producer.

In this thesis, composed of three essays, design and implementation of EPR-based environmental regulations are discussed. We specifically consider the markets where new and remanufactured products co-exist (essays one and two), and then try to promote environmental performance of the environmental regulations as well as commenting on their social welfare implications.

In the first paper which is titled "*A Mechanism to Promote Product Recovery and Environmental Performance*", we find the underlying concept of various EPR-based environmental regulation and then try to use it as a decision support system (i) to design new regulations, and (ii) to compare different regulations in a single framework. The market consists of a manufacturing entity and a regulator. The manufacturing entity may represent a producing company or a centralized supply chain. The producer manufactures new products in the first period, and then collects the used products, remanufactures them, and sells them to the market in the second (future) period as substitutes of the new products. The regulator imposes the environmental regulation and assesses its environmental performance.

The main finding of the first research is that a performance-based mechanism with collection and remanufacturing target rates is the underlying concept of many seemingly different environmental regulations. The addressed performance-based mechanism consists of target rates for collection and remanufacturing, and coefficients that measure the differences between the target rates and the achieved rates, and then reward or penalize the manufacturing entity, accordingly. The importance of this finding is two-fold. Firstly, assigning certain values to the target rates and coefficients, a wide range of existing environmental regulations can be imitated. Shifting from one regulation to another by modifying one or more parameters (target rates and associated coefficients), the regulator understands the relation between these regulation, and consequently which one to choose to achieve a better performance of a specific goal. Secondly, this research provides the regulator with an opportunity to try designing new regulations which can be more effective and easier to control. Finally, in this paper we prove that the availability of products to collect and remanufacture, or the number of products which are produced before lunching the regulation, may change the way the environmental regulation affects the environmental performance, concluding that the actions of the manufacturing entity before implementing the regulation must be taken into consideration.

This research is based on a number of assumptions whose relaxations may significantly change the conclusions. Firstly, we assumed that the collected products are remanufactured and sold as a substitute product. This may not always be the case as some manufacturers may use the parts in the collected products in producing brand new products, and then sell them as new products. It means that product collection reduces the production cost of the new product without cannibalizing the sales. This way, the manufacturer may produce more in order to reduce production cost in the future, which might not be environmentally desirable. Secondly, based on the statistical analysis presented in the literature, it is assumed that the remanufactured products as the greener version of the brand new products are attractive to a small proportion of the potential consumers. If it is not the case for a specific product in a specific market, cannibalization effect would be intensified and consequently higher rewards for remanufacturing are required to encourage it. However, if these rewards are too high, the manufacturer produces more to benefit from future rewards. Therefore, obtaining an appropriate value for the rewards (penalties) of remanufacturing would become more important to avoid unwanted environmental consequences.

The second essay is titled:"*Extended Producer Responsibility: Regulation Design and Responsibility Sharing Policies for a Supply Chain*". In the first paper, we discussed the design of a regulation assuming that the producer is the manufacturer or a centralized supply chain. However, the definition of producer in EPR differs from a region to another. This paper deals with this matter by analyzing and comparing different ways of defining *producer*. In other words, we put one step beyond what is done in the first essay by defining several scenarios based on how the responsibilities imposed by the environmental regulation should be distributed among the members of a supply chain. Responsibilities are defined in two categories: physical and financial. Physical responsibilities refers to collecting and remanufacturing the used products. By financial responsibility, we mean dealing with the environmental regulation in the financial form which is imposed on the supply chain (i.e. paying the penalties or receiving the rewards).

To address the research question which is the definition of producer in a decentralized supply chain, we consider a supply chain consisting of a manufacturer and a retailer, where new and remanufactured products are produced and sold, with the remanufactured product as an inferior substitute of the brand new product. Based on who is financially responsible for meeting the target rates of product recovery, and who is responsible for collecting the products, 4 scenarios are defined. Firstly, it is proven that allocating responsibilities and designing the regulation must be done simultaneously. Putting differently, one cannot prescribe a specific environmental regulation without knowing who is responsible for what in a supply chain, and also it is not effective to define the producer disregarding the imposed environmental regulation. Secondly, it is shown that holding the retailer fully responsible for collection yields the highest collection rate. Finally, analyzing the data from three different electronic products reveals that the type of responsibility sharing policy is as important as the type of the products in assessing the impact of target rates on environmental performance.

What is concentrated on in the second paper is the vertical competition between the manufacturer and a distributor. In many cases, an independent remanufacturer (IR) enters the market and changes the equilibrium. How the equilibrium changes depends on who is allowed to collect the products, how the regulator decides to handle the IR, and what happens if the IR is allowed to collect the product while deterring the retailer and the manufacturer to meet the targets. Furthermore, it may not always be the case that the remanufactured products are absolutely inferior to the brand new products (please see the first article). Existing a horizontal competition together with semi-substitutable remanufactured version of the product which is always cheaper than a the brand new one may shift production toward more new or remanufactured version, and therefore the environmental regulation and allocation of responsibilities should be adjusted accordingly.

The title of the third essay is: "*Dynamic Strategic Interactions between a Municipal-*

ity and a Firm in the Presence of an Extended Producer Responsibility Regulation". The main idea of an EPR approach to design environmental regulation is to shift the burden of product recovery partially or wholly from the municipalities to producers. If the producers do not have the knowledge and infrastructure to satisfy regulation requirements, it is up to the municipality to act with the aim of increasing social welfare or decreasing environmental impact. For this purpose, first, we extract the most effective factors of collection program success from the literature, and then try to use them to devise a dynamic policy for the municipality and the producer to optimize social welfare and profit, respectively. The producer invests in information campaigns and similar activities to raise community's environmental awareness, which in turns leads to higher collection rate. The municipality invests in developing the collection infrastructure and its capacity in the way that return convenience for the community is improved. The relationship between the producer and the social welfare maximizing municipality is modelled as a feedback Stackelberg game where the dynamic pricing and investing policies depend on two state variables: environmental awareness and return convenience. Through sensitivity analysis it is observed that the producer may use a higher product's disposition pollution as a lever to invite more investment from the municipality in collection infrastructure, so that the collection rate increases and it pays less penalty. The municipality, in return, might increase the penalty to improve social welfare, if disposition pollution is higher than a certain threshold. However, if disposition pollution is dropped by the producer below that threshold, the regulator is better off reducing the penalty and this way the producer's profit jump. Furthermore, the conducted sensitivity analysis confirms correlation between the amount of toxic materials in the product (disposition pollution) and the penalty value, suggesting that the penalty (or tax) should be set according to the product itself and therefore proposing a single regulation for a wide variety of products is not efficient.

In the third paper, despite the first two papers, the economic opportunity of product recovery is neglected. If the remanufactured products are available and profitable, or if recycling the collected products has positive financial returns, the producer would invest more on promoting environmental awareness to benefit from remanufacturing profit, and consequently the equilibrium investing policies change. Although considering this assumption adds to mathematical complexity of the problem, a thorough numerical analysis can be used to address this scenario.

Bibliography

Abbey, J.D., Blackburn, J.D. & Guide, V.D.R. (2015). Optimal pricing for new and remanufactured products. *Journal of Operations Management, 36*, 130-146.

Abbey, J. D., Kleber, R., Souza, G. C., & Voigt, G. (2017). The role of perceived quality risk in pricing remanufactured products. *Production and Operations Management, 26*(1), 100-115.

Assavapokee, T., & Wongthatsanekorn, W. (2012). Reverse production system infrastructure design for electronic products in the state of Texas. *Computers & Industrial Engineering, 62*(1), 129-140.

Atasu, A., Sarvary, M., & Van Wassenhove, L.N. (2008). Remanufacturing as a Marketing Strategy. *Management Science, 54*(10), 1731-1746.

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

Bernard, S. (2011). Remanufacturing. *Journal of Environmental Economics and Management, 62*(3), 337-351.

Bulmuş, S. C., Zhu, S. X., & Teunter, R. H. (2014). Optimal core acquisition and pricing strategies for hybrid manufacturing and remanufacturing systems. *International Journal of Production Research, 52*(22), 6627-6641.

Chen, J. X., & Chen, J. (2017). Supply chain carbon footprinting and responsibility allocation under emission regulations. *Journal of Environmental Management, 188*, 255-267.

Chen, D., Demirbag, M., Ignatius, J., Marra, M., Sun, D., Zhan, S., & Zhou, C. (2018). Reverse logistics pricing strategy for a green supply chain: A view of customers' environmental awareness. *International Journal of Production Economics*, *Article in Press*, https://doi.org/10.1016/j.ijpe.2018.08.031.

Cheng, J., Li, B., Gong, B., Cheng, M., & Xu, L. (2017). The optimal power structure of environmental protection responsibilities transfer in remanufacturing supply chain. *Journal of Cleaner Production, 153*, 558-569.

De Giovanni, P. (2011). Quality improvement vs. advertising support: which strategy works better for a manufacturer?. *European Journal of Operational Research, 208*(2), 119-130.

De Giovanni, P., & Zaccour, G. (2013). Cost–Revenue Sharing in a Closed-Loop Supply Chain. In Advances in Dynamic Games (pp. 395-421). Birkhäuser, Boston, MA.

De Giovanni, P., & Zaccour, G. (2014). A two-period game of a closed-loop supply chain. *European Journal of Operational Research, 232*(1), 22-40.

De Giovanni, P., Reddy, P. V., & Zaccour, G. (2016). Incentive strategies for an optimal recovery program in a closed-loop supply chain. *European Journal of Operational Research, 249*(2), 605-617.

Debo, L. G., Toktay, L. B., & Van Wassenhove, L. N. (2005). Market segmentation and product technology selection for remanufacturable products. *Management Science, 51*(8), 1193-1205.

Dewis, G., & Van Wesenbeeck, P. (2016) Trash talking: Dealing with Canadian household e-waste. Catalogue no. 16-002-, Statistics Canada, Available at http://www.statcan.gc.ca/pub/16-002-x/2016001/article/14570-eng.htm, [Verified 15 April 2018].

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

Esenduran, G., E. Kemahlıoğlu-Ziya, J.M. Swaminathan. (2016). Take-Back Legislation: Consequences for Remanufacturing and Environment. *Decision Sciences. 47*(2), 219-256.

Esenduran, G., Kemahlıoğlu-Ziya, E., & Swaminathan, J.M. (2017). Impact of Take-Back Regulation on the Remanufacturing Industry. *Production and Operations Management, 26*(5), 924-944.

Expòsito, A., & Velasco, F. (2018). Municipal solid-waste recycling market and the European 2020 Horizon Strategy: A regional efficiency analysis in Spain. *Journal of Cleaner Production, 172*, 938-948.

Ferguson, M.E., & Toktay, L.B. (2006). The effect of competition on recovery strategies. *Production and Operations Management, 15*(3), 351-368.

Ferguson, M., Souza, G. C., & Toktay, L. B. (2016). Examples of Existing Protable Practices in Product Take-Back and Recovery. In Closed-Loop Supply Chains (pp. 162-177). Auerbach Publications.

Ferrer, G., & Swaminathan, J.M. (2006). Managing new and remanufactured products. *Management Science, 52*(1), 15-26.

Guide, V.D.R., & Srivastava, R. (1998). Inventory buffers in recoverable manufacturing. *Journal of Operations Management, 16*(5), 551-568.

Guide Jr, V. D. R., Jayaraman, V., & Linton, J. D. (2003). Building contingency planning for closed-loop supply chains with product recovery. *Journal of operations Management, 21*(3), 259-279.

Guide Jr, V.D.R. & Li, J. (2010). The potential for cannibalization of new products sales by remanufactured products. *Decision Sciences, 41*(3), 547-572.

Gutowski, T. G., Sahni, S., Boustani, A., & Graves, S. C. (2011). Remanufacturing and energy savings. *Environmental Science & Technology, 45*(10), 4540-4547.

Huang, J., Leng, M., & Liang, L. (2012). Recent developments in dynamic advertising research. *European Journal of Operational Research, 220*(3), 591-609.

Haurie, A., Krawczyk, J. B., & Zaccour, G. (2012). *Games and dynamic games (Vol. 1)*. World Scientific Publishing Company.

Jacobs, B. W., & Subramanian, R. (2012). Sharing responsibility for product recovery across the supply chain. *Production and Operations Management, 21*(1), 85-100.

Jørgensen, S., & Zaccour, G. (2003). Channel coordination over time: Incentive equilibria and credibility. *Journal of Economic Dynamics and Control, 27*(5), 801-822.

Jørgensen, S., & Zaccour, G. (2014). A survey of game-theoretic models of cooperative advertising. *European Journal of Operational Research, 237*(1), 1-14.

Ko, E., Hwang, Y. K., & Kim, E. Y. (2013). Green marketing functions in building corporate image in the retail setting. *Journal of Business Research, 66*(10), 1709-1715.

Li, Y., Xu, F., & Zhao, X. (2017). Governance mechanisms of dual-channel reverse supply chains with informal collection channel. *Journal of cleaner production, 155*, 125-140.

Lindhqvist, Thomas. (2000). Extended Producer Responsibility in Cleaner Production. IIIEE Dissertations 2000:2. Lund: IIIEE, Lund University.

Liu, B., Holmbom, M., Segerstedt, A., & Chen, W. (2015). Effects of carbon emission regulations on remanufacturing decisions with limited information of demand distribution. *International Journal of Production Research, 53*(2), 532-548.

Lund, R. (1998). Remanufacturing: An American resource Proceedings of the fifth international congress for environmentally conscious design and manufacturing on 16–17 June 1998. *Rochester, RY: Rochester Institute of Technology*.

Majumder, P., & Groenevelt, H. (2001). Competition in Remanufacturing. *Production and Operations Management, 10*(2), 125-141.

Martinho, G., Magalhães, D., & Pires, A. (2017). Consumer behavior with respect to the consumption and recycling of smartphones and tablets: An exploratory study in Portugal. *Journal of Cleaner Production, 156*, 147-158.

Montoro Rios, F. J., Luque Martinez, T., Fuentes Moreno, F., & Cañadas Soriano, P. (2006). Improving attitudes toward brands with environmental associations: an experimental approach. *Journal of Consumer Marketing, 23*(1), 26-33.

Munro, A. (2007) Recycling by Canadian Households. Catalogue no. 16-001-M, no. 13, Statistics Canada. Available at http://www.statcan.gc.ca/pub/16-001-m/2010013/part-partie1-eng.htm, [Verified 15 April 2018].

Nerlove, M., & Arrow, K. J. (1962). Optimal advertising policy under dynamic conditions. *Economica,* 129-142.

OECD (2001), Extended Producer Responsibility: A Guidance Manual for Governments, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264189867-en. [Verified 15 April 2018].

OECD. 2014. The State of Play on Extended Producer Responsibility (EPR): Opportunities and Challenges. OECD, Tokyo.

Ovchinnikov, A., Blass, V., & Raz, G. (2014). Economic and environmental assessment of remanufacturing strategies for product + service firms. *Production and Operations Management,* 23(5), 744-761.

Özdemir, Ö., Denizel, M., & Guide, V.D.R. (2012). Recovery decisions of a producer in a legislative disposal fee environment. *European Journal of Operational Research, 216*(2), 293-300.

Pazoki, M., & Zaccour, G. (2019). A mechanism to promote product recovery and environmental performance. *European Journal of Operational Research, 274*(2), 601-614.

Raz, G., Ovchinnikov, A., & Blass, V. (2017). Economic, environmental, and social impact of remanufacturing in a competitive setting. *IEEE Transactions on Engineering Management, 64*(4), 476-490.

Savaskan, R. C., & Van Wassenhove, L. N. (2006). Reverse channel design: the case of competing retailers. *Management Science, 52*(1), 1-14.

Schwepker Jr, C. H., & Cornwell, T. B. (1991). An examination of ecologically concerned consumers and their intention to purchase ecologically packaged products. *Journal of Public Policy & Marketing*, 77-101.

Schuhwerk, M. E., & Lefkoff-Hagius, R. (1995). Green or non-green? Does type of appeal matter when advertising a green product?. *Journal of advertising, 24*(2), 45-54.

Tojo, N., Lindhqvist, T., & Davis, G.A., EPR Programme Implementation: Institutional and Structural Factors. OECD Seminar on Extended Producer Responsibility, 13-14 December, 2001, OECD Headquarters, Paris, France.

Tojo, N., Lindhqvist, T., & Davis, G. (2003). EPR programme implementation: Institutional and structural factors. Proceedings of OECD Seminar on EPR: EPR Programme Implementation and Assessment. Part 2: Assessing EPR Policies and Programmes.

Wang, W., Zhang, Y., Zhang, K., Bai, T., & Shang, J. (2015). Reward–penalty mechanism for closed-loop supply chains under responsibility-sharing and different power structures. *International Journal of Production Economics, 170*, 178-190.

Wang, W., Fan, L., Ma, P., Zhang, P., & Lu, Z. (2017). Reward-penalty mechanism in a closed-loop supply chain with sequential manufacturers' price competition. *Journal of Cleaner Production, 168*, 118-130.

Webster, S., & Mitra, S. (2007). Competitive strategy in remanufacturing and the impact of take-back laws. *Journal of Operations Management, 25*(6), 1123-1140.

Greenwood, M. (2018, January 5). WHO: 7 million people a year die from air pollution. Retrieved from: https://thehill.com/policy/healthcare/385781-who-7-million-people-a-year-die-from-air-pollution.

Wu, C.H. (2013). OEM product design in a price competition with remanufactured product. *Omega, 41*(2), 287-298.

Yenipazarli, A. (2016). Managing new and remanufactured products to mitigate environmental damage under emissions regulation. *European Journal of Operational Research, 249*(1), 117-130.