Three essays on the effects of environmental regulations on supply chain practices

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THESE DE DOCTORAT
DE
L'UNIVERSITE PARIS-SACLAY
PREPAREE A "HEC PARIS"

ECOLE DOCTORALE N° 578
Sciences de l'homme et de la société (SHS)

Spécialité de doctorat : Sciences de gestion

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Three essays on the effects of environmental regulations on supply chain practices

Thèse présentée et soutenue Jouy-en-Josas, le 26 Août 2016

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Three Essays on the effects of Environmental Regulations on supply chain practices

a dissertation presented
by
Muhammad Shumail Mazahir
to
The Department of Operations Management and Information Systems

in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy
in the subject of
Operations Management

HEC Paris
Jouy en Josas, France
June 2016

Résumé

Introduction :

Depuis des années 2000, on a marqué une grosse augmentation dans les ventes des produits électronique. Gartner, une organisation principale d'études de marche a prévu des ventes des 317 Mn ordinateurs et 2 Bn des appareils cellulaires dans l'année 2016. En 2012, le ménage américain moyen a dépensé 1 312 $ sur produit électronique, selon une étude, par la Consumer Electronics Association (CEA) qui suggèrent aussi que sur une moyenne, chaque ménage américain possède 24 produits électroniques. Par suite, il y une augmentation formidable dans la génération de déchet électrique et électronique. Selon l'Agence américaine pour la protection de l'environnement (EPA), tous les jours 142 000 ordinateurs et téléphones mobiles se joindre à l 416,000 flux de déchets. Le déchet électrique et électronique est compose 2% de déchets municipale aux êtas unis. En 2016, il est prévu d'augmentation de déchets électronique global à 93.5 mn ton de 41.5 mn ton en 2011. Nous rappelons brièvement la raison pour laquelle nous abordons ce problème spécifique des déchets électriques et électroniques. Tout a bord, les produits électroniques contiennent des lanthanides qui non seulement exigent pas beaucoup de ressources des opérations minières et métallurgiques, mais ont également le potentiel de contamination des terres et des ressources en eau. La mise au rebut non réglementée des déchets électroniques peut nuire à la santé publique et à la qualité de notre environnement. Les déchets électroniques sont devenus aujourd'hui déjà un problème mondial. Cela signifie que les déchets électriques et électroniques devront être récoltés et non plus déversés. En outre, il n'y réside une valeur économique avec les produits électroniques au moment de l'élimination et à la valorisation de cette valeur peut aider la réduction des risqué environnementaux.

Un secteur d'intervention particulier pour des législateurs est celui des déchets électroniques. Il y a certaines législations qui ont été introduites pour réduire les menaces environnementales potentielles causées par les déchets électroniques. Dans notre thèse, nous étudions deux types de telles législations. Il n'y a directive législative DEEE (déchets d'équipements électriques et électroniques) qui est fondamentalement basé sur la notion de responsabilité élargie des producteurs. L'introduction de la responsabilité élargie du producteur dans la présente directive est l'un des moyens de soutenir la conception et la fabrication de produits selon des procédés qui prennent pleinement en compte et facilitent l'utilisation efficace des ressources tout au long de leur cycle de vie, y compris en matière de réparation, de réemploi, de démontage et de recyclage, sans compromettre la libre circulation des marchandises dans le marché intérieur. La deuxième directive ROHS est basée sur utilisation restreinte de certaines matières dangereuses dans l'équipement électrique et électronique. la directive relative à la limitation de l'utilisation de certaines substances dangereuses dans les équipements électriques et électroniques vise, lorsque c'est possible, à remplacer le plomb, le mercure, le cadmium, le chrome hexavalent, les polybromodiphényles (PBB) et les polybromodiphényléthers (PBDE) utilisés dans les équipements électriques et électroniques afin de faciliter la valorisation sûre des équipements concernés et d'éviter les problèmes lors de la phase de gestion des déchets (les CFC, les PCB et les PVC font l'objet d'autres textes législatifs de l'UE). Après le succès de son mise en œuvre dans l'Union européenne, d'autres pays ont suivi le chemin et ont développé leurs propres versions des directives similaires aux directives DEEE et ROHS.

Motivation :

Cette législation pourrait avoir un impact important sur la gestion de chaine d’approvisionnement. Ils sont bien capables d’augmenter cout de production et donc décroitre la compétitivité de l’entreprise. Par exemple, Apple devait abandonner fournitures du «i-sight camera en 2006 quand législation ROHS était impose dans la union européenne. Il est estime que la coût du compliance directive ROHS est environ 1-4% de chiffre d'affaires. Elle peut élever le prix jusqu' 10% qui évidement réduire la compétitivité des entreprises par rapport des entreprises localisé dans la région qui sont pas géré par cette législations. C'est la raison harvard business review a commenté "Parler assez longtemps avec les PDG, en particulier dans les Etats-Unis ou l'Europe, et leurs préoccupations répandrai : rendre nos opérations durables et élaboration de produits " verts " nous met dans une position désavantageuse vis-à-vis de concurrents dans les pays en développement que ne subissent pas les mêmes pressions"

En raison d'énormes coûts associés à ces législations environnementales Il est important de comprendre deux points importants.

Il est important d'étudier le rendement comparatif de ces législations et validez si ils atteignent leurs objectifs environnementaux.

Il est important de comprendre que la façon dont la décision et pratiques de la chaîne d'approvisionnement va changer avec l'application de ces législations.

Réutilisation des produits est considérée comme une stratégie supérieure au niveau environnemental est l'un des piliers de la mise en place de l'économie circulaire Une économie circulaire faisant appel à la responsabilité des producteurs par-delà les étapes de la production a été mise en place dans des pays européennes. Cependant, la réutilisation du produit n'a pas été étudiée dans le cadre de législations de récupération. Il n'est également pas étudié que si ces législations encouragent la réutilisation des produits.

Problématique de la Recherche et Contribution :-

La question que nous nous concentrons dans cette thèse appartient à deux classes différentes. Premier ensemble de questions portent sur l'évaluation comparative des performances des différents régimes législatifs en présence de réutilisation des produits. Cet ensemble de questions exigent la perspective de la firme et le législateur où notre objectif reste à développer une meilleure compréhension de l'interaction entre les différents paramètres économique, environnementaux et sociaux. Nous prenons un spectre plus large et mettre en évidence les aspects stratégiques.

L'autre type de question que nous avons pris en compte est d'étudier comment la présence de ces législations vont influencer l'entreprise et comment l'entreprise peut répondre en présence de ces législations. Ces questions sont intéressantes puisque décideur doit avoir l'assurance que réponse ferme n'atténuera pas l'effort du décideur politique. De la perspective de l'entreprise, il demeure difficile de maintenir l'avantage concurrentiel dans une société axée sur la législation. Donc il doit réagir dans une manière stratégique pour rétablir son compétitivité.

Chapitre 2 :

Ce chapitre est consacré à l'étude comparative des performances des différents schémas de reprise en présence de réutilisation des produits. Avec un jeu Stackelberg entre un décideur politique qui maximise le bien-être social et une entreprise monopolistique qui maximise son profit, nous étudions des politiques optimales de récupération et réutilisation des produits. Un décideur politique sélectionne l'un des régimes de législation entre (i) Objectif du taux de récupération basé sur le nombre de produits recyclés ou le pourcentage récupéré par rapport au nombre vendus (ii) régime de taxes et de subventions (un taxe sur chaque nouvelle produit vendu avec une subvention sur chaque produit réutilisé) (iii) une approche mixte en combinant des éléments des deux politiques. Avoir choisi un politique, il décide des paramètres des législations pour d'entreprise en prenant en compte la meilleure réponse de l'entreprise. Nous avons employé un cadre unifié-qui inclut les notions d'impôt effectif et des subventions effectifs-d 'examiner trois différents régimes de politique législative avec un cas où il n'y a pas de législation. Nous avons caractérisé le comportement de cette entreprise, qui comprend à la fois le prix des produits neufs et les produits réutilisé et le choix d'une stratégie de marché (single versus dual channel), en réponse à la mise en œuvre de politiques. Nous caractériser deux différentes stratégies de marché, stratégie pour le marché unique représente le cas lorsque les deux produits sont introduit dans le même marché. Toutefois, cela peut déclencher la demande cannibalisation lorsque les entreprises risquent de perdre la vente de nouveaux produits pour des produits réutilisé/ remanufacturés. Cette demande cannibalisation est un raison connu lesquelles les entreprises sont réticentes à introduire les produits remanufacturés/ réutilisé. Les entreprises peuvent éviter ce problème en utilisant une stratégie de marché où un marché différent est sélectionné pour la vente de produits réutilisé. À l'aide d'un modèle de demande largement utilisé dans la littérature, nous avons considéré une fonction objective pour le décideur politique qui intègre à la fois les préoccupations environnementales et économiques; nous avons ensuite caractérisé les paramètres optimaux pour chaque régime législatif et stratégie de marketing associés identifiés préféré par les parties respectives (c'est-à-dire, ferme et décideurs). L'intervention législative dans le domaine de la récupération des produits est conçu principalement pour protéger l'environnement et créer une économie plus durable. Le principal avantage pour l'environnement d'une politique qui impose une cible minimale de récupération découle d'atténuer les effets néfastes sur l'environnement en réduisant les déchets d'enfouissement. En revanche, un régime d'encouragement " soft " favorise la refabrication/réutilisation et vise pour la réduction de la production. Notre argument central dans ce document n'est qu'une approche mixte qui combine les deux politiques fonctionne bien en termes de critères à la fois économiques et environnementaux, ce qui conduit à un plus grand bien-être social. Afin d'effectuer un contrôle robuste sur nos constatations, nous prenons une quantité fondée fonction objective pour le décideur et imposer une stricte neutralité budgétaire contrainte signifiant que le décideur n'a pas mis les fonds provenant de sources externes. Les résultats sont semblables en ce sens que la dominance de l'approche mixte reste établie. Notre approche peut certainement être encore enrichie le long de plusieurs dimensions, l'incertitude des paramètres (p. ex., en ce qui concerne le coût de fabrication) et compétitifs plutôt que les conditions du marché monopolistique. Cela étant dit, nous croyons que notre principale revendication, à savoir la supériorité d'une approche mixte-ne serait pas contrecarré par aucune de ces extensions possibles. Le modèle présenté ici a été exprimés de manière concise mais raisonnablement pratique qui maintient le modèle maniable et intuitif mais encore capable de livrer un message important pour les décideurs, dont les décisions ont de vastes conséquences économiques et environnementales.

Chapter 3 :

Ce chapitre est une extension pour le chapitre précédent où nous tenter de capturer une image plus réaliste en tenant compte des décisions d’innovation fréquente qui sont des caractéristiques de secteur de consommateurs électronique. Nous avons également étudie d'incitatif des conceptions pour mettre réutilisation des produits qui éventuellement décider le coût l'attrait de la réusinage (remanufacturing). En outre, dans la distinction avec le chapitre précédent où l'empreinte environnementale a été mesurée avec la production et l'incidence de fin de vie ; nous tentons de prendre une approche basée sur le cycle de vie et capture de l'empreinte environnementale aux différents stages de la vie d'un produit. Notre principal objectif demeure d'évaluer mérites comparatifs des deux régimes populaires de récupération des produits, une cible basée sur la récupération et l'autre basé le régime de taxes et subventions. Contrairement au chapitre précédent, on ne considère que la structure du marché où les produits neufs et réusiné sont offerts dans le même marché. Comme nous considérons les innovations fréquente des produit, nous supposons que le nouveau produit offert sont différents des produits offerts au cours de la dernière période. Par conséquent, les produits perçus pour la deuxième transformation sont différentes de produits actuels. Cela laisse l'entreprise monopolistique avec trois options lorsqu'il s'agit de stratégie avec réusinage (i) mettre à niveau tous les produits de la transformation (ii) n'entraîne pas la mise à niveau des produits de la transformation (iii) mettre à niveau certains des produits de la transformation. Nous avons d'abord caractérisé la maximisation de profit de la firme monopolistique de problème et d'analyser l'effet sur l'empreinte totale environnementale. Étonnamment, nous notons que l'innovation qui est perçue comme une menace pour la durabilité critères réellement peuvent obtenir en ligne avec l'objectif de réduction de l'empreinte environnementale. De même, mettre des produits réutilisables, peut n'aussi pas nécessairement conduire à une réduction de l'empreinte environnementale et peut conduire à plus de production. De façon similaire, escalade des couts pour mettre des produits réutilisables, conduisent toujours à la réduction de l'empreinte environnementale et structure de subvention sur le recyclage comme actuellement débattue peut effectivement conduire à une augmentation de l'empreinte environnementale. En outre, nous caractérisons le problème comme un jeu entre un décideur politique et l'entreprise en similaire du chapitre 2. Nous avons noté que le paramètre optimaux pour un taxe/subvention dans la politique qui constitue avec une taxe/subvention sont les fonctions monotone de l'innovation, réutilisabilité niveaux, réutilisabilité, coût de recyclage et de coûts Les coûts environnementaux. Toutefois, le taux de récupération et recyclage pour d'autre politique peut augmenter ou diminuer avec ces paramètres, selon une valeur de seuil de coût de recyclage. En d'autres termes, l'efficacité du recyclage (i.e., coût de recyclage contre l'empreinte environnementale il empêche) est un paramètre clé pour ce type de politique. En fin de compte, nous avons effectué une série complète d'étude numérique pour comparer la performance environnementale des deux politiques et trouver que l'empreinte environnementale totale est faible en politique qui constitue un taux de récupération. Donc, on trouve que la politique avec un taux de récupération même possède un seul levier politique mais réussi à dominer la politique avec un taxe/subvention.

Chapitre 4 :

Les deux premiers chapitres comportent la discussion sur les législations basée sur récupération des produits que nous analysons avec un jeu stackelberg. Le but principal était de commenter l'efficacité de ces régimes législatifs. Comme nous en avons discuté plus tôt que de tels systèmes législatifs ont des conséquences financières importantes pour les entreprises et par conséquent entreprise doit concevoir une stratégie d'absorber les répercussions de ces législations et garder son compétitivité. Ce chapitre est consacré à l'étude de sélection des configurations du produit et des décisions d'affectation sous des législations en présence d'incertitudes. Au cours de cette étude, nous ne considérons qu'une chaîne d'approvisionnement mondiale avec une seule entreprise desservant un certain nombre de marchés. Ces marchés ont leur propre cadre législatif selon les conditions socio-politiques. Il existe trois types de marchés au niveau des législations:

1) Les marchés avec pas de législations en place

2) Marchés avec l'une ou l'autre de taux de récupération/ législations sur la conformité des produits en place

3) Marchés avec les deux régimes législatifs (taux du récupération+ législations sur conformité des produits).

Nous mettons en évidence les incohérences entre les diverses lois en fonction de la conformité des régimes en déclarant certains produits qui sont admissibles en vertu d'un marché peuvent se révéler inadmissible en vertu de marché différent. Nous motivons cette hypothèse par l'exemple de la loi Dodd-Frank bill qui met des restrictions a des entreprises américaines d'utiliser de matériel source de République démocratique du Congo alors que de telles contraintes ne sont pas exercé ailleurs. Sur une note similaire, une étude approfondie par l'Environnemental Protection Agency (EPA) révèle que le souder plomb/ étain ont moins empreinte de carbone. Toutefois, les contraintes de la directive ROHS de l'Union européenne limite l'utilisation de plomb dans les produits électroniques de consommation.

Par conséquent, parmi une liste d'options de configuration du produit qui peuvent être uniquement différencié en ce qui concerne les frais et les normes de conformité, une entreprise doit sélectionner des configurations pour satisfaire la demande globale. Notez que nous n'avons pas supposé que les clients peuvent faire la distinction entre ces configurations de produit et, par conséquent, il n'influence pas leur volonté de payer et par conséquent la demande. Au contraire, une entreprise peut répondre par développer un produit générique et standard qui conforme tous les standards mais cette stratégie peut mettre l'entreprise en désavantage avec des firmes locale en particulaire dans les pays développant. Nous avons d'abord formulé avec une entière mixte programmation linéaire formulation avec tous les paramètres déterministe. Une entreprise sélectionne les configurations de produit et à l'attribution des quantités dans chacun des marchés. Nous avons ensuite tenir compte des incertitudes liées aux coûts de fabrication et de recyclage avec les produits en supposant que plus cher les configurations de produit auront un plus petit degré d'incertitude. Nous utilisons l'approche de Bertsimas et Sim (2004) l'attribution d'un budget d'incertitude. Nous partons du principe que seul un sous-ensemble de paramètres de coût seront soumis aux incertitudes et formuler une formulation robuste du problème. Nous considérons ensuite des demandes stochastique et de démontrer que l'importance d'emploi d'un approche robuste est fortement augmente en présence de demande stochastique par rapport à demande déterministe. Nous accommoder des incertitudes associées aux scénarios de la demande et d'élaborer un modèle d'optimisation robuste distributionnelle pour répondre aux incertitudes de la demande. Nous prendre un problème à grande échelle avec 50 marchés et 3000 configurations de produit disponibles montrent que ce problème peut être résolu en un temps raisonnable, même en présence de contraintes sur le nombre maximal de configurations du produit. En outre, il reflète cette présence d'incertitudes n'a pas seulement influer sur les décisions d'allocations, mais modifier considérablement les décisions de sélection de produits. Nos simulations numériques montrent que la méthode robuste parvient à éviter un certain nombre des pires cas sans compromettre de façon significative sur les bénéfices.

Conclusion :

Cette thèse est pertinente pour les chercheurs universitaires ainsi que des décideurs et des entreprises qui sont soumis aux cadres législatifs. Il souligne l'importance de prendre en compte tous les paramètres pertinents de l'industrie lors de la conception d'un cadre de politique. Il souligne également en prenant une approche législative plus globale que nous montrent que les politiques législatives peuvent entraîner les conséquences environnementales imprévues. Cette thèse est parmi les quelques œuvres qui capture la perspective de décideur politique et l'entreprise en présence de législations de récupération et de présenter la façon dont ces paramètres de la politique optimale doit être définie. Deuxièmement, il invite les entreprises à adopter une approche plus robuste lors de la conception de la réponse aux politiques législatives car il a montré que les effets des incertitudes sont amplifiés dans les marchés prévus par des législations.

To my mother, father and Alvina
As a token of love and gratitude
for their countless contributions
in my life

Acknowledgement

I take this opportunity to acknowledge the efforts of those who have assisted me during the completion of this dissertation.

First, I would like to acknowledge Pr. Laoucine Kerbache, who allowed me independence to work on the topic of my choice and kept faith in me during all these years. He has also taught me to understand and focus on the managerial implications of my work and his role has undoubtedly been pivotal in the preparation of this dissertation. I would also like to thank Marc Lassagne who has inspired and mentored me during earlier stages of my research career. I am indebted to him for teaching me the fundamentals of research and using his research budget to cover my research errands. I also acknowledge the role of Sam Aflaki who has patiently guided me through these stages. I am indebted to him for investing a significant part of his time on the first part of thesis, guiding me through all the steps of academic writing. I would also like to thank Christian Van delft for guiding me through the last part of the dissertation and advising me through an unfamiliar terrain that required considerable technical training. I am also thankful to the PhD office for the support they have extended throughout this period. I acknowledge the funding of 15000 euro/year four four years and a partial funding of 8000 euros for the fifth year. I also acknowledge their funding for attending two of the academic conferences (i) POM annual conference, Atlanta 2014 (ii) INFORMS annual conference, San Francisco, 2014.

I must also thank my mother,father and siblings for demonstrating their support and encouragement during darker hours of this journey. I will always be indebted to my wife Alvina for her unfaltering support, inexhaustible patience and cheerful companionship during our married life.

Abstract

The focus of this dissertation is the influence of environmental regulations on supply chain practices. The economical costs accrued to the firm and the coveted goal of mitigated environmental footprint remain focal point of our study. The first two chapters take an overview of recovery based legislations, currently established recovery target based regimes as well as proposed incentive structures and study their performance over a range of economical and environmental parameters. The abstracts of each of chapter is presented as follows:

Chapter 2 seeks to identify the optimal policies for promoting product recovery and remanufacturing. Using a stylized equilibrium model, we analyze the problem as a Stackelberg game between a regulator and a monopolistic firm. We compare three types of policies that a regulator could enforce: (i) A *recovery target* policy that requires firms to recover no less than a specified fraction of their production for proper disposal or possible remanufacturing; (ii) a *taxation* policy that both taxes manufacturing and subsidizes remanufacturing; and (iii) a newly introduced *mixed* approach that incorporates a recovery target as well as taxes and subsidies. We study a firm's behavior under the three policy types, including pricing decisions for new and remanufactured products as well as the strategic decision of whether to create a secondary channel for remanufactured products. We find that legislative intervention makes it more likely that firms will maintain a single-market strategy. We further demonstrate the mixed approach's superiority as measured by a comprehensive set of economic and environmental criteria, and show that this finding is robust under two different objective functions for the policy maker, one that does and one that does not entail a budget neutrality constraint.

Chapter 3 is an extension to the previous chapter where we attempt to capture a more realistic picture taking into account frequent product innovation decisions which are characteristics of consumer electronic sector. We also accommodate the design incentive and in particular reusability decisions in product design which eventually decide the cost attractiveness of remanufacturing. Furthermore, in distinction with the previous chapter where environmental footprint was measured with production and end of life impact ; we attempt to take a life cycle based approach capturing the environmental footprint at the different stages of a product life. Our primary objective remains to evaluate comparative merits of two popular product recovery schemes one conventional one based on recovery target and the other based on taxation and subsidy scheme. Unlike the previous chapter, we only consider the market structure where both new and remanufactured products are offered in the same market. As we accommodate the frequent product innovations, we assume that the new product offered are different from the products offered in last period. Therefore, the products collected for remanufacturing are different from the current products. This leaves the monopolistic firm with three strategy options when it comes with remanufacturing (i) upgrade all products for remanufacturing (ii) does not upgrade any products for remanufacturing (iii) upgrade some of the products for remanufacturing. We first characterize the profit maximization problem of the monopolistic firm and analyze the effect on total environmental footprint. Surprisingly, we note that innovation which is perceived as a threat to sustainability criteria actually may get in line with the objective of reduced environmental footprint. Similarly, reusability initiatives may also not necessarily lead to reduced environmental footprint and may lead to over production. In a similar way, increasing reusability cos twill always lead to reduced environmental footprint and subsidy structure on recycling as currently debated may actually lead to reduced environmental footprint. Furthermore, we characterize the problem in the similar game theoretic setting between a policy maker and the firm. We noted that the optimal policy parameter with a taxation/subsidy policy are monotone functions of innovation, reusability levels,reusability cost, recycling cost and environmental costs. However, the optimal policy parameter with the recovery target based policy may increase or decrease with these parameters depending on a threshold value of recycling cost. In other words, the efficiency of recycling (i.e, recyling cost against the environmental footprint it prevents) is a key parameter for this type of policy. In the end, we performed a comprehensive set of numerical study to compare the environmental performance of both policies and find that the total environmental footprint is low under recovery target based policy in most of the cases. That is , a recovery target based policy despite having a single policy lever dominates the taxation/subsidy policy in most of the cases.

The earlier two chapters entail the discussion on product take back legislations which we analyze in a stackelberg game theoretic setting. The primary purpose was to comment on the efficacy of such legislative schemes. As we discussed earlier that such legislative systems have significant financial consequences for the firms and therefore firm needs to devise a strategy to absorb the effects of these legislation retaining the competitiveness.Chapter 4 is devoted to the study of firms product selection and allocation decisions under legislations in presence of uncertainties. During this study, we consider a global supply chain with a single firm serving a number of markets. These markets have their own legislative framework depending on its socio-political conditions. There are three types of markets : 1) Markets with no legislations in place 2) Markets with either recovery/compliance based legislations in place 3) Markets with both recovery and compliance based legislations in place.

We highlight the inconsistencies between different compliance based legislation regimes by stating certain products which are eligible under one market may turn out to be ineligible under different market. We motivate this assumption from Dodd-Frank bill which is only imposed in the US and restricts firms to source material from Democratic republic of Congo whereas such constraints are not exercised elsewhere. On a similar note, a comprehensive study by Environmental Protection agency (EPA) reveals that lead-tin solder have least carbon footprint. However, ROHS constraints in the European union restricts use of lead in consumer electronics. Therefore, among a list of product configuration options which can be only differentiated with respect to costs and compliance standards. Note that we did not assume that customers can distinguish among these product configurations and therefore it does not influence their willingness to pay and consequently the demand.We first formulate with a mixed integer linear programing formulation considering deterministic demands and costs parameters where a firm selects product configurations and allocate quantities in each of the market. We then accommodate for uncertainties associated with manufacturing and recycling costs with the products assuming that more expensive product configurations will have a smaller degree of uncertainty. We use the approach of Bertsimas and Sim (2004) allocating a budget of uncertainty. We assume that only a subset of cost parameters will be subjected to uncertainties and formulate a robust formulation of the problem. Then we consider stochastic demands and show that the importance of robust formulation is highlighted in presence of stochatic demands than in comparison with deterministic demands. We accommodate for uncertainties associated with demand scenarios and formulate a distributionally robust optimization model to cater for uncertainties with demands. We take a large scale problem with 50 markets and 3000 available product configurations and show that this problem can be solved in reasonable time even in presence of constraints on maximum number of product configurations. Furthermore, it reflects that presence of uncertainties does not only influence allocation decisions but significantly alter product selection decisions. Our numerical simulations show that the robust approach manage to avoid a number of worst cases without significantly compromising on profits.

This dissertation is relevant for the academic researchers as well as policy makers and the firms that are subjected to legislative frameworks. It underscores the importance of taking into account all relevant industry parameters while designing a policy framework. It also stresses upon taking a more comprehensive legislative approach as we show that legislative policies may lead to unintended environmental consequences.This dissertation is among the few works that capture the perspective of both policy maker and the firm in presence of recovery legislations and present how such optimal policy parameters should be set. Secondly, this paper calls upon the firms to take a more robust approach while designing the response to the legislated policies as it demonstrated that the effects of uncertainties are amplified in the legislated markets.

Contents

1 Introduction **25**

2 Recovery Targets vs. Taxation/Subsidy Policies to Promote Product Reuse **31**

2.1 Introduction 31

2.2 The Model 35

2.2.1 Demand Formulation and Customer Preferences 35

2.2.2 The Firm's Problem and Legislated Policies 38

2.2.3 The Firm's Behavior under a Fixed Policy 41

2.2.4 A Unifying Framework. 42

2.3 Optimal Legislated Policies: A Social Welfare Perspective 44

2.3.1 Policy Maker's Objective Function 44

2.4 Equilibrium Analysis 47

2.4.1 Policy $\mathcal{R}$. 47

2.4.2 Policy $\mathcal{T}$. 48

2.4.3 Policy $\mathcal{M}$. 50

2.4.4 Comparison of Policies 50

2.5 The Value of Secondary Markets 54

2.6 Optimal Policies from the Perspective of Product Quantity 58

2.6.1 Policy Budget Neutrality 58

2.6.2 Optimal Policy Parameter Values 59

2.6.3 Comparison of Policies 61

2.7 Conclusion 62

3 Environmental Performance of Recovery Legislations in Innovative industry 75

3.1 Introduction 75

3.2 Model 77

3.2.1 Cost Parameters 78

3.2.2 Firm's Problem 79

3.2.3 Customer Choices and Demand Processes 79

3.3 Policy Maker's Objective Function 80

3.3.1 Total Environmental Footprint (TE_i) 82

3.3.2 Cost of Policy B_i 85

3.3.3 Firm's Profitability Π_i 85

3.3.4 Consumer Surplus C_i 85

3.4 Analysis 86

3.4.1 Effect of Parameters on Total Environmental Footprint 86

3.4.2 Effect of Policy Parameters 90

3.5 Equilibrium Analysis 92

3.5.1 Recovery Target based Policy 93

3.5.2 Tax/Subsidy Policy 96

3.5.3 Comparison of Policies 99

3.6 Conclusion 102

4 Robust Product Portfolio Selection and Allocation Decisions with Environmental Legislations 105

4.1 Introduction 105

4.2 Model 109

4.2.1 Deterministic Model 111

4.2.2 Incorporating Cost uncertainty Deterministic Demand 112

4.2.3 Incorporating Cost uncertainties with Stochastic Demands 115

4.2.4 Uncertainty with Demands: Distributionaly Robust model 117

4.3 Numerical Experiment 119

4.3.1 Robust Optimization Model with Deterministic Demands 120

4.3.2 Robust Optimization Model with Stochastic Formulation of Demands 121

4.3.3 Distributionally Robust Demand Formulation 122

4.4 Conclusion 122

5 Conclusion 123

5.1 Key Findings and Contribution 124

5.2 Limitations and Future Research 125

1. Introduction

The signature of a land mark deal in Paris Climate Change Conference (2015) established a global consensus and commitment to address the climate change which includes adoption of comprehensive set of measures to curtail carbon emissions that could limit the temperature rise to 2 c°. Environmental issues that hover around for decades have now been prioritized and have become top-agenda items in political campaigns and bi-lateral discussions. Climate change was a key issue of discussion during the visit of Canadian Prime Minister to the United States in March 2016. This exhibits global consensus and commitment which would redefine trade and businesses. The energy projects with high carbon emissions are being rejected regardless of their cost efficiency and productivity. To the fury of energy industry, President Obama recently rejected a transnational pipeline project with environmental concerns.

Therefore, once overlooked environmental issues are assembling leaders on a single platform; and once considered insignificant of policy makers attention; we are witnessing more deliberations on environmental regulations. A discussion on climate change and carbon footprint is generally synonymous with a discussion on petroleum trade, mining & metallurgical operations and transportation. But there is also an emerging issue which is a direct consequence of digital economy growth that represents generation and growth of discarded electronic and electrical devices referred as E-Waste.

E-Waste which represents 2% of United States municipal waste accounts for 70% of all toxic wastes in the land filling. According to ElectronicsTakeback.com which is a coalition among world environmentalist organizations such as Basel Action Network; year 2013 marked 3.14 Mn tons generation of E-Waste. Moreover, Gartner forecasted global sales of 2 Bn cellular devices and 317 Mn computers and notebooks in 2016. Considering the high product obsolescence rate, a significant part of these would join E-Waste in five years. According to a market research report, the global generation of E-Waste is expected to be 93.5 Mn tons in 2016 from 41.5 Mn tons in 2011 with a growth rate of 17.6%.

These alarming figures uncover the tip of an important environmental challenge which would come up in a few years. There is not a straightforward method to calculate the environmental footprint associated with the E-waste. Generally, it is fathomed by the footprint caused by waste dumping and land filling but this does not capture everything and total environmental footprint associated with consumer electronics, considering mineral extraction from the mines in Chile and Kazakhistan to manufacturing operations and distribution can be manifold.

The consumer electronics constitute of significant proportion of rare and heavy metals which requires energy intensive mining and metallurgical operations. It is reported that the consumer electronics sector consumes 150 Bn KWH of energy annually which is equivalent to 104 Mn tons of carbon footprint. This footprint is only associated with production and assembly operations and is quite apart from footprint associated with mining and metallurgical processing of the raw materials required for production. As an example, 23% of annual copper production in the US goes to consumer electronics which accounts for 13.4 Bn KWH of energy.

The foremost challenge to the policy makers is the prevention of the piles of consumer electronics from the land fills in order to avoid contamination of land and water resources. Therefore, the concept of extended producer responsibility(EPR) is proposed to primarily focus on landfill diversions and resource contamination. OECD (Organization for Economic Co-operation and Development) defines extended producer responsibility as an environmental policy approach in which a producers responsibility for a product is extended to the post-consumer stage of a products life cycle.

An EPR policy is characterized by:

1. the shifting of responsibility (physically and/or economically; fully or partially) upstream toward the producer and away from municipalities
2. the provision of incentives to producers to take into account environmental considerations when designing their products.(Walls 2006)

Although EPR based initiatives primarily aim at land fill diversion, they are also expected to generate sufficient incentives for waste minimization, Design for Environment (DFE) initiatives, promotion of efficient designs with enhanced reusability (Walls 2006). There are two different concepts associated with the extended producer responsibility (i) individual producer responsibility (ii) collective producer responsibility. Individual producer responsibility transfers the responsibility to the individual producers about collection and recycling of their own products. While under collective producer responsibility schemes, the policy maker facilitates a shared collection and recycling platform for all the participant firms. Although collective take back schemes are more cost efficient, they do not spur design for environment initiatives and the firms who are aggressively pursuing environmental innovations prefer to opt out of such schemes.

After a number of environmental studies, the policy makers in the European Union have taken a legislative initiative which was enacted in 2006 and is known as WEEE (Waste Electrical and Electronic Equipment) legislative directive. This directive is fundamentally based on the principles of extended producer responsibility and holds the individual producers responsible for the post-use collection of their products. With the assignment of a mandatory recovery target, the firms are expected to make their own arrangements for the collection, transportation and recycling of their products. WEEE directive applies to seven product categories as presented in table. Although this directive primarily focuses

WEEE Legislations			ROHS Legislations	
S.NO	Industry	Recycling Rate	Hazardous substance	Max concentration
1	Large Household Appliances	80%	Cadmium	100ppm
2	Small Household Appliances	70%	Lead	1000ppm
3	IT Communication equipment	75%	Mercury	1000ppm
4	Consumer equipment	75%	Hexavalent Chromium	1000ppm
5	Lighting equipment	70%	PBBE	1000 ppm
6	Electric Tools	70%	PBDE	1000 ppm

Table 1 WEEE and ROHS Legislations

on diverting the E-waste from the land fills, it is expected to incentivize firms for taking design initiatives and promote product reuse. In fact, a proposal for incorporation of reuse targets has come under discussion. Apart from mandatory recovery rate based policy, there have been proposal of alternative schemes based on incentives structures. Such schemes include advanced recycling schemes, fees upon sales and subsidy schemes which are under consideration and in some cases have been implemented.

The scope of the WEEE legislation is somehow limited in a sense that although it provides DFE incentives; a basic structure for complete removal of hazardous substance from the electronics is missing. Therefore, in addition to WEEE directive, there is another directive called ROHS (Restriction on Hazardous Subsbtance) with a precise ambition for the removal of hazardous metals and chemicals. The electronic products are known to contain significant proportion of heavy metals that pose significant health risks upon exposure. For example, Cadmium which is used as plastic stabilizer has adverse effects on kidneys and bones. Hexavalent chromium which is used for corrosion prevention is known to cause DNA damage. In a similar way, lead and mercury which are commonly used in electronics can pose significant health risks to nervous and reproductive systems. Therefore, ROHS (Restriction on Hazardous Substance) directive has been enacted in the European Union in 2006 which sets maximum threshold limits on the use of six hazardous chemicals. According to this directive, any homogenous component can not contain more than a prescribed concentration of the hazardous chemicals. This directive applies generally to the same set of product categories covered by WEEE directive. It includes large and small household appliances, computational and telecommunication equipment, consumer electronics, lighting and power tools along with toys and automatic dispensers.

These environmental directives (WEEE and ROHS) come with a significant cost and are known to influence firms performance and profitability. The firms therefore face a more constraining and more challenging environment for maintaining their business growth. Scott McClendon, president of Allied Electronics said:

Export compliance is a huge additional cost in our business. It has affected our bottom line dramatically

Lisa Jackson, head of Apple Environmental Operations shared a mixed review. On one hand she acknowledged that *it is possible to be profitable while still being environmentally responsible* while at the same time she thinks that these regulations *constrain innovation.*

Research Questions

In this dissertation, stress has been laid to investigate broad questions:

1. How do/should firms respond to these regulations.
2. How do policy instruments serve their purpose.
3. What is the comparative performance of policies and how do they influence social costs.

As discussed above, the firms absorb a significant proportion of the cost of these regulations and hence it is exigent for them to re-devise their strategy in presence of the regulations. The compliance based and recovery regulations have potential of driving firms out of the market; may shift the competitive balance among the firms. We investigate how the firms can optimally respond to these regulations in order to maintain their profitability. An appropriate response strategy may include promoting reuse through remanufacturing, exploring other market alternatives such as secondary markets and optimal selection of product configurations.

Similarly, the policy maker's comprehension of the influence of their policy instruments should not be limited to the environmental performance but should be expanded to the analysis of the anticipated firm's response and the cost leverages associated with consumers and firms. It is essential to understand and avoid scenarios where a firm's optimal response may be against the expectations of the policy maker and the circumstances where policy tool creates more problems than it solves, should be best avoided.

The structure of the dissertation is as follows. In chapter 1, I compared three different types of legislative schemes which are either under practice or being proposed and studied their effect on firm and consumers. I then compared them for relative merits and demerits. In the second chapter of my dissertation, I investigated that how the policy parameters will change in an innovative industry which essentially captures existing consumer market structure and how design choices play their role. Chapter 3 combines the study of WEEE legislations and ROHS type legislations. The study encapsulates a global supply chain with a firm serving the demand of a number of markets with a set of regulations and come up with a robust decision aid tool to product selection and allocation problem

2. Recovery Targets vs. Taxation/Subsidy Policies to Promote Product Reuse

2.1. Introduction

In 2014, the global sales of electronic products was at its all-time high: approximately 2.4 billion units, including 279 million desktop and notebook computers, 216 million electronic tablets, and 1.8 billion cellular phones (Gartner 2015). This significant rise in global sales has coincided with shrinking product life cycles and a wave of consumerism. The average customer replaces a cellular device every 11 months, despite the seven-year average working life of a mobile phone (Sharpe 2005). Similarly, the average life span of computers has declined to just two years (from four in early 2000s; Kang and Schoenung (2006)). Hence it is not surprising that a considerable amount of used products are abandoned to the environment around the globe. The US Environmental Protection Agency (EPA) reports that 384 million used electronic products were discarded in the United States during 2010 alone (ICF International 2011). The Australian Bureau of Statistics reports that 17 million television sets and 37 million computers were dumped in landfills during 2008, when the rate of recycling computers was not even 10% (Australian Bureau of Statistics 2013). Although product recovery has increased to reduce waste, a significant mass of products remains unrecovered. France, which is one of the most pro-active countries regarding environmental policies, recovered less than half as many electronic units in 2010 as were added to the market during that year (European Commission 2014).

The problem of (e-)waste has prompted some firms to voluntarily create value through sustainability initiatives, which include product recovery and (in some cases) subsequent remanufacturing; however, the lack of sufficient incentives for that approach has led policy makers to intervene via legislative mechanisms that encourage firms to take environmental responsibility for their products. As Guide et al. (2003) put it, "in some cases sustainable solutions will never be profitable, no matter how intelligent or innovative is the business model. In those cases, legislation may be the only solution." In the context of product recovery, these legislated schemes can take different forms. The European Union's Directive on Waste Electrical and Electronic Equipment (WEEE), whose most recent version was enacted in 2012, imposes a minimum recovery target for a number of categories of electric and electronic products. Similar incentives are in place owing to state-level legislation in the United States. Alternative policy mechanisms, such as the California Electronic Waste Recycling Act (CEWRA), impose a recovery tax collected when the electronic product is sold (California State Board of Equalization 2014). Targets and taxes are different types of schemes, but they share two important aspects: both mechanisms focus mainly on recovery, and neither provides an incentive that specifically promotes remanufacturing. In this paper we seek to analyse the relative merits of these two approaches while considering incentives for remanufacturing.

Many economics and management researchers have considered the effect of environmental legislation on social welfare and on the firm's behavior in the supply chain. Although some economists argue that environmental legislation hinders both economic growth and the competitiveness of firms (Greenstone et al. 2012), others—for example, Jaffe et al. (1995), Porter (1996), —find no empirical evidence supporting that argument. We contribute to this discussion by proposing that properly written policies can account for (and counteract) the tendency of market intervention to inflate new product prices and hence to reduce new product manufacturing. In particular, our results indicate that recovery target and tax schemes, both of which are widely practiced, *have a synergistic effect* when used in combination; performance under the new policy is thereby *improved along both economic and environmental dimensions.*

Using a stylized economic model, this paper strives to answer a series of questions that concern legislative intervention in the context of product recovery/reuse. How does such intervention change the firm's pricing behavior? Within each policy type (i.e., recovery target or tax), what are the optimal policy parameters? How do legislated schemes based on recovery targets compare with those based on taxation/subsidies? Finally: Can the policies now in place be improved in any way? We shall address these questions by characterizing the Nash equilibrium of a Stackleberg game between a single firm and a policy maker. In a steady-state model, the policy maker decides on the legislative scheme and its associated parameters (e.g., recovery target or tax level). Once these are known, the firm decides on the prices for new and remanufactured products; these prices determine quantities through demand functions. We study three schemes that a policy maker might seek to implement: (i) a recovery target that sets (similarly to WEEE) a minimum fraction of the products to be recovered by the firm; (ii) a recovery tax imposed on manufacturing along with subsidy on remanufacturing to promote product reuse (similar in part to the CEWRA); and (iii) a mixed approach that includes a recovery target in addition to taxation on manufacturing and subsidies for remanufacturing. To the best of our knowledge, this third approach has not previously been discussed in the literature.

Our results also contribute to the field of closed-loop supply chain management (Atasu et al. 2008a, Guide and Van Wassenhove 2009, Souza 2013), an important offshoot of the sustainable operations literature (Kleindorfer et al. 2005, Corbett and Klassen 2006, Drake and Spinler 2013). More specifically, our framework is related to a growing literature within sustainable operations management that studies legislative schemes to promote product take back (see Atasu and Wassenhove 2012, for a recent review). Jacobs and Subramanian (2012) study the supply chain coordination issues in the presence of take-back laws. Plambeck and Wang (2009) investigate the decision to introduce a new product when such laws are enforced. In examining the strategic implications of product recovery, Webster and Mitra (2007) analyze the game between manufacturer and remanufacturer in a two-period model when there are take-back laws. Toyasaki et al. (2011) add a competitive dimension; they compare the monopolistic and competitive take-back schemes by analyzing the game between recycler and manufacturer. These authors find that competitive take-back schemes result in higher profits for both manufacturer and recyclers and often result in lower consumer prices; however, they do not consider remanufacturing as a business strategy. In contrast, Karakayali et al. (2012) and Esenduran and Kemahlıoğlu-Ziya (2015) do consider remanufacturing and its implications for the firm in a strategic environment. Karakayali et al. (2012) explore how remanufacturing requirements affect recovery levels and the environment. Esenduran and Kemahlıoğlu-Ziya (2015) look at the remanufacturing levels that follow the introduction of recovery legislation. They also investigate whether take-back laws lead firms to design a “greener” product. All these studies analyze a firm’s decision in the presence of legislation. Our paper differs in that it also characterizes the optimal legislation parameters by solving the regulator’s problem. In this context, we know of only two other papers, Atasu et al. (2009, 2013), that model the strategic environment as a game between policy maker and a firm and that describe not only the optimal policy parameters but also the firm’s decision variables. Yet two important factors distinguish our study from the papers of Atasu and colleagues. First, we try to capture the environmental footprint of the product *over its lifecycle* and consider product reuse and remanufacturing consistent with both the US and EU environmental agency guideline of 3R approach (Reduce, Reuse and Recycle; EPA 2015). Second, a central theme of our research—namely, presenting the notion and merits of a mixed approach—is not studied elsewhere. We also study, in addition to the extant welfare-based objective function, a quantity-based objective function under which welfare can be computed without the need for unit cost estimates.

The rest of this paper proceeds as follows. In Section 2.2 we present a demand model by first formulating customer preferences and then giving a formal description of the game between a firm and a policy maker. In this section we also elaborate on various legislative schemes (and their parameters) within a unifying framework before presenting our solution to firm's problem. In Section 2.3 we introduce a social welfare function; given the optimal behavior of the firm. In Section 2.4, we then characterize the policy maker's optimal decisions in terms of specific policy parameters and of the best policy scheme. In Section 2.5, we explore the firm and policy maker's preference over a market strategy in presence of legislative schemes. In Section 2.6, we introduce a quantity-based objective function for the policy maker as a robustness check and then compare the results with those found previously. Section 2.7 concludes the paper.

2.2. The Model

In this section we lay out the foundations of our model and introduce the various policies that have been designed to promote product recovery.

2.2.1. Demand Formulation and Customer Preferences There is a monopolistic *firm* that offers a single homogenous product. The dynamics of the product's life cycle is captured by a steady-state model in which the new product's price is p and the firm regularly collects, remanufactures, and resells a fraction of the product in the market at price p_r (where the subscript r stands for "remanufactured"). To model customer demand, we consider two distinct firm strategies regarding new and remanufactured products. In the first strategy, both product types are introduced through the same market channel. An example of this strategy is selling refurbished laptops via the Web stores of companies such as Apple, Dell, and Hewlett-Packard. However, that strategy risks triggering "demand cannibalization" (Ferguson and Toktay 2006), whereby sales of the remanufactured product eat into sales of new products. A different strategy, which is often used with products (e.g., cellphones) characterized by a shorter life cycle and a higher level of technological growth, involves supplying remanufactured products to a separate, distinct market that lags behind in technological growth and typically also in economic prosperity. For example, Apple's website offers reconditioned personal computers and laptops but no refurbished iPhones. Instead, Gazelle—a "recommerce" firm that specializes in Apple products—buys back used cellular phones, remanufactures/refurbishes them, and sells them in Asian or African markets.[1] Clearly, customer choices and hence total demand are affected by the firm's choice of a *single-market* versus a *dual-market* strategy. Next we shall formulate customer demand under each of these strategies.

2.2.1.1. *Single-Market Strategy.* In this case, we assume that there exists only one market and that the firm offers both new and remanufactured products to the same market. Following Ferguson and Toktay (2006), we assume also that customer utility from consumption of the new product is given by $\tilde{u} = \tilde{\theta} - p$, where $\tilde{\theta}$ denotes the random valuation of customers for the *new* product (that valuation is assumed to be uniformly distributed over the interval $[0, 1]$). Similarly, customer utility from consumption of the *remanufactured* product is given by $\tilde{u}_r = \delta\tilde{\theta} - p_r$; here $\delta \in [0, 1]$ denotes how much customer value is discounted for the remanufactured product as compared with the new product. A high δ signifies that customer valuation of the remanufactured product is relatively high, which implies that customers' willingness to pay for it is high. Thus the discount factor δ also represents a customer's willingness to pay for the remanufactured product. Without loss of generality, we normalize the total market size to 1. Ferguson and Toktay (2006) show that,

[1] According to (BusinessWeek 2005), Gazelle has supplied nearly half a million cellular devices to Asian markets and predicts even more future growth.

under these assumptions, the demand functions for the new and remanufactured products are given (respectively) by

$$q^s = \frac{1-\delta-p+p_r}{1-\delta} \quad \text{and} \quad q_r^s = \frac{\delta p - p_r}{\delta(1-\delta)}; \tag{1}$$

here the superscript s is used to mark a single-market strategy. This model has been widely used in the literature (Webster and Mitra 2007, Atasu et al. 2008b, Karakayali et al. 2012, Esenduran and Kemahlıoğlu-Ziya 2015) and captures the cannibalization effect. Note that increasing new product prices reduces the demand for new products but increases demand for remanufactured ones; conversely, reducing new product prices will increase the demand for them while reducing demand for remanufactured products.

2.2.1.2. *Dual-Market Strategy.* With distinct primary and secondary markets, we use the same utility principle to determine the demands of new and remanufactured product—but with the additional assumption that the remanufactured product is not available in the primary product market. In this case, a customer in the primary market derives utility $\tilde{\theta} - p$ from a new product, which implies that the probability of purchase is equal to $\Pr(\tilde{\theta} - p \geq 0) = \Pr(\tilde{\theta} \geq p) = 1 - p$. Analogously, only the remanufactured product is available in the secondary market. In this scenario we assume that customer valuation of the remanufactured product, $\tilde{\theta}_r$, is uniformly distributed in $[0, \Delta]$ (where $\Delta < 1$). The parameter Δ captures the lower valuation for the remanufactured product in the secondary market; something consistent with empirical observations that, in secondary markets, customers are more price sensitive and thus less willing to pay. The probability of purchase in this market is therefore equal to $\Pr(\tilde{\theta}_r - p_r \geq 0) = \Delta - p_r$. If we use Λ to denote the size of the potential secondary market, then total demand can be written as $q_r^d = \Lambda(\Delta - p_r)$ (where the superscript d is used to mark the dual-market strategy). In sum, total demand for new products and remanufactured products under a dual-market strategy are, respectively,

$$q^d = 1 - p \quad \text{and} \quad q_r^d = \Lambda(\Delta - p_r). \tag{2}$$

Having introduced our demand functions under the two different market strategies, our next task is to characterize the firm's problem under different legislated policy schemes. Throughout the paper, the absence of a superscript for demand quantities (as in q, q_r) signifies demand in its general form—that is, independent of the market structure.

2.2.2. The Firm's Problem and Legislated Policies There is a *policy maker* who seeks to regulate the market by way of legislatively enacted policy options. Such policies, once implemented, will affect the firm's decision process by altering its objective functions. In what follows we describe various legislated policies as well as the firm's objective function under each of them.

2.2.2.1. *No Legislation* ($\mathcal{P}_{\mathcal{N}}$). In this benchmark case, the policy maker refrains from market intervention. Under that scenario, the firm retrieves only the quantity equivalent to the demand of remanufactured products—because otherwise the firm risks incurring the cost of disposing the extra recovered products. The firm seeks to maximize its total profit,

$$\max_{p,p_r} \pi_{\mathcal{N}} = q(p-c) + q_r(p_r - c_r), \tag{3}$$

subject to the standard restriction to nonnegative variables (which we observe throughout but mention explicitly only here). Here c and c_r denote the unit manufacturing and remanufacturing costs, respectively, and q and q_r are the demand quantities given in Section 2.2.1.[2] So when the policy maker does not intervene, the optimal fraction of products to be remanufactured is $\phi^*_{\mathcal{N}} = q^*_r/q^* \geq 0$.

[2]In steady state, the remanufactured quantity is constrained not only by the availability of used manufactured products (known as *cores*) but also by market demand; that is, $q \geq q_r$. When this constraint is binding, there is no need to introduce any legislation that promotes product recovery. We focus only on the interesting case of when the constraint is not binding and so ignore the alternative hereafter.

2.2.2.2. *Recovery Target ($\mathcal{P}_\mathcal{R}$).* In this case, the policy maker addresses concerns about the effects of products left in the environment by establishing a recovery target. Thus the policy maker requires that firms recover at least some specified fraction $\phi_\mathcal{R} \in [\phi^*_\mathcal{N}, 1]$ of the quantity produced. Under that scenario, the firm remanufactures an amount equivalent to the demand q_r and disposes the remaining collected material at a unit cost of c_d. The firm's problem is then given by

$$\max_{p,p_r} \pi_\mathcal{R} = q(p-c) + q_r(p_r - c_r) - c_d(\phi_\mathcal{R} q - q_r). \tag{4}$$

The unit cost of disposal, c_d, includes the cost of product recovery, dismantling, removing any toxic content (e.g., lead, mercury) in accordance with prevalent environmental regulations, recycling the reusable components, and properly disposing the waste through incineration or landfilling. This cost varies widely among different product categories—and even within a given product category—as a function of the recovery program's efficiency. The Specified Home Appliances Recycling (SHAR) program in Japan requires that consumers deposit the equivalent of \$18–\$24 (USD) when returning a used television set. Similarly, Australian recycler MRI charges \$5.50 for recycling computers and notebooks, \$12 for a CRT screen, and \$7 for an LCD screen (Australian Recycler MRI 2014). In practice, the magnitude of the recovery target ϕ depends on recovery costs and also on possible environmental hazards due to unrecovered products. In the European Union, where recovery laws were enacted as early as 2003, legislation imposes 50%–70% recovery levels depending on the product category.

2.2.2.3. *Taxation on Manufacturing with Subsidy on Remanufacturing ($\mathcal{P}_\mathcal{T}$).* Under policy $\mathcal{P}_\mathcal{T}$ we consider the case in which there is a manufacturing tax per unit sale of the new product and also a per-unit remanufacturing subsidy. In this case, the firm's problem is

$$\max_{p,p_r} \pi_\mathcal{T} = q(p - c - t_\mathcal{T}) + q_r(p_r - c_r + s_\mathcal{T}). \tag{5}$$

Thus the new product's profit margin is reduced by the per-unit tax amount $t_{\mathcal{T}}$ while the remanufactured product's margin is augmented by the per-unit subsidy amount $s_{\mathcal{T}}$. The cost of remanufacturing includes all costs associated with restoring the product to "like new" condition by dismantling it, inspecting and replacing defective components, and reassembly. The remanufacturing operation is only 30%–50% as costly as manufacturing and uses just 10%–20% of the energy (Toffel 2004, BusinessWeek 2005). The Ontario Stewardship program in Canada and the CEWRA in the United States are two examples of imposing a recovery taxation on product sales. In Ontario, a $1.50 tax and a $3 tax is charged on the sale of laptops and desktops, respectively, and a $40 tax is charged on the sale of any TV set (Waste Diversion Ontario 2005). There is currently little evidence of a subsidy structure being incorporated into product remanufacturing, but the topic is extensively and visibly debated in academic circles and policy-making bodies (Mitra and Webster 2008). The special case of $s_{\mathcal{T}} = 0$ corresponds to what is widely practiced today.

Our subsidy in case when the firm choses a dual market strategy where the products are potentially exported to another country is a form of export subsidy. The rational behind export subsidies have been well studied in the economics literature (see e.g. Kinnaman and Yokoo. 2011, and the references within). OECD Publishing (2001) suggest export subsidies to offset the environmental effects of used/remanufactured products but caution that such subsidies can be countered by an "import tax" imposed by a local regulator. Legal frameworks in many jurisdictions also provide incentives for remanufacturing in the country of origin, which means that the remanufacturing subsidies should be paid there. For example The Basel Convention (2011) prevents the transboundary movement of any non-functional product. In most countries, export of any used products to developing market requires consent of the country-of-origin's regulator. As such, the regulator may very well take into account customer surplus in a foreign market, especially when taking such measures is budget neutral.

2.2.2.4. *Recovery Target Plus Taxation on Manufacturing with Subsidy on Remanufacturing ($\mathcal{P}_{\mathcal{M}}$).* This policy is a mixed approach that combines the features of both previously described policies. A recovery target is imposed; at the same time, a tax is placed on unit manufacturing and a subsidy is provided to unit remanufacturing. The firm's problem under this policy is as follows:

$$\max_{p,p_r} \pi_{\mathcal{M}} = q(p - c - t_{\mathcal{M}}) + q_r(p_r - c_r + s_{\mathcal{M}}) - (\phi_{\mathcal{M}} q - q_r)c_d. \tag{6}$$

The main goal of both recovery target policies ($\mathcal{P}_{\mathcal{R}}$) and tax/subsidy policies ($\mathcal{P}_{\mathcal{T}}$) is to reduce the environmental footprint of products; these approaches differ mainly in their respective mechanisms. Whereas the $\mathcal{P}_{\mathcal{R}}$ approach aims to reduce products left in the environment by enforcing recovery, the tax/subsidy policy $\mathcal{P}_{\mathcal{T}}$ penalizes new product manufacturing and incentivizes reuse through a remanufacturing subsidy. The mixed policy $\mathcal{P}_{\mathcal{M}}$ aims to use all these levers and to strike the appropriate balance between the "hard constraint" and "soft constraint" approaches. It is worth noting that a variety of other hybrid policies can be developed with the same goal. For example, the policy maker could implement a recovery target along with a tax on product *disposal* (instead of on manufacturing) in addition to a subsidy on remanufacturing. We can easily show that this particular policy is mathematically equivalent to our $\mathcal{P}_{\mathcal{M}}$ but with different administrative implications.

2.2.3. The Firm's Behavior under a Fixed Policy In this section we study the firm's behavior by characterizing the optimal prices for new and remanufactured products under an exogenous fixed policy.

Policy i	T_i	S_i
$\mathcal{N}$	0	0
$\mathcal{R}$	$\phi_{\mathcal{R}} c_d$	c_d
$\mathcal{T}$	$t_{\mathcal{T}}$	$s_{\mathcal{T}}$
$\mathcal{M}$	$\phi_{\mathcal{M}} c_d + t_{\mathcal{M}}$	$c_d + s_{\mathcal{M}}$

Table 2 Effective tax and effective subsidy for each policy.

2.2.4. A Unifying Framework. It is easy to demonstrate that the firm's problem under all the policies mentioned previously can be studied within a unified framework wherein the manufacturing cost is increased by an *effective tax* T_i for each policy i while the remanufacturing cost is subsidized by an *effective subsidy* S_i, where T_i and S_i are as given in Table 2. In other words, even the pure recovery target policy effectively increases manufacturing costs as compared with the case of no intervention. The same considerations apply with respect to the mixed policy $\mathcal{P}_{\mathcal{M}}$. We must therefore distinguish these *effective* taxes/subsidies from *policy-specific* taxes/subsidies. In this general framework, the firm's problem is

$$\max_{p,p_r} \pi_i = q(p - c - T_i) + q_r(p_r - c_r + S_i). \tag{7}$$

We now employ this unified framework to study the firm's optimal behavior under a fixed policy. As before, the subscript i indexes the policy under which the firm operates.

Proposition 1. *The optimal prices for new and remanufactured products are*

$$p^* = \frac{1}{2}(1 + c + T_i) \quad \text{and} \quad p_r^* = \frac{1}{2}(d + c_r - S_i), \tag{8}$$

respectively, where $d = \delta$ for a single-market strategy and $d = \Delta$ for a dual-market strategy.

Proposition 1 describes the optimal prices for new and remanufactured products under the firm's different market strategies. We observe that, in each market structure, the new product price is the same and increases proportionally with both the cost of manufacturing and the effective tax. Similarly, as customers' willingness to pay d increases and as the remanufacturing cost c_r increases, the remanufactured product's price also increases. These observations are hardly surprising, yet of perhaps some larger interest is how prices are affected by the effective taxes/subsidies. According to Proposition 1, introducing such legislation increases the price of manufactured product in a linear fashion. Hence every unit of effective tax imposed on manufacturing translates directly to a one-unit increase in the new product's price; a unit of effective subsidy likewise reduces the price of remanufactured products in a unit-for-unit fashion. It is noteworthy that the optimal prices for remanufactured products differ only in the used-product discount parameters δ and Δ across the two market strategies; therefore, the respective optimal prices are equal whenever $\delta = \Delta$ (i.e., when potential buyers of remanufactured products value them the same regardless of whether new products are available through the same channel).

LEMMA 1. *Case (a): Single-Market Strategy (i)* $q > 0$ *if and only if (iff)* $T_i + S_i < 1 - \delta - c + c_r$;

(ii) $q_r > 0$ *iff* $S_i + \delta T_i > c_r - \delta c$; *and*

(iii) $q > q_r$ *iff* $S_i(1+\delta) + 2\delta T_i < \delta(1 - \delta + c_r - 2c) + c_r$.

Case (b): Dual-Market Strategy (i) $q > 0$ *if and only if* $T_i < 1 - c$;

(ii) $q_r > 0$ *iff* $S_i > c_r - \Delta$; *and*

(iii) $q > q_r$ *iff* $\Lambda S_i + T_i < 1 - c + \Lambda(c_r - \Delta)$.

Lemma 1 gives necessary and sufficient conditions for the feasibility of manufacturing and remanufacturing under the firm's single- or dual-market strategy. In essence, these conditions are upper and lower bounds on the values of feasible effective taxation and subsidy. We observe that the condition for manufacturing feasibility is more difficult to satisfy when the firm pursues a single-market strategy (owing to cannibalization), from which it follows that the condition for remanufacturing feasibility is easier to satisfy with a single-market strategy. These observations are consistent with findings in the literature (see e.g. Karakayali et al. 2012). Our focus throughout the analysis is on the more interesting case in which both manufacturing and remanufacturing are feasible—in other words, cases where the conditions presented in Lemma 1 are satisfied.

Once the focal legislated policies have been implemented, the condition for profitable manufacturing (resp., remanufacturing) becomes tighter (resp., more relaxed). Proposition 1 and Lemma 1 together confirm our intuition that market intervention leads to reduced incentives for producing new products (an economic disadvantage) yet to greater incentives for remanufacturing (an environmental advantage). In the next section we seek a balance between these effects by presenting the policy maker's optimal decision.

2.3. Optimal Legislated Policies: A Social Welfare Perspective

We first present the policy maker's objective function in terms of social welfare; we then present our equilibrium analysis.

2.3.1. Policy Maker's Objective Function Anticipating the optimal reaction of the firm studied in Section 2.2, for each policy $i \in \{\mathcal{R}, \mathcal{T}, \mathcal{M}\}$ the policy maker selects the optimal policy parameters that maximize its objective function

$$O_i = \Pi_i - G_i. \tag{9}$$

This function has an economic component Π_i as well as an environmental footprint or 'green' component G_i. Throughout this section, we follow the established approach in the literature (Atasu et al. 2009, 2013, Krass et al. 2013) and assume that each of these components can be measured in both monetary terms and surplus terms. This approach clearly requires a monetary estimate of the cost and benefit components, which may not always be possible. For that reason, in Section 2.6 we take a different approach and consider quantities of manufactured and remanufactured products as representing economic and ecological costs or benefits. We show there that most of our results are robust to that transformation.

The economic part of the policy maker's objective function,

$$\Pi_i = \pi_i + \mathrm{CS}_i - C_i,$$

has three main components: the firm's profit π_i, the customer surplus CS_i, and the policy's direct cost C_i. As explained in Section 2.2.3, the firm's profit is given by $\pi_i = q(p - c - T_i) + q_r(p_r - c_r + S_i)$. Customer surplus is the total utility of the customers in the market, which is calculated as

$$\mathrm{CS}_i^s = \int_{\frac{p-p_r}{1-\delta}}^{1} (\theta - p)\, d\theta + \int_{p_r/\delta}^{\frac{p-p_r}{1-\delta}} (\delta\theta - p_r)\, d\theta \tag{10}$$

under a single-market strategy or as

$$\mathrm{CS}_i^d = \int_{p}^{1} (\theta - p)\, d\theta + \int_{p_r}^{\Delta} \Lambda(\theta - p_r)\, d\theta \tag{11}$$

under a dual-market strategy. After solving these equations, we can write the customer surplus in terms of demand quantity under the two market strategies as

$$\mathrm{CS}_i^d = \frac{1}{2}\frac{\Lambda q^2 + q_r^2}{\Lambda}, \qquad \mathrm{CS}_i^s = \frac{1}{2}\big((q + \delta q_r)^2 + \delta(1-\delta)q_r^2\big). \tag{12}$$

Finally the direct cost C of policies—in other words, the money that the policy maker pays to the firm (in the form of subsidies) that *exceeds* the tax it collects—is $C_{\mathcal{R}} = 0$ for $\mathcal{P}_{\mathcal{R}}$ (because there is no tax or subsidy involved). The direct cost of policies $i \in \{\mathcal{T}, \mathcal{M}\}$ are $C_i = q_r s_i - q t_i$.

The environmental or green component of the policy maker's objective function,

$$G_i = \mathrm{EP}_i + \mathrm{EOL}_i,$$

consists of the environmental impact during production (EP_i) and the impact after the product's end of life (EOL_i) when products are not retrieved, remanufactured, or disposed of properly. The environmental footprint during production includes the consumption of resources, the emissions associated with the production process, and total energy consumption (these factors are also identified under approaches based on analyzing the product's life cycle). Environmental effects that are evident after the product's end of life include the contamination of land and/or water resources as well as any emissions stemming from waste incineration by municipalities. In order to state these effects in monetary terms, Raz et al. (2013) assign unit costs to each. We follow the same approach, using ε to denote the unit cost of production effects and γ to denote the unit cost of effects after the product's end of life. In this paper we assume that, from the policy maker's perspective, the cost associated with a product that is simply dumped in the environment is higher than the cost associated with properly disposing of it (i.e., $\gamma > c_d$); otherwise, there is no avenue for policy intervention. In short, the total environmental cost of a policy is the sum of environmental effects due to the production of new products and of environmental effects arising subsequent to the useful life of those products. We ignore the environmental costs associated with actually using the product because, it brings a temporal dimension to the model which is beyond the scope of this paper.[3]

[3]Such costs are significant for some products but are negligible for others. An example of the latter is the average yearly consumption of an iPhone: 2.2 kWh, which costs the typical US electricity consumer about 25 cents (California EPRI 2012).

2.4. Equilibrium Analysis

For each policy, we present the optimal parameters in equilibrium based on our results in Section 2.2.3 and the policy maker's objective function elaborated in Section 2.3.1. We then compare the policies and market structures in terms of those derived equilibria.

2.4.1. Policy $\mathcal{R}$. Let $E = \varepsilon + \gamma$ represent the total environmental cost that the policy maker associates with the production and end-of-life effects of a unit product, and let $\underline{E}$, $\bar{E}$, and ξ be the positive auxiliary parameters—respectively, the minimum and maximum of E—defined formally in Appendix 1.

PROPOSITION 2. *Case (a): Single-Market Strategy (i) The optimal recovery target $\phi_{\mathcal{R}}^{s*} = 0$ if and only if $E < \underline{E} - \xi$, and*

(ii) $\phi_{\mathcal{R}}^{s*} = 1$ iff $E > \bar{E} - \xi$;

(iii) otherwise, the optimal recovery target is given by

$$\phi_{\mathcal{R}}^{s*} = \frac{2Ec_d - (1-c)(3c_d - 2\gamma)}{c_d(4\gamma - 3c_d)} + \xi. \tag{13}$$

Case (b): Dual-Market Strategy (i) The optimal recovery target $\phi_{\mathcal{R}}^{d*} = 0$ if and only if $E < \underline{E}$, and

(ii) $\phi_{\mathcal{R}}^{d*} = 1$ iff $E > \bar{E}$;

(iii) otherwise, the optimal recovery target is given by $\phi_{\mathcal{R}}^{d*} = \phi_{\mathcal{R}}^{s*} - \xi$.

Cases (a) and (b) in Proposition 2 present the optimal policy parameters for single- and dual-market strategies, respectively. If the total unit environmental cost E is low, then the policy maker finds it optimal not to intervene and sets $\phi_{\mathcal{R}}^{*} = 0$; recall that the firm will remanufacture the fraction $\phi_{\mathcal{N}}^{*}$ of its products in any case provided remanufacturing is profitable. If the total environmental cost is extremely high (i.e., high $\bar{E}$), then the policy maker implements the strictest level of regulation: $\phi_{\mathcal{R}}^{*} = 1$. However, if the total environmental cost is equal to some intermediate value, then the policy maker sets a recovery target in the $(0,1)$ interval.

Comparing the firm's two market strategies (single versus dual), we observe that the optimal recovery target under a single-market strategy is higher (because $\xi \geq 0$). The reason is that, when cannibalization is a concern, the firm is naturally more reluctant to recover and remanufacture; hence the policy maker puts a stricter policy in place by increasing the recovery target value.

When there are two distinct markets, the optimal recovery target ϕ^{d*} is independent of the demand parameters associated with the remanufactured product (i.e., of c_r and δ). Yet in a single-market setting, the cannibalization effect causes $\phi^{s*}_{\mathcal{R}}$ to be increasing in c_r but decreasing in δ. So as the remanufactured product becomes less attractive in the market, the policy maker will put less emphasis on regulation that favors remanufacturing.

2.4.2. Policy $\mathcal{T}$. Recall from Proposition 1 that d is equal to δ or Δ according as whether the firm pursues a single-market or a dual-market strategy.

PROPOSITION 3. *The optimal taxation and subsidy under policy $\mathcal{T}$ are, respectively,*

$$t^*_{\mathcal{T}} = -1 + c + 2E \quad \textit{and} \quad s^*_{\mathcal{T}} = d - c_r + 2\gamma. \tag{14}$$

It is interesting that the optimal tax is equal across both market strategies. Furthermore, the policy maker will encourage remanufacturing more in the market strategy where customer valuation for remanufactured products is higher. For example, if $\Delta > \delta$ then Proposition 3 suggests that the optimal subsidy under a dual-market strategy is higher than under a single-market strategy. This result runs counter to the argument that incentives for remanufacturing should be higher in a single-market setting, where the firm is more reluctant to remanufacture. Which finding applies to a given situation depends, naturally enough, on the demand parameters—in particular, on customer valuation of remanufactured products under the two market structures.

It is intuitive why increasing the total unit environmental cost E leads to higher production taxes, much as increasing the cost of end-of-life effects leads to higher subsidies for remanufacturing. However, matters are less straightforward with respect to the unit manufacturing and remanufacturing costs. We remark that, as the product cost c increases, so does the optimal manufacturing tax. This dynamic arises because higher product cost leads to less customer surplus (through increased price) and less firm profit (through decreased demand). As a result, the policy maker seeks to balance these adverse effects by increasing the environmental benefits of lower consumption—that is, by further increasing the manufacturing tax. The same logic explains why increased remanufacturing cost c_r leads to a *lower* remanufacturing subsidy. These seemingly counterintuitive results follow directly from how the policy maker's objective function is specified. Therefore, in Section 2.6 we consider an alternative objective function based on product quantities.

Proposition 3 also provides a framework for considering trade-offs faced by the firm when designing a product. On the one hand, a firm can invest in product design to reduce c; however, such redesign could increase the remanufacturing cost and also the product's EOL environmental cost. This might happen if, for example, the product's modularity were reduced (Zhang and Gershenson 2003). But under a taxation/subsidy scheme, the net benefits of a redesign might well be offset by increased manufacturing taxes (due to increased E). On the other hand, a firm that increases product cost in order to reduce environmental effects may receive a payoff in terms of lower manufacturing taxes. Finally, observe that the optimal tax structure creates an asymmetric incentive for the firm to invest in reducing ε versus γ: whereas high ε does not benefit the firm (in fact, it increases the firm's tax), high γ does lead to a larger remanufacturing subsidy.

2.4.3. Policy $\mathcal{M}$. The following proposition presents the optimal parameters for the mixed approach that combines policy variables from $\mathcal{P}_{\mathcal{R}}$ and $\mathcal{P}_{\mathcal{T}}$.

PROPOSITION 4. *The optimal values of recovery target, taxation, and subsidy values in this case are given, respectively, as follows:*

$$\phi^*_{\mathcal{M}} = 1, \quad t^*_{\mathcal{M}} = -1 + c + c_d + 2\varepsilon, \quad s^*_{\mathcal{M}} = d - c_r + c_d. \tag{15}$$

We find that it is optimal for a policy maker to enforce a maximum recovery level. A 100% recovery target is not unheard of—and is consistent with the results of Atasu et al. (2009, 2013), who propose a full recovery target under a different policy scheme. We also note that the optimal taxation and subsidy in this case are similar to those obtained under $\mathcal{P}_{\mathcal{T}}$. When the recovery target is maximized, the environmental costs associated with the product's EOL phase (γ) are replaced by the disposal cost c_d, which makes both the optimal tax and the optimal subsidy *lower* under $\mathcal{P}_{\mathcal{M}}$ than under $\mathcal{P}_{\mathcal{T}}$ (because $\gamma \geq c_d$). A mixed approach thus places more weight on recovery targets while easing the policy's economic dimension. In Section 2.4.4 we demonstrate the superiority of this approach to either of its components when used alone. We conclude our discussion on optimal policy parameters with the summary given in Table 3.

2.4.4. Comparison of Policies The following corollary presents the ranking order of the policies associated with effective taxes/subsidies, the equilibrium prices, and the optimal quantities of new and remanufactured products.

COROLLARY 1. *Regardless of the firm's market strategy, the following statements hold.*

(i) The optimal effective tax and effective subsidies are ranked as $T^*_{\mathcal{T}} > T^*_{\mathcal{M}} > T^*_{\mathcal{R}}$ *and* $S^*_{\mathcal{T}} > S^*_{\mathcal{M}} > S^*_{\mathcal{R}}$*, respectively.*

Policy Type	Optimal Parameters (single market)	Optimal Parameters (dual market)
$\mathcal{R}$	$\phi^*_{\mathcal{R}} = \frac{2Ec_d+(2\gamma-3c_d)(1-\delta-c+c_r-c_d)}{(4\gamma-3c_d)c_d}$	$\phi^*_{\mathcal{R}} = \frac{2Ec_d+(1-c)(2\gamma-3c_d)}{c_d(4\gamma-3c_d)}$
$\mathcal{T}$	$t^*_{\mathcal{T}} = -1+c+2E$	$t^*_{\mathcal{T}} = -1+c+2E$
	$s^*_{\mathcal{T}} = \delta - c_r + 2\gamma$	$s^*_{\mathcal{T}} = \Delta - c_r + 2\gamma$
$\mathcal{M}$	$\phi^*_{\mathcal{M}} = 1$	$\phi^*_{\mathcal{M}} = 1$
	$t^*_{\mathcal{M}} = -1+c+c_d+2\varepsilon$	$t_{\mathcal{M}} = -1+c+c_d+2\varepsilon$
	$s^*_{\mathcal{M}} = \delta - c_r + c_d$	$s^*_{\mathcal{M}} = \Delta - c_r + c_d$

Table 3 Summary of optimal policy parameters.

(ii) The new and remanufactured product prices are ranked as $p^*_{\mathcal{T}} \geq p^*_{\mathcal{M}} \geq p^*_{\mathcal{R}}$ *and* $p^*_{\mathcal{R}_r} \geq p^*_{\mathcal{M}_r} \geq p^*_{\mathcal{T}_r}$*, respectively.*

(iii) The new and remanufactured product quantities are ranked as $q^*_{\mathcal{R}} \geq q^*_{\mathcal{M}} \geq q^*_{\mathcal{T}}$ *and* $q^*_{\mathcal{T}_r} \geq q^*_{\mathcal{M}_r} \geq q^*_{\mathcal{R}_r}$*, respectively.*

In equilibrium, $\mathcal{P}_{\mathcal{T}}$ puts the highest tax burden on manufacturing and offers the greatest possible incentives for remanufacturing. This approach results in the highest possible prices for new products and hence in fewer new products in the market; another consequence is that the price (resp., quantity) of remanufactured products declines (resp., increases). The opposite happens under $\mathcal{P}_{\mathcal{R}}$, and our mixed approach lies somewhere between the two.

Our next proposition makes this comparison while accounting for all the criteria in the policy maker's objective function (discussed in Section 2.3.1). Let $\mathcal{C}_i \succeq \mathcal{C}_j$ signify the policy maker's preference for policy i over policy j according to criteria $\mathcal{C}$.

Proposition 5. *The following statements hold irrespective of the market structure and the parameters associated with environmental costs: (a)* $\mathcal{C}_{\mathcal{M}} \succeq \mathcal{C}_{\mathcal{T}}$ *for* $\mathcal{C} \in \{EOL, \pi, CS, O\}$*; (b)* $\mathcal{C}_{\mathcal{M}} \succeq \mathcal{C}_{\mathcal{R}}$ *for* $\mathcal{C} \in \{EP, EOL, \pi, CS, O\}$*.*

When $\mathcal{P}_{\mathcal{M}}$ and $\mathcal{P}_{\mathcal{T}}$ are directly compared, Proposition 5(a) indicates that the EOL environmental effects of products are less under $\mathcal{P}_{\mathcal{M}}$ and that the firm's profit (π), the customer surplus (CS), and the total objective function of the policy maker (O)—as defined in Section 2.3.1—are all higher. From an environmental perspective, it is not surprising that $\mathcal{P}_{\mathcal{M}}$ performs better at the end-of-life phase since there is a mandated full recovery target. Nonetheless, the firm produces more under $\mathcal{P}_{\mathcal{M}}$ (since prices are lower per Corollary 1) and so the environmental impact of the production phase is greater under $\mathcal{P}_{\mathcal{M}}$. Yet this increase is offset by the lower EOL environmental impact due to full recovery and by the increase, in both firm profit and customer surplus, that results from lower tax levels. Proposition 5(b) gives similar results when directly comparing $\mathcal{P}_{\mathcal{R}}$ and $\mathcal{P}_{\mathcal{M}}$. The combination of taxes/subsidies and a maximum recovery level renders $\mathcal{P}_{\mathcal{M}}$ superior to $\mathcal{P}_{\mathcal{R}}$ in terms of environmental benefits. In addition, $\mathcal{P}_{\mathcal{M}}$ is economically preferable to $\mathcal{P}_{\mathcal{T}}$ because the former yields greater profitability and more customer surplus, which increases the social welfare value. Given that $\mathcal{P}_{\mathcal{R}}$ and $\mathcal{P}_{\mathcal{T}}$ are essentially constrained versions of $\mathcal{P}_{\mathcal{M}}$, it is not surprising at all to see $\mathcal{P}_{\mathcal{M}}$ performing better when it comes to the objective function O. Yet, our LCA approach allows us to analyse all the subcomponents that make the objective function, including production phase and EOL environmental impacts. All in all, Proposition 5 establishes the superiority of a mixed policy over the policies of pure taxation and pure recovery target from the perspective of *all* the subcomponents of the objective function. This is not mathematically obvious, and is an evidence that there is a synergy effect between $\mathcal{P}_{\mathcal{R}}$ and $\mathcal{P}_{\mathcal{T}}$. The pure tax policy $\mathcal{P}_{\mathcal{T}}$ does not have a direct instrument to curtail the environmental effects during end-of-life phase of the product. Therefore, it lays an additional emphasis on curbing the environmental effects from production phase which leads to additional taxation and a lowering of the economical criteria. On the other hand, $\mathcal{P}_{\mathcal{R}}$ does not have much lever to curtail production and its negative environmental impact. Full mandated recovery target and taxation makes $\mathcal{P}_{\mathcal{M}}$ to dominate both $\mathcal{P}_{\mathcal{R}}$ and $\mathcal{P}_{\mathcal{T}}$ on environmental impacts, while controlling for the economical damage by the subsidy structure.

Our findings are well in tune with a growing number of economists and policy makers who suggest combination of regulatory standards (such as our recovery target) with tax mechanisms (see e.g. West and Wolverton 2005). The standard objection against such hybrid policies is the transaction cost argument which highlights higher implementation cost of such policies. From a practical standpoint Eskeland and Devarajan (1996) note that such combinations require little additional resource for monitoring and enforcement. In fact, according to the European Environmental Agency (EEA) "the EU 6th environmental action programme promotes a blend of instruments: legal requirements ('command and control' measures), technology transfer, market-based instruments, research, environmental liability provisions, green public procurement and voluntary schemes and agreements.". This is because "there is no single universal policy tool that can provide solutions to all problems" (EEA 2012). US Environmental Protection agency has also acknowledged the rising popularity of mixed approaches among the policy makers (see National Center for Environmental Economics 2015). However, they note that such policies are not necessarily the most efficient when it comes to environmental criteria, perhaps based on an intuition that while one policy is medicine a cocktail of two might be poison. On the contrary, our research demonstrates that the mixed approach might actually relieve policy burden from an economic perspective, while providing additional environmental benefits.

Now that we have compared the policy maker's options, in the next section we turn to the firm's strategic decision concerning the selection of an appropriate marketing strategy.

2.5. The Value of Secondary Markets

In this section we explore firms/policy makers incentives between choice of marketing strategy. The firm can stick to the same customer base and offer both new and remanufactured products to the same customer base (Ghose et al. 2005, Oraiopoulos et al. 2012). Some researchers have argued that a diversification of product portfolios (such as offering both manufactured and remanufactured product) allows to fully exploit market potential while others refer to the interface between two customer segments that may lead to demand cannibalization of the primary product[4]. Although, appropriate solutions such as relicensing fees may alleviate the effect of demand cannibalization, the key trade off remains between the additional customer base and risks of demand cannibalization (Oraiopoulos et al. 2012). An alternative strategy is to prevent the interaction between the products in the same portfolio by finding an additional and separate customer base for the remanufactured products. Thus addressing the issue of demand cannibalization while maintaining a market for remanufactured product. As will be explained by Proposition 6, neither strategy dominates and the firms preference depends on on the potential of the additional customer base. In parallel, although a policy maker does not have a direct influence over selection of the firm's market strategy, it may indirectly influence firms choice (by carefully setting of policy parameters) based on which strategy would yield a higher social welfare.

[4]The risk of such cannibalization depends on various factors, including the product's characteristics and its main customers. For example, Guide and Li (2010) show that this risk is higher for a "business/functional product" than for a "consumer product". These authors observe that, for a business product (a Cisco device), customers tend to show interest in both new and remanufactured products simultaneously whereas, for a consumer product (a hand tool), there are two fairly distinct customer groups: those showing interest in a new product seldom demonstrate any interest in the remanufactured version (and vice versa).

Our next proposition compares π_i^d with π_i^s and compares O_i^d with O_i^s toward the end of characterizing the optimal market structure from (respectively) the firm's and the policy maker's viewpoint. The firm shifts from a single-market to a dual-market strategy if and only if $\pi_i^d \geq \pi_i^s$. Similarly, comparison of the respective total social welfare (O_i) will determine the policy maker's preference. Intuitively, the size Λ of the secondary market—along with such customer valuation parameters as Δ and δ—should figure largely in determining the two strategy optima. Proposition 6 confirms this intuition. (For each policy i, the auxiliary variables $\bar{\Delta}_i$ are defined in Appendix 1.)

Proposition 6. *(A) There exists threshold values $\bar{\lambda}_i$ (resp., $\bar{\Lambda}_i$) for the size of the secondary market above which which the firm (resp., the policy maker) prefers the dual-market strategy to the single-market strategy. These threshold values are given in Table 4.*

(B) (i) $\Lambda_{\mathcal{R}} \geq \lambda_{\mathcal{R}}$; (ii) $\Lambda_{\mathcal{N}} \geq \lambda_{\mathcal{N}}$ if and only if $\Delta > \bar{\Delta}_{\mathcal{N}}$; and (iii) $\Lambda_i = \lambda_i$, $i \in \{\mathcal{T}, \mathcal{M}\}$.

(C) (i) $\lambda_{\mathcal{M}} \geq \lambda_{\mathcal{R}}$; (ii) $\lambda_{\mathcal{T}} \geq \lambda_{\mathcal{M}}$ iff $\Delta > \bar{\Delta}_{\mathcal{MT}}$; (iii) $\lambda_{\mathcal{T}} \geq \lambda_{\mathcal{N}}$ iff $\Delta > \bar{\Delta}_{\mathcal{N}}$; and (iv) $\bar{\lambda}_{\mathcal{M}} \geq \bar{\lambda}_{\mathcal{N}}$ iff $\Delta > \bar{\Delta}_{\mathcal{NM}}$.

(D) $\bar{\lambda}_i$ and $\bar{\Lambda}_i$ are decreasing in Δ and are increasing in both δ and c.

Proposition 6 presents several remarkable insights about the adoption of a dual-market strategy. Part (A) presents the respective thresholds, in equilibrium, for the secondary market size over which the firm or policy maker prefers a dual-market to a single-market strategy. One might expect that, since the secondary market size is an exogenous factor, the firm's profit is always higher under a dual-market strategy because it reduces cannibalization. Yet Proposition 6(A) does not confirm this intuition. In fact, for each of the four policies there is a threshold for the secondary market size below which the firm prefers a single-market strategy. Here we should emphasize that, although a dual-channel strategy

Policy i	$\bar{\lambda}_i$	$\bar{\Lambda}_i$
$\mathcal{N}$	$\frac{(\delta c-c_r)^2}{\delta(1-\delta)(\Delta-c_r)^2}$	$\frac{(\delta c-c_r)(3(\delta c-c_r+\gamma+\delta E)+\gamma+\delta E)}{\delta(1-\delta)(\Delta-c_r)(3(\Delta-c_r+\gamma)+\gamma)}$
$\mathcal{R}$	$\frac{R_{\mathcal{R}}^2-\delta(1-\delta)\xi c_d(2-2c-2\phi_{\mathcal{R}}^{d*}c_d-c_d\xi)}{\delta(1-\delta)(\Delta-c_r+c_d)^2}$	$\frac{4\delta(E-\gamma\phi_{\mathcal{R}}^{d*})(R_{\mathcal{R}}+c_d\xi(1-\delta))}{3\delta(1-\delta)(\Delta-c_r+c_d)^2}+\bar{\lambda}_{\mathcal{R}}$
$\mathcal{T}$	$\frac{(\delta c-c_r+\gamma+\delta E)^2}{\delta(1-\delta)(\Delta-c_r+\gamma)^2}$	$\frac{(\delta c-c_r+\gamma+\delta E)^2}{\delta(1-\delta)(\Delta-c_r+\gamma)^2}$
$\mathcal{M}$	$\frac{(\delta c-c_r+c_d+\delta c_d+\delta\varepsilon)^2}{\delta(1-\delta)(\Delta-c_r+c_d)^2}$	$\frac{(\delta c-c_r+c_d+\delta c_d+\delta\varepsilon)^2}{\delta(1-\delta)(\Delta-c_r+c_d)^2}$

Table 4 Secondary-market size threshold above which, for each policy i, the firm (second column) and the policy maker (third column) prefer a dual-market strategy over a single-market strategy.

reduces the risk of cannibalization, it also reduces the firm's ability to sell to those primary market customers with less willingness to pay. In contrast, a single-market strategy increases this ability by expanding the product portfolio offered to that primary customer base from only new to both new and remanufactured items. Therefore, if the risk of cannibalization is low (i.e., if the secondary market size is small) then the firm actually prefers a single-market strategy. Clearly, these market size thresholds differ as a function of the legislated policies faced by the firm.

In Proposition 6(B) we compare the firm's and the policy maker's respective thresholds. Under $\mathcal{P}_{\mathcal{R}}$, the policy maker prefers a single-market strategy for a wider range of the secondary market size because, ceteris paribus, that strategy features lower environmental effects from EOL handling. Under $\mathcal{P}_{\mathcal{N}}$, this is only the case when customer valuation in the secondary market is high enough (i.e., greater than $\bar{\Delta}_{\mathcal{N}}$). Otherwise, the firm is more willing than the policy maker to maintain a single-market strategy because that strategy allows the firm to exploit the higher valuations of primary-market customers by offering them remanufactured products also; in contrast, the policy maker prefers to offset EOL impact by increasing the extent of remanufactured items being offered to secondary market customers. It is interesting that the size threshold does not differ between policies $\mathcal{T}$ and $\mathcal{M}$. This finding suggests another advantage for the mixed policy: it coordinates the incentives of the firm and the policy maker with respect to market strategy. In other words, the policy maker can rest assured that, under either $\mathcal{P}_{\mathcal{T}}$ or $\mathcal{P}_{\mathcal{M}}$, the firm adopts a dual-market structure whenever doing so is optimal also for the policy maker.

Part (C) of the proposition compares the thresholds $\bar{\lambda}_i$ to evaluate different policies in terms of their ability to induce a greater preference (on the firm's side) for a single-market strategy. A firm is more likely to prefer a single-market strategy under the mixed policy approach $\mathcal{P}_{\mathcal{M}}$ than under $\mathcal{P}_{\mathcal{R}}$. The reason is that the effective tax is equal under both marketing strategies in a $\mathcal{P}_{\mathcal{M}}$ regime but is lower under a dual-market strategy in $\mathcal{P}_{\mathcal{R}}$; this difference incentivizes the firm to adopt a dual-market strategy at a lower secondary market size than in the $\mathcal{P}_{\mathcal{R}}$ case. Using similar logic, Proposition 6(C) states that, if offering remanufactured products in a secondary market is sufficiently unappealing (i.e., if Δ is low enough), then $\mathcal{P}_{\mathcal{M}}$ is more likely than $\mathcal{P}_{\mathcal{T}}$ to induce the firm to employ a single-market strategy; conversely, if Δ is high enough then $\mathcal{P}_{\mathcal{T}}$ is more likely than $\mathcal{P}_{\mathcal{M}}$ to effect that desired policy outcome.

Proposition 6(D) presents comparative statics results with regard to the secondary market size thresholds. Our first observation is that all these thresholds move in the same direction as a function of changes in the market parameters Δ, δ, and c. As customers in a potential secondary market begin to value the remanufactured product more highly (i.e., as Δ increases), both the firm and the policy maker prefer the adoption of a dual-market strategy. As customers in the primary market begin to value the remanufactured product more highly (i.e., as δ increases), a larger secondary market is needed to convince either the firm or the policy maker to prefer a single-market strategy. Finally, a higher production cost c leads both firm and policy maker to prefer a single-market strategy. This is because, given the higher price resulting from higher production costs, the firm prefers a single-market strategy with a wider portfolio of products (i.e., both new and remanufactured) that can be sold to its primary customers. Hence there is less need for the policy maker to push firms toward the strategy with less of an environmental footprint (here, the single-market strategy).

2.6. Optimal Policies from the Perspective of Product Quantity

So far we have established the dominance of a mixed policy for a wide range of parameters while using an objective function for the policy maker that is widely used in the literature. In this section we propose an alternative objective function that has two advantages: (i) it does not require unit cost estimates; (ii) it allows us to impose a budget neutrality constraint, which enables a fair comparison between different policies. In this approach, we use the number of products that are recovered from the market to proxy for a policy's environmental effects. Each item recovered reduces the environmental impact of left-over products, regardless of whether it is remanufactured or recycled; hence product recovery is a reasonable and effective measure for the *environmental* performance of a legislated policy. We formalize a policy's *economic* impact as the total number of products in the market, $Q_i = q_i + q_{ri}$, because it captures total customer surplus as well as the firm's profit.

2.6.1. Policy Budget Neutrality The $\mathcal{P}_{\mathcal{R}}$ policy is inherently cost neutral, whereas $\mathcal{P}_{\mathcal{T}}$ and $\mathcal{P}_{\mathcal{M}}$ both require funds in order to provide subsides for remanufacturing. So that we can have a fair price and quantity comparison between these latter two policies and those that do not involve subsides, $i \in \{\mathcal{N}, \mathcal{R}\}$, we impose a budget neutrality constraint for $i \in \{\mathcal{T}, \mathcal{M}\}$.[5] In other words, we impose the condition that these policies do not

[5]For the objective function studied previously in Section 2.3.1, budgetary issues were accommodated by considering the total cost of a policy in the function. Alternatively, in that case one could consider an objective function

require external funds to be allocated for the subsides, which are thus funded solely by the manufacturing-related taxes collected. We have

$$\max_{x_i} \Omega_i(x_i) = \omega R_i + (1-\omega)Q_i \quad \text{s.t. the relevant budget neutrality constraint,} \tag{16}$$

where $x_i \subset \{\phi_{\mathcal{R}}, t_{\mathcal{T}}, s_{\mathcal{T}}, \phi_{\mathcal{M}}, t_{\mathcal{M}}, s_{\mathcal{M}}\}$ and $\Omega_i(x_i)$ are (respectively) the relevant decision variable and the target function under policy i. The policy maker selects the optimal policy (which translates into T_i and S_i) so as to maximize a convex combination of (a) the quantity of recovered products and (b) the total quantity of products in the market.

So in this setup, the convex combination parameter $\omega \in [0,1]$ represents the weight given to "green" concerns by the policy maker. Since higher values of ω correspond to policy makers who are relatively more concerned with environmentally related issues, we refer to ω as the *green weight*.

2.6.2. Optimal Policy Parameter Values The policy maker's problem is solved using the firm's optimal response, as characterized in Proposition 7, to obtain the optimal policy parameters. Then the optimal T_i and S_i are calculated using the values given in Table 2. For each policy $i \in \{\mathcal{R}, \mathcal{T}, \mathcal{M}\}$, let $(\underline{\omega}_i, \bar{\omega})$ signify the lower and upper thresholds of the green weight ω. (See Appendix 1 for the definition of these terms.)

PROPOSITION 7. *There exist threshold values $\underline{\omega}_i$ and $\bar{\omega}_i$ for $i \in \{\mathcal{R}, \mathcal{T}, \mathcal{M}\}$ such that the following statements hold.*

(a) If $\omega \le \underline{\omega}_i$ then $\mathcal{P}_i$ is not optimal.

independent of policy costs while imposing a budget neutrality constraint—although the analysis would quickly become intractable owing to the variety of parameters in that function. Notwithstanding complexity issues, in Section 2.3.1 we chose to remain consistent with the literature in order to facilitate comparability of results across the approaches discussed in this paper.

Policy i	Single-Market Strategy	Dual-Market Strategy
	Optimal Policy Parameters	
$\mathcal{R}$	$\phi^{s*}_{\mathcal{R}} = \frac{1-c-\delta+c_r-c_d}{2c_d}$	$\phi^{d*}_{\mathcal{R}} = \frac{\omega(1-c)-c_d(1-\omega)}{2\omega c_d}$
$\mathcal{T}$	$t^{s*}_{\mathcal{T}} = \frac{1-c}{2} - \frac{1-\omega}{2}\sqrt{\frac{\delta(1-\delta)(1-c)^2+(\delta c-c_r)^2}{1-\delta+\omega^2\delta}}$ $s^{s*}_{\mathcal{T}} = -\frac{\delta-c_r}{2} + \frac{1}{2}\sqrt{\frac{\delta(1-\delta)(1-c)^2+(\delta c-c_r)^2}{1-\delta+\omega^2\delta}}$	$t^{d*}_{\mathcal{T}} = \frac{1-c}{2} - \frac{1-\omega}{2}\sqrt{\frac{(1-c)^2+\Lambda(\Delta-c_r)^2}{(1-\omega)^2+1}}$ $s^{d*}_{\mathcal{T}} = -\frac{\Delta-c_r}{2} + \frac{1}{2}\sqrt{\frac{(1-c)^2+\Lambda(\Delta-c_r)^2}{(1-\omega)^2+1}}$
$\mathcal{M}$	$\phi^{s*}_{\mathcal{M}} = \frac{\delta(1-\delta)\omega^2(1-c)^2-(1-\delta)c_d^2(1-\omega)^2+\omega^2(\delta c-c_r+c_d)^2}{2\delta\omega^2 c_d(1-\delta-c+c_r-c_d)}$ $t^{s*}_{\mathcal{M}} = \frac{(\omega c_r+c_d-\omega\delta-2\omega c_d)(\omega(\delta c-c_r+c_d)+c_d(1-\delta)(1-\omega))}{2\omega^2\delta(1-\delta-c+c_r-c_d)}$ $s^{s*}_{\mathcal{M}} = \frac{\omega c_r+c_d-\omega\delta-2\omega c_d}{2\omega}$	$\phi^{d*}_{\mathcal{M}} = \frac{\omega^2(1-c)^2+\omega^2\Lambda(\Delta-c_r+c_d)^2-c_d^2(1-\omega)^2(1+\Lambda)}{2\omega c_d(\omega(1-c)+c_d(1-\omega))}$ $t^{d*}_{\mathcal{M}} = \frac{\Lambda(\omega\Delta-\omega c_r+c_d)(\omega c_r+c_d-\omega\Delta-2\omega c_d)}{2\omega(\omega(1-c)+c_d(1-\omega))}$ $s^{d*}_{\mathcal{M}} = \frac{\omega c_r+c_d-\omega\Delta-2\omega c_d}{2\omega}$
	Effective Taxes and Effective Subsidies	
$\mathcal{R}$	$T^{s*}_{\mathcal{R}} = \frac{(1-c-\delta+c_r-c_d)}{2}$ $S^{s*}_{\mathcal{R}} = c_d$	$T^{d*}_{\mathcal{R}} = \frac{(\omega(1-c)-c_d(1-\omega))}{2\omega}$ $S^{d*}_{\mathcal{R}} = c_d$
$\mathcal{T}$	$T^{s*}_{\mathcal{T}} = t^{s*}_{\mathcal{T}}$ $S^{s*}_{\mathcal{T}} = s^{s*}_{\mathcal{T}}$	$T^{d*}_{\mathcal{T}} = t^{s*}_{\mathcal{T}}$ $S^{d*}_{\mathcal{T}} = s^{d*}_{\mathcal{T}}$
$\mathcal{M}$	$T^{s*}_{\mathcal{M}} = T^{d*}_{\mathcal{R}}$ $S^{s*}_{\mathcal{M}} = \frac{c_d-\omega(\delta-c_r)}{2\omega}$	$T^{d*}_{\mathcal{M}} = T^{d*}_{\mathcal{R}}$ $S^{d*}_{\mathcal{M}} = \frac{c_d-\omega(\Delta-c_r)}{2\omega}$

Table 5 Optimal policy parameters and effective taxes/subsidies under a quantity-based objective function for the policy maker.

(b) If $\omega \geq \bar{\omega}_i$ then the policy maker implements the most stringent policy parameters, which leads to the highest effective tax.

(c) If $\underline{\omega}_i < \omega < \bar{\omega}_i$, then the optimal values of policy parameters and their associated effective taxes/subsidies are as presented in Table 5.

According to parts (a) and (b) of Proposition 7, the green weight ω has a lower threshold below which policy intervention is suboptimal. On the one hand, part (a) states that if the policy maker is concerned only with the total number of products in the market, then those ends are best served by *not* intervening via legislated policy options. On the other hand, part (b) states that if the policy maker weights environmental concerns highly enough (i.e, if $\omega > \bar{\omega}$), then the policy parameters selected are those that maximize product recovery and remanufacturing: either $\phi = 1$ for policy $i \in \{\mathcal{R}, \mathcal{M}\}$ or selecting a tax/subsidy system that ensures 100% remanufacturing under policy $\mathcal{P}_{\mathcal{T}}$. Between these two extreme cases, the optimal subsidy is always greater than the optimal tax and, by part (c), $\phi^* < 1$ for $i \in \{\mathcal{P}_{\mathcal{R}}, \mathcal{P}_{\mathcal{M}}\}$. Observe that, unlike the results under a social welfare–based objective function, there is no need for "full recovery" (with optimal policy parameters) when our alternative objective function is used. This finding suggests that $\phi^*_{\mathcal{M}} = 1$ is simply a consequence of the particular objective function discussed in Section 2.3.1.

2.6.3. Comparison of Policies In this section, we compare the objective function of the policy maker for each policy when evaluated at the optimal parameters presented in Table 5.

Proposition 8. *(a) (i)* $p^d_{\mathcal{R}} = p^d_{\mathcal{M}}$*, and* $p^s_{\mathcal{R}} > p^s_{\mathcal{M}}$ *if and only if* $\omega < c_d/(\delta - c_r + 2c_d)$*; (ii)* $p_{\mathcal{R}r} \geq p_{\mathcal{M}r}$*; and (iii)* $p_{\mathcal{T}} \geq p_{\mathcal{M}}$*, and* $p_{\mathcal{T}r} \geq p_{\mathcal{M}r}$ *if and only if* $\omega < \bar{\bar{\omega}}$*.*

(b) Irrespective of the market structure and parameters: (i) $\Omega_{\mathcal{M}} \succeq \Omega_{\mathcal{R}}$*; and (ii)* $\Omega_{\mathcal{M}} \succeq \Omega_{\mathcal{T}}$*.*

Proposition 8 characterizes the preference order for the various policies. Part (a) shows that, the new product prices are equal for $\mathcal{P}_{\mathcal{R}}$ and $\mathcal{P}_{\mathcal{M}}$ under a dual-market strategy. Under a single-market strategy, new product price under $\mathcal{P}_{\mathcal{R}}$ only exceeds that of $\mathcal{P}_{\mathcal{M}}$ if the green weight (ω) is sufficiently low. Similarly, for sufficiently low values of green weight, $\mathcal{P}_{\mathcal{T}}$ offers higher prices for new and remanufactured products as compared to $\mathcal{P}_{\mathcal{M}}$.

Part (b) of the proposition establishes the Pareto dominance of $\mathcal{P}_{\mathcal{M}}$ over $\mathcal{P}_{\mathcal{R}}$ (today's most practiced policy), and it also establishes the dominance of $\mathcal{P}_{\mathcal{M}}$ over $\mathcal{P}_{\mathcal{T}}$ with respect to our quantity-based objective function. This result serves as a robustness check on the findings ascertained via proposition 5 because it shows that, even when the objective function for social welfare is modified and budget neutrality is enforced, the $\mathcal{P}_{\mathcal{M}}$ policy still leads to better solutions than do the other two schemes. This superior performance follows because the availability of both inducement levers—recovery targets *and* taxation/ subsidies—allows the policy maker to be more flexible when making adjustments under a range of parameters

2.7. Conclusion

In this paper we studied optimal product take-back legislation using a (Stackelberg) game-theoretic model that accounts for the firm's response to such legislated policies. We employed a unified framework—that incorporates the notions of effective tax and effective subsidies—to consider three different legislated policy schemes along with a no-legislation alternative. We characterized the firm's behavior, which includes both the pricing of new and remanufactured products and the choice of a market strategy (single versus dual channel), in response to implemented policies; we also explained the trade-off between adding a secondary market and cannibalizing the firm's primary market. Using a standard demand model widely used in the literature, we considered an objective function for the policy maker that incorporates both environmental and economic concerns; we then characterized the optimal parameters for each policy scheme and identified the associated marketing strategy preferred by the respective parties (i.e., firm and policy maker).

Legislative intervention in the area of product recovery is designed mainly to protect the environment and create a more sustainable economy. The main environmental benefit from a policy (i.e., $\mathcal{P}_{\mathcal{R}}$) that enforces a minimum recovery target stems from mitigating environmental effects by reducing landfill waste. In contrast, a "soft" incentive scheme (policy $\mathcal{P}_{\mathcal{T}}$) promotes remanufacturing and aims for reduced production. Our central argument in this paper is that a mixed approach that combines the two policies works well in terms of both economic and environmental criteria, which leads to greater social welfare. We have shown our finding to be robust in the sense that it holds under two different objective functions for the policy maker—one that mandates budget neutrality and one that does not.

Our approach can certainly be further enriched along several dimensions, parameter uncertainty (e.g., as regards manufacturing cost) and competitive rather than monopolistic market conditions. That being said, we believe that our principal claim—namely, the superiority of a mixed approach—would not be countered by any of these possible extensions. The model presented here has been cast in a concise but reasonably practical setting that keeps the model tractable and intuitive yet still capable of delivering an important message to policy makers, whose decisions have wide-ranging economic and environmental consequences.

Appendix 1: Summary of Notation

The following table summarizes the notation that we use. In the main text, the subscript indices $\mathcal{N}, \mathcal{R}, \mathcal{T}, \mathcal{M}$ refer to policy types introduced and elaborated in Section 2.2.2; the additional subscript r signifies *remanufactured* product. The superscripts s and d refer to the firm's *single*- and *dual*-market strategies as introduced in (respectively) Sections 2.2.1.1 and 2.2.1.2. The absence of super- or subscript indicates that the variable is in its generic form.

Main Notation	Definition
c	Unit cost of manufacturing
c_r	Unit cost of remanufacturing
c_d	Unit cost of disposal/recycling
δ	Customer's valuation of the remanufactured product in the primary market
Δ	Customer's valuation of the remanufactured product in the secondary market
ε	Environmental cost due to unit production of the new product
γ	Environmental cost due to not recovering a product
$E = \varepsilon + \gamma$	Total environmental cost of a product

Auxiliary Variables	Definition
$\underline{E}$	$= \frac{(1-c)(3c_d-2\gamma)}{2c_d}$
$\bar{E}$	$= \underline{E} + 2(\gamma - 3c_d/4)$
ξ	$= \phi^s_{\mathcal{R}} - \phi^d_{\mathcal{R}} = \frac{(3c_d-2\gamma)(\delta-c_r+c_d)}{c_d(4\gamma-3c_d)}$
$R_{\mathcal{R}}$	$= (\delta c - c_r + c_d + \delta(\phi^{d*}_{\mathcal{R}} + \xi)c_d)$
$\bar{\Delta}_{\mathcal{N}} = \bar{\Delta}_{\mathcal{NT}}$	$= \frac{\delta(Ec_r+\gamma c)}{\delta E+\gamma}$
$\bar{\Delta}_{\mathcal{NM}}$	$= \frac{\delta(\varepsilon c_r+c_d c_r+c_d c)}{\delta\varepsilon+\delta c_d+c_d}$
$\bar{\Delta}_{\mathcal{TM}}$	$= \frac{\delta(c+c_r+\varepsilon)}{1+\delta}$
$\underline{\omega}_{\mathcal{R}}$	$= \frac{c_d}{1-c+c_d}$
$\bar{\omega}_{\mathcal{R}}$	$= \frac{c_d}{1-c-c_d}$
$\underline{\omega}_{\mathcal{T}}$	$= \frac{-1+c+d-c_r}{d-c_r}$
$\bar{\omega}^s_{\mathcal{T}}$	$= \frac{(1-3\Lambda)(\Delta-c_r)+(1-c)(3-\Lambda)}{2(1-c)(\Delta-c_r)}$
$\bar{\omega}^s_{\mathcal{T}}$	$= \frac{(1-\delta)(1-\delta-c)+4\delta c-3c_r-\delta c_r}{4\delta c+\delta c_r-c_r-3\delta-\delta^2}$
$\underline{\omega}^d_{\mathcal{M}}$	$= \frac{c_d\left(\sqrt{(1+\Lambda)\Big((\Delta-c_r+c_d)^2+(1-c)^2\Lambda\Big)}-(1+\Lambda)c_d\right)}{(1-c)^2+\Lambda(\Delta-c_r+c_d)^2-c_d^2(1+\Lambda)}$
$\bar{\omega}^d_{\mathcal{M}}$	$= \frac{c_d}{\Delta-c_r+2c_d}$ iff $c_d > \frac{1}{3(1-\Delta-c+c_r)}$
	$= \frac{\sqrt{(1+\Lambda)\Big(\Lambda(\Delta-c_r+c_d)^2+(1-c-c_d)^2\Big)}-\Lambda c_d^2-\Lambda c_d}{(1-c-c_d)^2+(\Delta-c_r+c_d)^2-\Lambda c_d^2}$ otherwise
$\underline{\omega}^s_{\mathcal{M}}$	$= \frac{c_d\sqrt{(1-\delta)\Big((\delta c-c_r+c_d)^2+\delta(1-\delta)(1-c)^2\Big)}-(1-\delta)c_d^2}{(\delta c-c_r+c_d)^2+\delta(1-\delta)(1-c)^2-(1-\delta)c_d^2}$
$\bar{\omega}^s_{\mathcal{M}}$	$= \frac{c_d}{\delta-c_r+2c_d}$ iff $c_d > \frac{1}{3(1-\delta-c+c_r)}$
	$= \frac{-(1-\delta)c_d+\sqrt{(1-\delta)\Big((\delta c-c_r+c_d)^2+\delta(1-\delta)(1-c)^2-2c_d(1-\delta-c+c_r-c_d)\Big)}}{(\delta c-c_r+c_d)^2+\delta(1-\delta)(1-c)^2-c_d^2(1-\delta)-2c_d\delta(1-\delta-c+c_r-c_d)}$ otherwise
$\bar{\bar{\omega}}^d$	$= \frac{c_d\left(-c_d+\sqrt{(1+\Lambda)((1-c)^2+\Lambda(\Delta-c_r)^2)-\Lambda c_d^2}\right)}{(1-c)^2+\Lambda(\Delta-c_r)^2-c_d^2}$
$\bar{\bar{\omega}}^s$	$= c_d\sqrt{\frac{1-\delta}{\delta(1-\delta)(1-c)^2+(\delta c-c_r)^2-\delta c_d^2}}$

Appendix 2: Proofs

Proof of Proposition 1. The optimal prices are obtained by substituting the demand functions (1) and (2) into the profit function, equation (7), and solving the resulting first-order conditions (FOCs) as follows.

Case 1: Single-Market Strategy

$$\frac{\partial \pi_i^s}{\partial p_i} = \frac{1-\delta+c-c_r+T_i+S_i-2p+2p_r}{1-\delta} = 0;$$
$$\frac{\partial \pi_i^s}{\partial p_{ri}} = \frac{\delta c-c_r+\delta T_i+S_i-2\delta p+2p_r}{\delta(\delta-1)} = 0.$$

Case 2: Dual-Market Strategy

$$\frac{\partial \pi_i^d}{\partial p_i} = 1+c+T_i-2p_i = 0;$$
$$\frac{\partial \pi_i^d}{\partial p_{ri}} = \Lambda(\Delta+c_r-S_i-2p_r) = 0.$$

Solving this system of FOCs yields the optimal prices given in equation (13).

The second-order conditions (SOCs) are checked by calculating the Hessian matrices under each marketing strategy:

$$H^s = \begin{bmatrix} -2/(1-\delta) & 2/(1-\delta) \\ 2/(1-\delta) & -2/\delta(1-\delta) \end{bmatrix}, \qquad H^d = \begin{bmatrix} -2 & 0 \\ 0 & -2\Lambda \end{bmatrix}.$$

Indeed, after calculating the leading principal minors $|H_1^s| = -2/(1-\delta) \leq 0$ and $|H_2^s| = 4/\delta(1-\delta) \geq 0$ (for the single-market case) as well as $|H_1^d| = -2 \leq 0$ and $|H_2^d| = 4\Lambda \geq 0$ (for the dual-market case), we verify that H^d and H^s are each negative semidefinite. This establishes sufficiency of the FOCs.

Proof of Lemma 1. We substitute the optimal prices given in Proposition 1 into the demand functions (1),(2) to obtain $q_i^s = (1-\delta-c+c_r-T_i-S_i)/2(1-\delta)$ and $q_{ri}^s = (\delta c - c_r + S_i + \delta T_i)/2\delta(1-\delta)$ for the single-market strategy and to obtain $q_i^d = (1-c-T_i)/2$ and $q_{ri}^d = \Lambda(\Delta c - c_r + S_i)/2$ for the dual-market strategy. Solving for $q_i \geq 0$, $q_{ri} \geq 0$, and $q_i \geq q_{ri} \geq 0$ yields the desired result.

Proof of Proposition 2. Under $\mathcal{P}_{\mathcal{R}}$, the policy maker can intervene by setting a recovery target $\phi^*_{\mathcal{R}}$ that maximizes the social welfare function given in equation (9). The policy maker's objective function under $\mathcal{P}_{\mathcal{R}}$ is

$$\max_{\phi\in[0,1]} O_{\mathcal{R}}(\phi_{\mathcal{R}}) = \pi_{\mathcal{R}} + \mathrm{CS}_{\mathcal{R}} - \varepsilon q_{\mathcal{R}} - (1-\phi_{\mathcal{R}})\gamma q_{\mathcal{R}}.$$

The SOC is satisfied because $\partial^2 O^s_{\mathcal{R}}/\partial\phi^2_{\mathcal{R}} = -c_d(4\gamma - 3c_d)/4(1-\delta) < 0$ for the single-market case and $\partial^2 O^d_{\mathcal{R}}/\partial\phi^2_{\mathcal{R}} = -c_d(\gamma - 3c_d/4) < 0$ for the dual-market case. Since we have assumed $\gamma \geq c_d$, it follows that the optimal $\phi_{\mathcal{R}}$ satisfies the first-order conditions given next.

Case 1: Single-Market Strategy

$$\frac{\partial O^s_i}{\partial \phi^s_{\mathcal{R}}} = (3c_d - 2\gamma)(1 - c - c\delta + c_r) + \phi^s_{\mathcal{R}} c_d(4\gamma - 3c_d) - c_d(3c_d + 2\varepsilon) = 0.$$

Case 2: Dual-Market Strategy

$$\frac{\partial O^d_{\mathcal{R}}}{\partial \phi^d_{\mathcal{R}}} = -(1-c)(2\gamma - 3c_d) + 2Ec_d + 3c_d(\phi^d_{\mathcal{R}} c_d + c) = 0.$$

Solving and simplifying these FOCs, we obtain $\phi^{d*}_{\mathcal{R}}$ and $\phi^{s*}_{\mathcal{R}}$; the respective values of optimal effective taxes and subsidies are then derived from Table 2. Solving for $\phi^{s,d}_{\mathcal{R}} > 0$ and $\phi^{s,d}_{\mathcal{R}} < 1$ yields (respectively) the upper and lower thresholds on the total environmental cost E.

Proof of Proposition 3. The policy maker's objective function for $\mathcal{P}_{\mathcal{T}}$ is

$$\max_{t_{\mathcal{T}}, s_{\mathcal{T}}} O_{\mathcal{T}}(t_{\mathcal{T}}, s_{\mathcal{T}}) = \pi_{\mathcal{T}} + \mathrm{CS}_{\mathcal{T}} - C_{\mathcal{T}} - q_{\mathcal{T}}\varepsilon - (q_{\mathcal{T}} - q_{\mathcal{T}_r})\gamma.$$

The FOCs for each market strategy are given as follows.

Case 1: Single-Market Strategy

$$\frac{\partial O^s_{\mathcal{T}}}{\partial t^s_{\mathcal{T}}} = \frac{-1 + c - c_r + \delta + 4\gamma + 2\varepsilon - s^s_{\mathcal{T}} - t^s_{\mathcal{T}}}{4(1-\delta)} = 0;$$

$$\frac{\partial O^s_{\mathcal{T}}}{\partial s^s_{\mathcal{T}}} = \frac{\delta c - c_r + 2\gamma\delta + 2\delta\varepsilon + 2\gamma - s^s_{\mathcal{T}} - \delta t^s_{\mathcal{T}})}{4\delta(1-\delta)} = 0.$$

Case 2: Dual-Market Strategy

$$\frac{\partial O^d_{\mathcal{T}}}{\partial t^d_{\mathcal{T}}} = \frac{-1+c+E-t^d_{\mathcal{T}}}{4} = 0;$$
$$\frac{\partial O^d_{\mathcal{T}}}{\partial s^d_{\mathcal{T}}} = \frac{\Lambda(\Delta - c_r + 2\gamma - s^d_{\mathcal{T}})}{4} = 0.$$

The SOCs are checked by calculating the Hessians for both the single- and dual-market cases:

$$H^s = -\frac{1}{4(1-\delta)}\begin{bmatrix} 1 & 1 \\ 1 & 1/\delta \end{bmatrix}, \qquad H^d = \begin{bmatrix} -1/4 & 0 \\ 0 & -1/4\Lambda \end{bmatrix}.$$

Much as in the proof of Proposition 1, we calculate leading principal minors $|H^s_1| = -1/4(1-\delta \leq 0$ and $|H^s_2| = 1/16\delta(1-\delta) \geq 0$ for the single-market case as well as, for the dual-market case, $|H^d_1| = -1/4 \leq 0$ and $|H^s_2| = 1/16\Lambda \geq 0$. We find that the Hessians are negative semidefinite and so the SOCs are satisfied. Solving this system of FOCs yields the optimal policy parameters given in equation (14).

Proof of Proposition 4. The policy maker's objective function under the mixed approach is

$$\max_{\phi_{\mathcal{M}}, t_{\mathcal{M}}, s_{\mathcal{M}}} O_{\mathcal{M}}(\phi_{\mathcal{T}}, t_{\mathcal{M}}, s_{\mathcal{M}}) = \pi_{\mathcal{M}} + \mathrm{CS}_{\mathcal{M}} - C_{\mathcal{M}} - q_{\mathcal{M}}\varepsilon - (q_{\mathcal{M}} - q_{\mathcal{M}_r})\gamma.$$

First we check the SOCs by computing the Hessians for both the single- and dual-market cases:

$$H^s = \begin{bmatrix} c_d(3c_d - 4\gamma) & c_d - 2\gamma\delta & c_d - 2\gamma\delta \\ c_d - 2\gamma\delta & -1 & -1/\delta \\ (c_d - 2\gamma\delta)/4 & -1 & -1/\delta \end{bmatrix} \frac{1}{4(1-\delta)};$$

$$H^d = \begin{bmatrix} -\gamma c_d + 3c_d^2/4 & -(2\gamma - c_d)/4 & 0 \\ -(2\gamma - c_d)/4 & -1/4 & 0 \\ 0 & 0 & -\Lambda/4 \end{bmatrix}.$$

The leading principal minors for the single-market case are $|H_1^s| = -c_d(4\gamma - 3c_d)/4(1-\delta) \leq 0$, $|H_2^s| = -(\gamma - c_d)^2/4(1-\delta)^2 \leq 0$, and $|H_3^s| = (\gamma - c_d)^2/16\delta(1-\delta)^2 \geq 0$; for dual-market case, they are $|H_1^d| = -c_d(4\gamma - 3c_d)/4 \leq 0$, $|H_2^d| = -(\gamma - c_d)^2/4 \leq 0$, and $|H_3^d| = \Lambda(\gamma - c_d)^2/16 \geq 0$. It is clear that the Hessian matrices are *not* negative semidefinite with respect to $\phi_{\mathcal{M}}$, $t_{\mathcal{M}}$, or $s_{\mathcal{M}}$; however, the objective function is jointly concave with respect to $t_{\mathcal{M}}$ and $s_{\mathcal{M}}$. Hence there exists a boundary value solution for $\phi_{\mathcal{M}}$ that takes either the value 0 or the value 1.

Next we show that the objective function's value under either market strategy is higher for $\phi = 1$ than for $\phi = 0$.

Case 1: Single-Market Strategy

$$O_{\mathcal{M}}(\phi = 1) - O_{\mathcal{M}}(\phi = 0) = \frac{\gamma - c_d}{1-\delta}\left(1 - c - \delta - \varepsilon - \frac{3c_d}{2} - \frac{\gamma}{2}\right) > 0$$
$$\iff q_{\mathcal{T}} > 0, \gamma > c_d.$$

Case 2: Dual-Market Strategy

$$O_{\mathcal{M}}(\phi = 1) - O_{\mathcal{M}}(\phi = 0) = (\gamma - c_d)\left(1 - c - \varepsilon - \frac{\gamma}{2} - \frac{c_d}{2}\right) > 0$$
$$\iff q_{\mathcal{T}} > 0, \gamma > c_d.$$

We therefore take $\phi_{\mathcal{M}} = 1$ as the optimal policy parameter value for $\mathcal{P}_{\mathcal{M}}$. Given $\phi_{\mathcal{M}} = 1$, the FOCs for each of the firm's market strategies can be written as follows.

Case 1: Single-Market Strategy

$$\frac{\partial O_{\mathcal{M}}^s}{\partial t_{\mathcal{M}}^s} = -1 + \delta + c - c_r + 2\varepsilon + 2c_d - t_{\mathcal{M}}^s - s_{\mathcal{M}}^s = 0;$$
$$\frac{\partial O_{\mathcal{M}}^s}{\partial s_{\mathcal{M}}^s} = \delta c - c_r + c_d + \delta c_d + 2\delta\varepsilon - t_{\mathcal{M}}^s\delta - s_{\mathcal{M}}^s = 0.$$

Case 2: Dual-Market Strategy

$$\frac{\partial O^d_{\mathcal{M}}}{\partial t^d_{\mathcal{M}}} = 2E - 1 + c - t^d_{\mathcal{M}} + c_d = 0;$$
$$\frac{\partial O^d_{\mathcal{M}}}{\partial s^d_{\mathcal{M}}} = (\Delta - c_r - s_{\mathcal{M}}) + c_d = 0.$$

Solving these FOCs gives the optimal values for taxes and subsidies, as given in equation (15).

Proof of Corollary 1 For part (i), the optimal policy parameters obtained from equations (13), (14) and (15) are substituted in the values of T_i and S_i in Table 2; we then solve $T_{\mathcal{T}} > T_{\mathcal{M}} > T_{\mathcal{R}}$ and $S_{\mathcal{T}} > S_{\mathcal{M}} > S_{\mathcal{R}}$ for respective prices. Part (ii) of the corollary is proved by substituting values of T_i and S_i determined in part (i), into (8) and by making the focal comparison. Similarly, part (iii) is proved by plugging in the values of respective prices p_i and p_{ri} (part (ii)) in (1),(2) and then comparing the results.

Proof of Proposition 5.

Comparison of Policy $\mathcal{M}$ and Policy $\mathcal{T}$. If $\phi = 1$ then $\mathrm{EOL}_{\mathcal{M}} = 0$; hence $\mathrm{EOL}_{\mathcal{M}} < \mathrm{EOL}_{\mathcal{T}}$. Recall that $\mathrm{EP}_i = \varepsilon q$ for each policy i. From Corollary 1 it follows that $q_{\mathcal{M}} > q_{\mathcal{T}}$ and so $\mathrm{EP}_{\mathcal{T}} < \mathrm{EP}_{\mathcal{M}}$.

To compare the social welfare under the two policies, we calculate the difference $\pi_{\mathcal{M}} - \pi_{\mathcal{T}}$ using the optimal parameters given in Table 3. Under the single-market strategy, we obtain

$$\pi^s_{\mathcal{M}} - \pi^s_{\mathcal{T}} = \frac{(\gamma - c_d)(2\delta + 2c_r + 2\delta c_r - c_d - 3\delta c_d\gamma - 2\delta^2 - 4\delta c - 4\varepsilon\delta - \gamma - 3\delta\gamma)}{\delta(1-\delta)}$$
$$= \frac{(\gamma - c_d)((q_{\mathcal{T}} - q_{r\mathcal{T}}) + (q_{\mathcal{M}} - q_{r\mathcal{M}}))}{\delta(1-\delta)} \geq 0$$

because, by Lemma 1, $\gamma > c_d$ and $q_i \geq q_{ri}$ for all policies i. Similarly, under the dual-market strategy we have $O^d_{\mathcal{M}} \geq O^d_{\mathcal{T}}$ because

$$\pi^d_{\mathcal{M}} - \pi^d_{\mathcal{T}} = (\gamma - c_d)((q_{\mathcal{T}} - q_{r\mathcal{T}}) + (q_{\mathcal{M}} - q_{r\mathcal{M}})) \geq 0.$$

Proofs for the other criteria (CS and O) follow the same line of reasoning and are omitted for brevity.

Comparison of Policy $\mathcal{M}$ and Policy $\mathcal{R}$. Our proof for the comparison of EOL and EP parallels the proof given when comparing policies $\mathcal{M}$ and $\mathcal{T}$. In order to compare firm profits under the two policies, we calculate $\pi_{\mathcal{M}} - \pi_{\mathcal{R}}$ using the optimal parameters given in Table 3. We then solve for $\pi_{\mathcal{M}} - \pi_{\mathcal{R}} \geq 0$ to obtain a threshold for $\phi_{\mathcal{R}}$, denoted ϕ_π, where if $\phi_{\mathcal{R}} > \phi_\pi$ then $\pi_{\mathcal{M}} \geq \pi_{\mathcal{R}}$. Recall that the optimal value of $\phi_{\mathcal{R}}$ is given by Proposition 2.

Case 1: Single-Market Strategy

$$\phi_\pi = \frac{1-\delta-c+c_r-c_d}{\delta} - \frac{\sqrt{4\delta^2(1-\delta-c+c_r-2c_d+\varepsilon)^2+3\delta(1-\delta)(\delta-c_r+c_d)^2}}{\delta c_d}.$$

Using $\phi_{\mathcal{R}}^{s*}$ as given in Proposition 2, it is straightforward to verify that $\phi_{\mathcal{R}}^{s*} \geq \phi_\pi$ if and only if $\gamma > c_d$ *and* $\delta - c_r + c_d > 0$.

Case 2: Dual-Market Strategy

$$\phi_\pi = \frac{1-c-\sqrt{4(1-c-\delta-\varepsilon-c_d)^2+3\Lambda(\Delta-c_r+c_d)^2}}{c_d}.$$

Similarly to the single-market case, $\mathcal{R}^{d*} \geq \phi_\pi$ iff $\gamma > c_d$ and $\Delta - c_r + c_d > 0$.

As before, to save space we omit the analogous proofs for criteria CS and O.

Proof of Proposition 6. (A) The firm prefers a dual-market strategy if and only if $\pi_i^d > \pi_i^s$. Similarly, the policy maker prefers a dual-market strategy if and only if $O_i^d > O_i^s$. Solving these inequalities for the secondary market size yields the values given in Table 4.

(B), (C) We substitute the respective threshold values obtained from Table 4 and then solve for $\bar{\Lambda}_i - \bar{\lambda}_i$ and $\bar{\lambda}_j - \bar{\lambda}_i$, where $i, j \in \{\mathcal{N}, \mathcal{R}, \mathcal{T}, \mathcal{M}\}$:

$$\begin{aligned}\bar{\Lambda}_{\mathcal{N}} - \bar{\lambda}_{\mathcal{N}} &= \frac{4(\delta c-c_r)\big(4\delta E(\Delta-c_r)+\gamma(\Delta-\delta c)\big)}{\delta(1-\delta)(\Delta-c_r)^2(3\Delta-3c_r+4\gamma)} \\ &> 0 \iff \Delta > \frac{\delta(Ec_r-\gamma c)}{\delta E+\gamma};\end{aligned}$$

$$\bar{\Lambda}_{\mathcal{R}} - \bar{\lambda}_{\mathcal{R}} = \bar{\lambda}_{\mathcal{R}} + \frac{4(\gamma+\varepsilon-\gamma\phi^d_{\mathcal{R}})(2\delta q^s_{\mathcal{R}} + c_d\xi)}{3(\Delta - c_r + c_d)^2} - \bar{\lambda}_{\mathcal{R}}$$

$$> 0, \quad \text{because } \phi \leq 1;$$

$$\bar{\lambda}_{\mathcal{T}} - \bar{\lambda}_{\mathcal{N}} = \frac{\big((\Delta - c_r)(q^s_{\mathcal{T}r} + 2q^s_{\mathcal{N}r}) + 2\gamma q^s_{\mathcal{N}r}\big)\big(\delta E(\Delta - c_r) + \gamma(\Delta - \delta c)\big)}{(\Delta - c_r)^2(\Delta - c_r + \gamma)^2}$$

$$> 0 \iff \Delta > \frac{\delta(Ec_r + \gamma c)}{\delta E + \gamma};$$

$$\bar{\lambda}_{\mathcal{M}} - \bar{\lambda}_{\mathcal{N}} = \frac{\big((\Delta - c_r)(q_{\mathcal{T}r} + 2q_{\mathcal{N}r}) + 2c_d q_{\mathcal{N}r}\big)\big(\delta(\varepsilon + c_d)(\Delta - c_r) + c_d(\Delta - \delta c)\big)}{(\Delta - c_r + c_d)^2(\Delta - c_r)^2}$$

$$> 0 \iff \Delta > \frac{\delta(\varepsilon c_r + c_d c_r + c_d c)}{c_d + \delta(\varepsilon + c_d)};$$

$$\bar{\lambda}_{\mathcal{T}} - \bar{\lambda}_{\mathcal{M}} = \frac{(\gamma - c_d)(\Delta - \delta c - \delta\varepsilon + \delta\Delta - \delta c_r)\big((\Delta - c_r)(q_{\mathcal{M}r} + q_{\mathcal{T}_r}) + \gamma q_{\mathcal{M}r} + c_d q_{\mathcal{T}r}\big)}{(\Delta - c_r + \gamma)^2(\Delta - c_r + c_d)^2}$$

$$> 0 \iff \Delta > \frac{\delta(c + c_r + \varepsilon)}{1 + \delta};$$

$$\bar{\lambda}_{\mathcal{M}} - \bar{\lambda}_{\mathcal{R}} = \frac{c_d\xi(2 - 2c - 2c_d\phi^d_{\mathcal{R}} - c_d\xi)}{(\Delta - c_r + c_d)^2} + \frac{(\varepsilon + c_d - \phi^s_{\mathcal{R}} c_d)\big(4\delta(1-\delta)q^s_{\mathcal{R}} + \delta(\varepsilon + c_d - \phi^s_{\mathcal{R}} c_d)\big)}{(1-\delta)(\Delta - c_r + c_d)^2}$$

$$> 0, \quad \text{because } \delta \leq 1.$$

(D) It is straightforward to obtain comparative statics results by simple differentiation.

Proof of Proposition 7.

Policy ($\mathcal{P}_{\mathcal{R}}$)**.** The policy maker's objective function under $\mathcal{P}_{\mathcal{R}}$ is

$$\max_{\phi_{\mathcal{R}}} \Omega_{\mathcal{R}}(\phi_{\mathcal{R}}) \;\text{ s.t. } \omega\phi_{\mathcal{R}} q_{\mathcal{R}} + (1-\omega)Q_{\mathcal{R}}.$$

The SOC for the single-market strategy is $\partial\Omega^2_{\mathcal{R}}/\partial\phi^s_{\mathcal{R}} = -\gamma c_d/(1-\delta) < 0$ and that for the dual-market case is $\partial\Omega^2_{\mathcal{R}}/\partial\Omega^d_{\mathcal{R}} = -\gamma c_d < 0$. Therefore, the FOC is sufficient. The condition for each marketing strategy is given as follows.

Case 1: Single-Market Strategy

$$\frac{\partial\Omega_{\mathcal{R}}}{\partial\phi^s_{\mathcal{R}}} = \frac{\gamma(1 - \delta + c_r - c_d - c - 2\phi^s_{\mathcal{R}} c_d)}{2(1-\delta)}.$$

Case 2: Dual-Market Strategy

$$\frac{\partial \Omega_{\mathcal{R}}}{\partial \phi^d_{\mathcal{R}}} = \gamma - \gamma c - 2\gamma \phi^d_{\mathcal{R}} c_d - c_d + \gamma c_d.$$

The optimal policy parameters are obtained by solving the FOCs and are given in Table 5. We solve for $\phi > 0$ and $\phi < 1$ to obtain $\underline{\omega}_{\mathcal{R}}$ and $\bar{\omega}_{\mathcal{R}}$ under each market strategy.

The proofs for **Policy** $(\mathcal{P}_{\mathcal{T}})$ and **Policy** $(\mathcal{P}_{\mathcal{M}})$ follow the same lines i.e, (a) Checking the second order conditions to determine sufficiency condition for first-order-conditions; (b) Solution of system of first-order conditions. We have, therefore, omitted their proofs for brevity.

Proof of Proposition 8 (a) The policy parameters presented in Table 5 are used to compute the optimal level of effective taxation T_i and the optimal subsidy S_i. We can then use (8) (from Proposition 1) and the optimal (T_i, S_i) to derive the optimal prices, which are compared to obtain the relation presented in Proposition 8(a).

In order to prove part (b), we must make the two comparisons described next.

Comparison of $\mathcal{P}_{\mathcal{M}}$ and $\mathcal{P}_{\mathcal{R}}$. Using the optimal policy parameters given in Table 3 together with (1), (2), and (8), we obtain the objective function's optimal value as given by (16). We solve for $\Omega_{\mathcal{M}} - \Omega_{\mathcal{R}}$ under both single- and dual-market strategies while observing, as elsewhere, the standard constraint that values be nonnegative.

Case 1: Single-Market Strategy

$$\Omega^s_{\mathcal{M}} - \Omega^s_{\mathcal{R}} = \frac{(\gamma\delta - \gamma c_r - c_d + 2\gamma c_d)^2}{8\gamma\delta c_d} > 0.$$

Case 2: Dual-Market Strategy

$$\Omega^d_{\mathcal{M}} - \Omega^d_{\mathcal{R}} = \frac{\Lambda(\Delta\gamma - \gamma c_r - c_d + 2\gamma c_d)^2}{8\gamma c_d} > 0.$$

Comparison of $\mathcal{P}_{\mathcal{M}}$ and $\mathcal{P}_{\mathcal{T}}$. We solve for $\Omega_{\mathcal{M}} - \Omega_{\mathcal{T}} > 0$ to obtain the threshold value for c_d under each marketing strategy.

Case 1: Single-Market Strategy

$$\overline{c_d}^s = \gamma\sqrt{\frac{\delta(1-\delta)(1-c)^2 + (\delta c - c_r)^2}{1-\delta+\gamma^2\delta}}.$$

Note also that $\Omega_{\mathcal{T}}$ is independent of c_d and that $\Omega_{\mathcal{M}}$ is a convex function of c_d, where the distinctobscure? minimum of that function is

$$\frac{\partial\Omega^2}{\partial c_d^2} = \gamma\frac{\delta(1-\delta)(1-c)^2 + (\delta c - c_r)^2}{4c_d^3\delta(1-\delta)} > 0;$$
$$\frac{\partial\Omega}{\partial c_d} = -\frac{\gamma^2\big(\delta(1-\delta)(1-c)^2 + (\delta c - c_r)^2\big) - c_d^2(1-\delta-\gamma^2\delta)}{8\gamma\delta(1-\delta)c_d^2}.$$

Solving the FOC, we obtain

$$\overline{\overline{c_d}}^s = \gamma\sqrt{\frac{\delta(1-\delta)(1-c)^2 + (\delta c - c_r)^2}{1-\delta+\gamma^2\delta}}.$$

Observe that the point of intersection lies on the minimum (i.e., $\overline{c_d}^s = \overline{\overline{c_d}}^s$); therefore, $\Omega_{\mathcal{M}} \geq \Omega_{\mathcal{M}}|_{\overline{c_d}^s} = \Omega_{\mathcal{T}}$.

Case 2: Dual-Market Strategy Similarly,the solution to $\Omega_{\mathcal{M}} - \Omega_{\mathcal{T}}$ is given as

$$\overline{c_d}^d = \overline{c_d}^d = \gamma\sqrt{\frac{\Lambda(\Delta - c_r)^2 + (1-c)^2}{(1-\gamma)^2 + \Lambda}}.$$

The minimum of $\Omega_{\mathcal{M}}$ is then

$$\frac{\partial\Omega^2}{\partial c_d^2} = \gamma\frac{(1-c)^2 + \Lambda(\Delta - c_r)^2}{4c_d^3} > 0;$$
$$\frac{\partial\Omega}{\partial c_d} = -\frac{\gamma^2(1-c)^2 - c_d^2(1-\gamma)^2 + \gamma^2\Lambda(\Delta - c_r)^2 - \Lambda c_d^2}{8\gamma c_d^2};$$
$$\overline{\overline{c_d}}^d = \gamma\sqrt{\frac{\Lambda(\Delta - c_r)^2 + (1-c)^2}{(1-\gamma)^2 + \Lambda}}.$$

Note that once again the point of intersection coincides with the minimum; that is, $\overline{c_d}^d = \overline{\overline{c_d}}^d$. Therefore, $\Omega_{\mathcal{M}} \geq \Omega_{\mathcal{M}}|_{\overline{c_d}^d} = \Omega_{\mathcal{T}}$.

3. Environmental Performance of Recovery Legislations in Innovative industry

3.1. Introduction

The digital era has witnessed a growth in the sales of consumer electronics which has coincided with shrinking product lifecycle. More than 60 Mn computer devices, 27 Mn tablets and 183 Mn smartphones are expected to be sold in 2016, a significant proportion of which will end up as E-Waste in a few years (Electronics 2016). The electronics manufacturing is a resource intensive operation with significant environmental footprint. Kuehr and Williams (2003) reported that manufacturing of a complete desktop computer require 240 kg of fossil fuels, 22 kgs of chemical and 1.5 tonnes of water. Furthermore, due to concentration of chemicals and rare earth metals; these consumer electronics have a significant environmental footprint and severe health consequences, if they are irresponsibly recycled or allowed to contaminate land and water resources. Around 40% of heavy metals such as mercury, lead and Cadmium in the land fillings are sourced from consumer electronics (Electronics 2016). With the enormous environmental footprint associated with electronics, recycling and reuse have come up with effective strategies to offset some of the environmental footprint. While reuse offers a substitute for new product manufacturing giving a new life to already used products; recycling diverts the environmental footprint from land fillings. The Environmental Protection Agency (EPA) has proposed a 3R guideline (Reduce, Reuse and Recycle) to address the environmental issue laying stress on reduced consumption and reuse prior to recycling.(Agency 2016).

A number of legislative frameworks have been introduced to address the E-Waste issue. Two categories of legislations are currently under practice; one is based on hard constraint model such as WEEE (Waste Electrical and Electronic Equipment) legislations in the European union where a recovery target is provided to firms to recover a certain fraction of sales and treat them in accordance with environmental standards. On the other hand, there are incentive schemes such as taxation/subsidy based schemes. This includes fee upon sales model currently being practiced in Japan and being proposed in some of US states. The primary objective of the legislations have been to promote recycling. However, in recent years in consistent with EPA guidelines, the policy maker are contemplating the addition of **reuse targets** in addition to mandatory recovery rates in the European Union countries (Fabrellas 2015). Some of the academic work encapsulated incorporation of remanufacturing and studied the incentives current legislations provide for promoting reuse (Webster and Mitra 2007, Karakayali et al. 2012, Esenduran et al. 2015).

However, the current literature does not capture the role of frequent innovations and product updates which nullify the reuse potential of the products and offer diminished incentives for incorporation reusability in the design. To the best of our understanding, there are only two papers (Galbreth et al. 2013, Boyaci et al. 2015) that cover the innovation angle. However, these two papers have only explored the potential for reusability and reuse in presence of innovation. We make a distinction with their work as we investigate the total environmental footprint associated with the product by capturing the footprint during all phases of the product (Raz 2015, Esenduran et al. 2015). Moreover, we extend the discussion to develop policy guidelines and analyze how current legislative framework aligns towards the goal of diminished environmental footprint. More precisely, we intend to study how innovation influence the environmental footprint for the products. Secondly, how the current legislation practices respond to the innovation. Furthermore, we investigate if reuse and reusability would always lead us to the objective of diminished environmental footprint? Moreover, what is the influence of cost of reusability and recycling on product reuse and total environmental footprint? and if the subsidy structure on recycling as currently proposed aligns itself with the goal of reduced environmental footprint.

A stackeberg game model between a social welfare maximizing policy maker *the stackelberg leader* and a profit maximizing monopolistic firm *the stackelberg follower* allows to perform an equilibrium analysis and analyze optimal policy parameters and how they react to our changing parameters of interest and more importantly how the total environmental footprint can be curtailed with these policy levers.

3.2. Model

We pursue the approach of Galbreth et al. (2013) which is pioneer study on the effect of innovation and reusability on product reuse. We extend their work by studying the effects of these decisions on total environmental footprint. In addition to that, we study how the optimal policy parameters are set and how do they align themselves with the goals of low environmental footprint and high social welfare. Consistent with the literature, we capture the internal competition with a steady state model. So there is a monopolistic firm which offers a new and remanufactured product to a market. The firm has taken a long term decision of product reusability represented by (β_u) which come with a cost $\beta_u k$. Furthermore, the firm incrementally innovates the product in each period by (β). A returned core from previous period sales is different from the current generation new product with a fraction of (β). Therefore, a firm selects among three strategies:

1. The firm can upgrade them while remanufacturing bringing them to same functional performance as of the current generation product. This includes rebuilding the β of the product and recycling the removed component. The reusable part from the remaining product is remanufactured while the non-reusable part is built from scratch using previous generation technology.
2. The firm can remanufacture them by simply restoring them to their own generation functionality. This includes remanufacturing reusable part while rebuilding non-reusable part using previous generation technology.

$\beta\{0,1\}$	Innovation coefficient
$\beta_u\{0,1\}$	Degree of Product Reusability
k	Cost for making a product fully reusable ($\beta_u = 1$)
c	Cost of manufacturing of a fully innovative product ($\beta = 1$)
c_o	Cost of manufacturing of a previous generation product ($\beta = 0$)
τ	Recycling cost for a non remanufactured recovered product
δ	Costumer Valuation for a remanufactured product
q, q_u, q_r	represent quantity for new and remanufactured products with and without upgrade
p, p_u, p_r	represent prices for new and remanufactured products with and without upgrade
$\{\mathcal{R}, \mathcal{T}\}$	capture recovery target and tax/subsidy based policy

Table 6 Notations and their explanation

3. The firm can recycle them in accordance with relevant standards at a recycling cost τ.

We assume that all the removed components from the collected products are responsibly recycled at cost (τ) even if no such legislation is in place.[6].

3.2.1. Cost Parameters Table 6 presents notations and the definition of the parameters of the problem. We assume without loss of generality in consistency with (Galbreth et al. 2013) that the cost of remanufacturing is normalized to 0.

Therefore, the manufacturing costs for a new and remanufactured product (with and without upgrade) are given as:

$$c_{new} = \beta c + (1-\beta)c_o + k\beta_u$$

[6]We do not make any assumption that degree of reusability is restricted by innovation i.e, $\beta_u \le (1-\beta)$ to cater for the cases where remanufacturing (without upgrade) becomes more attractive

$$c_{upg} = \beta c + (1-\beta)(1-\beta_u)c_o$$

$$c_{rem} = (1-\beta_u)c_o$$

3.2.2. Firm's Problem A monopolistic firm maximizes its profits, it obtains from the sales of (i) new and remanufactured product (ii) new and remanufactured products with upgrade (iii) new and remanufactured products with and without upgrade. A firm selects one of these strategies and solves a profit maximization problem for respective prices that would lead to quantities.

$$\Pi = q(p - c_{new}) + q_u(p_u - c_{upg}) + q_r(p_r - c_{rem}) - \mathcal{C}_i \qquad i \in \{\mathcal{R}, \mathcal{T}\},$$
$$\mathcal{C}_{\mathcal{R}} = (\phi q - q_u - q_r)\tau \quad \mathcal{C}_{\mathcal{T}} = qt - q_u s_u - q_R s_r \tag{17}$$

The firm may select not to upgrade and in this case q_u and subsequently s_u will be zero. Similarly, a firm may upgrade all the products and in this case $q_r, s_r = 0$.

3.2.3. Customer Choices and Demand Processes Most of the remanufacturing literature takes into account the demand formulation based on heterogeneous customers with utility uniformly distributed in the interval of $\{0,1\}$(Ferguson and Toktay 2006, Atasu et al. 2008b, Esenduran et al. 2015). More precisely we follow the approach of (Galbreth et al. 2013) who capture the effect of innovation. A customer derives a utility θ from the new product. A customer derives a discounted utility from a remanufactured product that has been upgraded to its latest version given by $\delta\theta$ and the utility a customer derives from a remanufactured product which has not been upgraded is given as $\delta(1-\beta)\theta$; where β represents the innovation coefficient. A product which is remanufactured without an upgrade represent previous generation and is different from current new product with a fraction (β).

$$V_n = \theta - p \qquad V_u = \delta\theta - p_u \qquad V_r = \delta(1-\beta) - p_r$$

	Price	Quantity
New	$1/2\Big(1+c_o(1-\beta)+\beta c+k\beta_u\Big)$	$\Big(1-\delta+\tau-k\beta_u-\beta_u(c_o+\tau)(1-\beta)\Big)\Big/(2(1-\delta))$
Upgraded	$1/2\Big((c_o+\tau)(1-\beta_u+\beta\beta_u)+\beta(c-c_o)+\delta\Big)$	$\Big(c_o-c+\delta c+\delta k\beta_u-(c_o+\tau)(\delta+\beta_u+\delta\beta\beta_u-2\delta\beta_u\Big)\Big/(2\delta(1-\delta))$
Remanufactured	$1/2\Big((c_o+\tau)(1-\beta_u)+\delta(1-\beta)\Big)$	$\Big((1-\beta)(c-c_o)-(c_o+\tau)(1+\beta\beta_u-2\beta_u\Big)\Big/(2\delta(1-\beta))$

Table 7 Optimal Prices and Production Quantities

If all three products are available in the market, we solve the indifference point for θ with the solution $V_n = V_u$, $V_u = V_r$ and $V_r = 0$ to give thresholds for θ as under:

$$\theta_1 = (p - p_u)/(1-\delta) \qquad \theta_2 = (p_u - p_r)/\delta\beta \qquad \theta_3 = p_r/\delta(1-\beta)$$

All the customers with utility between 1 and θ_1 will buy new product whereas, all the customers with their utility between θ_1 and θ_2 will buy remanufactured products with upgrade and all the customers with their utility between θ_2 and θ_3 will purchase remanufactured product (without upgrade). While the customers with their utility below θ_3 will abstain from purchase. This gives us the demands corresponding to production quantities. We insert these values into equation 17 and solve the profit maximization problem for optimal quantities and prices which are given in table 7.

A similar exercise is required to obtain the demand for the cases where one of the product is absent i.e, the firm either fully upgrades all retrieved products during remanufacturing or no upgrade is performed at all.

3.3. Policy Maker's Objective Function

A policy maker selects a policy and its policy levers as a measure to curb the environmental footprint. However, a policy maker bears a larger perspective of the problem and her consideration include but are not limited to the environmental footprint of the products. Literature on the study of environmental legislations considers a social welfare maximizing policy maker when it comes to selection of legislative parameters.(Atasu et al. 2009, 2013, Drake 2015). Social welfare represents the social well being and accommodates the effect of policy on firm's profits, the consumer surplus as well as captures any financial consequences of the policy which are translated to the taxpayers. In addition to that, the environmental cost that captures the total environmental footprint serves as another component for the social welfare. Based on this, a policy maker selects between the following two policies and selects optimal policy parameters.

1) Recovery Target based Policy: Under this policy, a policy maker adds a recovery target making it mandatory for the firm to retrieve a certain fraction of its new products after use ($\phi . q$) and make sure to recycle it in accordance with the prevalent environmental standards.

2) Tax/Subsidy based Policy: Under this policy a policy maker imposes a tax on the sales of the product and provides a subsidy on unit remanufacturing. The policy maker will provide a subsidy on both types of remanufacturing (i) one where upgrade follows up remanufacturing (ii) where remanufacturing is done without an upgrade. The amount of subsidy will depend upon the incentives they provide for social welfare.

As discussed previously, the policy maker's objective is to maximize overall social welfare which includes (a) Total Environmental Footprint (b) Profitability of firm (c) Consumer Surplus in the Market (d) Monetary cost of the policy which is translated to taxpayer. It is evident that recovery target based policy is cost neutral i.e, it does not add a cost to the policy maker. The taxation based scheme is not necessarily cost neutral and may require funds for subsidy mechanism.

$$G_i = \Pi_i + C_i - B_i - \epsilon T E_i \tag{18}$$

where G_i represents the total social welfare. Π_i denotes firm's profitability, C_i total consumer surplus, B_i caters for any positive cost incurred by the policy maker due to implementation of tax/subsidy based policy and TE_i captures total environmental footprint of the firm i. We use ϵ as a monetary translation parameter which translate environmental footprint into monetary costs consistent with other components of social welfare function. The calculation of ϵ is beyond the scope of this study, however, one way of looking at it is to compute total carbon discharge which can be multiplied by carbon costs. Next, we compute each of the following:

3.3.1. Total Environmental Footprint (TE_i) We follow the approach consistently being used in the recent literature such as (Ovchinnikov et al. 2014, Esenduran et al. 2015, Raz et al. 2013). This approach based on total environmental footprint is also popular in ecology literature and among practitioners(Energy 2008, Jain 2011, Sloma 2013). We calculate the environmental footprint during all phases of the product which can be captured by total energy utilization or carbon emissions during the entire life cycle of the product. The product lifecycle comprises manufacturing, remanufacturing, use, recycle and disposal phase. In absence of the legislations or in presence of incentive scheme of tax/subsidy, the collection will be equivalent to the quantity retrieved for remanufacturing while a recovery target based policy ensures a mandatory collection rate equivalent to (ϕq).

We associate e_m,e_{rm},e_u,e_{rc} and e_d as environmental footprint of the product during production,remanufacturing,use, recycle and improper disposal (when the products are left in the environment after use) phases.

Total Environmental Footprint		
Tax/Subsidy	Recovery Target	
$Eq + E_R q_r$	$(E - \phi\xi)q + (E_R + \xi)q_r$	With ALL upgrade
$Eq + E_u q_u$	$(E - \phi\xi)q + (E_R + \xi)q_u$	With NO upgrade
$Eq + E_u q_u + E_R q_r$	$(E - \phi\xi)q + (E_u + \xi)q_u + (E_R + \xi)q_r$	With PARTIAL upgrade

Table 8 Total Environmental Footprint

Total Environmental Footprint with remanufacturing and upgrades

For tax/subsidy Case

$$TE = \overbrace{(e_m + e_u + e_d)}^{E} q + \overbrace{\Big(e_m + e_m\beta\beta_u + e_{rc}\beta\beta_u + e_{rc} + e_u + e_{rm}\beta_u - e_{rm}\beta\beta_u - e_m\beta_u - e_{rc}\beta_u\Big)}^{E_u} q_u$$
$$+ \underbrace{\Big(e_m + e_{rm}\beta_u + e_{rc} + e_u - e_m\beta_u - e_{rc}\beta_u\Big)}_{E_R} q_r$$

For Recovery Policy

$$TE = \overbrace{(e_m + e_u + e_d - \phi e_d + \phi e_{rc})}^{E - \phi\xi} q + \overbrace{\Big(e_u + e_d + e_m(1 - \beta_u + \beta\beta_u) - \beta_u(e_{rc} - e_{rm})(1 - \beta)\Big)}^{E_u + \xi} q_u$$
$$+ \underbrace{\Big(e_m + e_d + e_u - \beta_u(e_m - e_{rm} + e_{rc})\Big)}_{E_R + \xi} q_r \tag{19}$$

Similarly, the total environmental footprint can be obtained for the other two cases with and without upgrade option and is presented in table 8.

We make a simplifying yet reasonable assumption here (i) $e_m > e_{rm}$, (ii) $e_d > e_{rc}$ which suggests that environmental footprint from production is higher than that of remanufacturing and environmental footprint from improper disposal/landfill dumping is higher than the footprint from recycling. The difference between the environmental footprint from disposal with the environmental footprint of recycling is an important driver for recovery target based policy ($\xi = e_d - e_{rc}$) and defines environmental efficiency of recycling. These two assumptions serve as the proponents of remanufacturing/recycling as a tool to offset environmental footprint. If the converse were true, neither recycling nor remanufacturing would qualify as a green operation.

Lemma 2. *If $e_m > e_{rm}$ and $e_d > e_{rc}$ then following are true,*

- *(i) $E > E_u > E_R$*
- *(ii) (a)if $\phi < \left(\beta_u(1-\beta)(e_m - e_{rm} + e_{rc}\right) \Big/ (e_d - e_{rc})$ then $E - \phi\xi > E_u + \xi > E_R + \xi$. (b) If $\left(\beta_u(1-\beta)(e_m - e_{rm} + e_{rc}\right) \Big/ (e_d - e_{rc}) > \phi < \left(\beta_u(e_m - e_{rm} + e_{rc})\right) \Big/ (e_d - e_{rc})$ then, $E_u + \xi > E - \phi\xi > E_R + \xi$ (c) otherwise,$E_u + \xi > E_R + \xi > E - \phi\xi$*

Lemma 2 reveals some interesting facts about the environmental footprint of the products. These results have important policy implications on total environmental footprint and will be used later for comparisons. When there is no legislation or taxation/subsidy based policy in implementation, there is a clear preference ordering for the environmental footprint associated with products; proving that new product environmental footprint is always higher than the remanufactured ones with the difference increasing in (e_m) and (ξ). Therefore, any effort aimed at substitution of the new products with the remanufactured ones would contribute towards mitigation of total environmental footprint and would establish itself as a green strategy. However, such strict preference can not be inferred while studying the recovery based policy. In comparison with the other scenario, the environmental footprint associated with remanufactured products (upgraded or not) increases by (ξ) and one associated with new products decreases by ($\phi\xi$). However, the environmental footprint associated with the upgraded products in this case is still lower than the environmental footprint associated with new products in the previous case i.e, $(E > E_u + \xi)$ but the same cannot be said about comparison with the new products in recovery legislation. A high reusability, low level of innovation and higher environmental footprint associated with production would make new product environmental footprint higher while a higher recovery target or a high value of ξ would make $E_u + \xi > E - \phi\xi$. However, the environmental footprint associated with remanufacturing without upgrade continue to be lower than one with upgrade. These results further suggest that merely substitution of new products with the remanufactured ones does not lead to higher environmental incentives under this policy so it may not align the goal of diminished environmental footprint with increase in reuse and reuse potential.

3.3.2. Cost of Policy B_i The policy cost is calculated as the funds directed by the policy maker as it may have financial consequences. Please note that a policy cost is only accrued with tax/subsidy policy which is given as $q_u s_u + q_r s_r - qt$ where t represent the taxation amount and s_i where $i \in \{u, r\}$ represents subsidy provided on unit manufacturing and remanufacturing.

3.3.3. Firm's Profitability Π_i The firm's profitability serves as one of the components of the policy maker's concerns due to economic activity it generates. A policy maker does not select policy levers which have severe financial implications for the firms. The firm's profitability in absence of legislation is given by equation 17.

3.3.4. Consumer Surplus C_i The consumer surplus represents the well-being of the customers in the market. It controls for the financial consequences by policy levers that may be translated to the consumers. It is captured as

Table 9 Comparative Statics of Total Environmental Footprint

	Recovery Legislation	Tax/Subsidy Policy
	Product remanufacturing with ALL upgrades	
$\partial TE/\partial\beta < 0$	$(E-\phi\xi)/(E_u+\xi) < \Big(1/\delta + (1-\delta)(c-c_o)/\delta\beta_u(c_o+\tau)\Big)$	$E/E_u < \Big(1/\delta + (1-\delta)(c-c_o)/\delta\beta_u(c_o+\tau)\Big)$
$\partial TE/\partial\beta_u > 0$	$(E-\phi\xi)/(E_u+\xi) < 1 + (1-\delta)(1-\beta)(c_o+\tau)/\delta(k+(1-\beta)(c_o+\tau))$	$E/E_u < 1 + (1-\delta)(1-\beta)(c_o+\tau)/\delta(k+(1-\beta)(c_o+\tau))$
$\partial TE/\partial k < 0$	$(E-\phi\xi) - (E_u+\xi) > 0$	$E > E_u$
$\partial TE/\partial\tau < 0$	$(E-\phi\xi)/(E_u+\xi) < 1 + \beta_u(1-\delta)(1-\beta)/\delta(\beta_u - \beta\beta_u + \phi)$	$E/E_u < 1/\delta$
	Product remanufacturing with NO upgrades	
$\partial TE/\partial\beta < 0$	$(E_R+\xi)/(E-\phi\xi-E_R-\xi) > \delta(1-\beta)^2/(1-\beta+\delta\beta)^2\Big(-\delta + \frac{c-c_o-\delta c-\tau\phi\delta-\delta k\beta_u}{-c_o+\beta_u c_o+\beta_u\tau}\Big)$	$E_R/(E-E_R) > \delta(1-\beta)^2/(1-\beta+\delta\beta)^2\Big(-\delta + \frac{c-c_o-\delta c-t\delta-\delta k\beta_u}{s_r-\tau-c_o+\beta_u c_o+\beta_u\tau}\Big)$
$\partial TE/\partial\beta_u > 0$	$(E-\phi\xi)/(E_R+\xi) < 1/\delta(1-\beta)\Big(1-k(1-\delta+\delta\beta)/(c_o+\tau+k)\Big)$	$E/E_R < 1/\delta(1-\beta)\Big(1-k(1-\delta+\delta\beta)/(c_o+\tau+k)\Big)$
$\partial TE/\partial k < 0$	$(E-\phi\xi) - (E_R+\xi) > 0$	$E > E_R$
$\partial TE/\partial\tau < 0$	$(E-\phi\xi)/(E_R+\xi) > 1 + \beta_u(1-\delta+\delta\beta)/\delta(1-\beta)(\beta_u+\phi)$	$E/E_R < 1/\delta(1-\beta)$
	Product remanufacturing with PARTIAL upgrades	
$\partial TE/\partial\beta < 0$	$(E_R+\xi)/(E-E_u-\xi-\phi\xi) > \Big(\delta\beta_u(1-\beta)^2\Big)\Big/(\frac{c_o}{c_o+\tau}-\beta_u)(1-\delta)$	$(E-E_u)/(E_u-E_R) + \frac{E_R}{E_u-E_R}\frac{(1-\delta)(s_r-c_o-\tau+c_o\beta_u+\tau\beta_u}{\delta\beta_u(1-\beta)^2(c_o+\tau)} < \frac{(1-\delta)(s_r-s_u)}{\beta^2\delta\beta_u(c_o+\tau)}$
$\partial TE/\partial\beta_u > 0$	$\big(1/(E-E_u)\big)\Big(E_R-E_u+E_R/(1-\beta)\Big) > (\delta/1-\delta)\Big(-\beta+1+k/(c_o+\tau)\Big)$	$1/(E-E_u-\xi-\phi\xi)\Big(E_R-E_u+(E_R+\xi)/(1-\beta)\Big) > \delta/(1-\delta)\Big(1-\beta+k/(\tau+c_o)\Big)$
$\partial TE/\partial k < 0$	$E > E_u$	$E-\phi\xi > E_u-\xi$
$\partial TE/\partial\tau < 0$	$\big(1/(E-E_u)\big)\Big(\beta_u(E_u-E_R)+E_R(1-\beta_u)/(1-\beta)\Big) > \delta(1-\beta_u+\beta\beta_u)/(1-\delta)$	$1/(E-E_u-\xi-\phi\xi)\Big(E_u-E_R-(E_R+\xi)/(1-\beta)\Big) > \delta(-\phi-\beta_u+\beta\beta_u)\Big/\beta_u(1-\delta)$

$$C_i = \int_{\frac{p-p_u}{1-\delta}}^{1} \big(\theta - p\big)\, d\theta + \int_{\frac{p_u-p_R}{\delta\beta}}^{\frac{p-p_u}{1-\delta}} \big(\delta\theta - p_u\big)\, d\theta + \int_{\frac{p_R}{\delta(1-\beta)}}^{\frac{p_u-p_R}{\delta\beta}} \big(\delta(1-\beta)\theta - p_R\big)\, d\theta \tag{20}$$

3.4. Analysis

3.4.1. Effect of Parameters on Total Environmental Footprint In this section, we analyze the effects of reusability, innovation etc on environmental footprint.

PROPOSITION 9. *The comparative statics of total environmental footprint with innovation coefficient, reusability level, reusability cost and recycling costs are presented in table 9.*

Contrary to the popular belief, which holds innovation and frequent product updates responsible for diminished environmental incentives, we find that innovation may align with the goal of low environmental footprint as under some conditions, an increase in innovation would lead to a decrease in total environmental footprint. An increasing rate of innovation tends to reduce the incentives for remanufactured products regardless of the

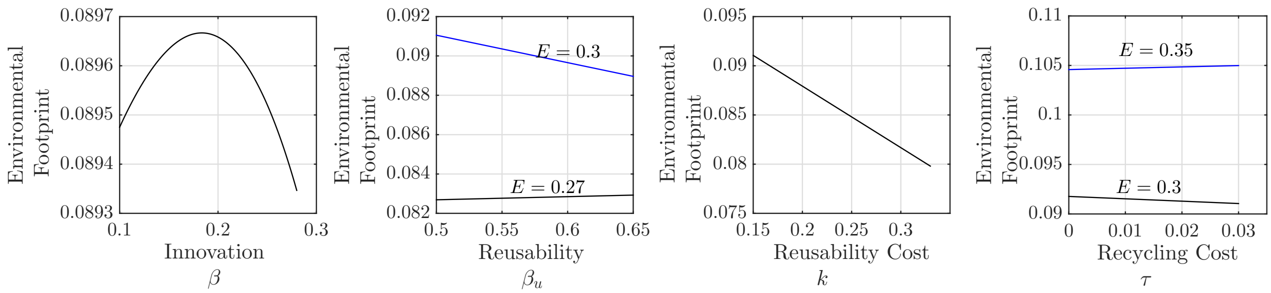

Figure 1 **Influence of Innovation and environmental parameters on Total Environmental Footprint in absence of legislations**

fact they are upgraded or not and therefore reduces environmental footprint associated with remanufacturing. However, the quantity and therefore, the environmental footprint associated with new products tends to increase. The environmental advantage achieved on the frontier of remanufactured products may offset the increase in environmental footprint associated with new products leading to an overall reduced environmental footprint. A low level of reusability would contribute to the satisfaction of such condition. Similarly, a comparatively low environmental footprint associated with new products or comparatively high environmental footprint associated with remanufacturing would ease out the satisfaction of the implying conditions. It is interesting to compare the conditions for recovery target and taxation/subsidy based policies. Please observe the case where full product upgrade is the only option with product reuse strategy, note that it is more likely that these conditions are satisfied for a recovery target based policy than a tax/subsidy based policy. With the case where product upgrade is not offered, the condition is still more likely to be satisfied for the recovery legislations than tax/subsidy policy as long as $(E - \phi\xi - E_u - \xi) > 0$. The qualitative insights remain the same for the case where a mix strategy is adopted for product remanufacturing. In the similar fashion, a low recycling cost will facilitate the satisfaction of these conditions.

In a similar fashion, reusability which is believed to be a proponent of environmental benefits may under certain conditions lead to adverse environmental consequences. This condition is more likely to be satisfied with low levels of innovation and is more easily satisfied with a recovery target based policy than taxation/slash subsidy scheme. An increasing reusability level offers reduced incentives for new products therefore reducing the footprint associated with them and on the other hand it increases the incentives for remanufactured products. The environmental advantage with reduced new products can be dominated by increase in remanufactured products leading to higher environmental footprint. Interestingly, when remanufactured products are offered in both upgraded and non upgraded forms, $E - \phi\xi - E_u - \xi > 0$ becomes necessary conditions for the satisfaction of the implying conditions.

A significant driver of policy maker's intervention is to incentivize firms to increase product reusability. The policy makers are assisting firms in the research and development initiatives which increase the product reusability without much adverse economical consequences i.e, without significant addition to product cost. What we find that the total environmental footprint actually decreases with an increase in reusability cost (k). With taxation/subsidy policy, this result completely holds true regardless of the upgradability strategy used with the remanufactured products. With recovery target based policy, it also holds good as long as $E - \phi\xi > E_u + \xi$. Recall that $\xi = e_d - e_{rc}$ suggesting that if the environmental footprint associated with improper disposal is large enough, this relation may not hold true. This surprising result of reducing environmental footprint by increasing reusability cost stems from the fact that higher reusability cost leads to reduced new products. The quantity of remanufactured products increases but since the environmental footprint associated with new products dominates remanufactured ones; higher reusability leads to lower environmental footprint . The same finding holds for the mandatory recycling rate based policy provided the environmental footprint from production is higher than that of upgraded remanufacturing. If the converse were true, the environmental benefits harvested from reduced new product production would be wasted by the increased upgrading.

Low recycling cost is perceived to be a necessary condition for environmental incentives and the policy makers contemplate subsidy infrastructure on recycling which they believe, will lead to low environmental footprint. However, we find that it is not necessary that such a subsidy structure will lead to lower environmental footprint as that under some conditions a higher recycling cost corresponds well to the goal of reduced environmental footprint. This case emphasizes the need of selection of appropriate policy mechanism as both policies work in contradiction. With taxation/subsidy policy in place, an increasing recycling cost increases incentives for new products and decreases incentives for remanufactured products. Therefore, an increasing recycling cost would lead to reduced environmental footprint if environmental advantage achieved from remanufacturing is high enough to balance the rise in new products. On the other hand, when a recovery target based policy is in place, an increasing recycling cost would lead to reduced new products but higher remanufactured products. The total environmental footprint is mitigated only if the environmental advantage associated with new products dominates the remanufactured products. A low innovation and higher level of reusability are likely to make these conditions easier to satisfy. Therefore, this acts us as caveat for the policy makers who consider inclusion of a subsidy structure in addition to a mandatory recycling rate that such steps may backfire if the other parameters such as rate of innovation and reusability levels are not considered and the environmental footprint associated with different stages of product is not taken into account.

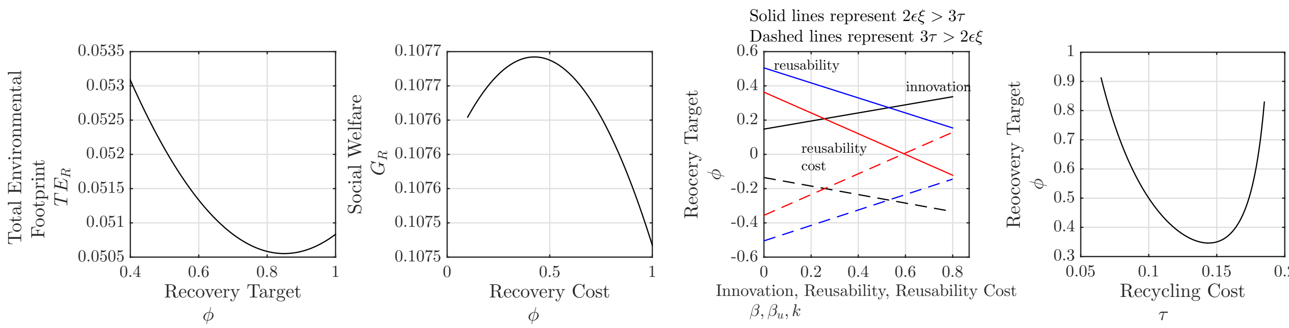

Figure 2 **Recovery Target based Legislation.**

3.4.2. Effect of Policy Parameters In the previous section, we studied the influence of innovation and environmental parameters on total environmental footprint. This section is devoted to the discussion on the influence of policy levers on total environmental footprint and other components of total social welfare. The objective is to see how much the components of social welfare including the environmental footprint is sensitive to the policy levers.

PROPOSITION 10. *Let q, q_u, q_r represent respective quantities of new upgraded and remanufactured products with each strategy under both policies.The comparative statics is given in table 10*

This proposition encapsulates the effect of policy levers on the set of our economical and environmental parameters. It is not surprising to observe the recovery targets and taxations have an adverse effect on firm's profitability as well as consumer surplus. However, the environmental footprint strictly decreases with the increasing taxation levers for a taxation/subsidy policy. For a recovery target based policy, it is also expected to decrease with the increasing recovery target if the cost associated with disposal is not too high i.e,($E - \phi\xi - E_R - \xi > 0$) with no upgrade strategy and $(E - \phi\xi - E_u - \xi) > 0$ with a pure upgrade strategy. The effect on social welfare is compounded by the individual effect on environmental and economical components of social welfare. Therefore, as

Recovery Legislation	Tax/Subsidy
With product remanufacturing NO upgrades	
$\frac{\partial \Pi}{\partial \phi} = -q\tau$	$\frac{\partial \Pi}{\partial t} = -q, \quad \frac{\partial \Pi}{\partial s_r} = q_r$
$\frac{\partial C}{\partial \phi} = -q\tau/2$	$\frac{\partial C}{\partial t} = -q/2, \quad \frac{\partial C}{\partial s_r} = q_r/2$
$\frac{\partial TE}{\partial \phi} = -q\xi - \frac{E-\phi\xi-E_R-\xi}{2(1-\delta+\delta\beta)}$	$\frac{\partial TE}{\partial t} = -\frac{E-E_R}{1-\delta+\delta\beta} \quad \frac{\partial TE}{\partial s_r} = \frac{E_R+\delta\beta E-\delta E}{\delta(1-\beta)(1-\beta+\delta\beta)}$
$\frac{\partial G}{\partial \phi} = \frac{q(-3\tau+2\epsilon\xi)}{2} + \frac{\epsilon\tau(E-\phi\xi-E_R-\xi)}{2(1-\delta+\delta\beta)}$	$\frac{\partial G}{\partial t} = \frac{-q}{2} + \frac{\epsilon E-\epsilon E_R-t-s_r}{2(1-\delta+\delta\beta)} \quad \frac{\partial G}{\partial s_r} = \frac{q_r}{2} + \frac{-\epsilon E\delta+t\delta+s_r+\epsilon E_R+\epsilon E\delta\beta-t\delta\beta}{2\delta(-1+\beta)(1-\delta+\delta\beta)}$
With product remanufacturing ALL upgrades	
$\frac{\partial \Pi}{\partial \phi} = -q\tau/2$	$\frac{\partial \Pi}{\partial t} = -q, \quad \frac{\partial \Pi}{\partial s_u} = q_u$
$\frac{\partial C}{\partial \phi} = -q\tau/2$	$\frac{\partial C}{\partial t} = -q/2, \quad \frac{\partial C}{\partial s_u} = q_u/2$
$\frac{\partial TE}{\partial \phi} = -\xi q - \frac{E-\phi\xi-E_u-\xi}{2(1-\delta)}$	$\frac{\partial TE}{\partial t} = -\frac{E-E_u}{2(1-\delta)} \quad , \frac{\partial TE}{\partial s_u} = -\frac{E\delta-E_u}{2(1-\delta)}$
$\frac{\partial G}{\partial \phi} = \frac{\epsilon\tau(E-\phi\xi-E_u-\xi)}{2(1-\delta)} + \frac{q(-3\tau+2\epsilon\xi)}{2}$	$\frac{\partial G}{\partial t} = -\frac{q}{2} + \frac{\epsilon E-\epsilon E_u-t-s_u}{2(1-\delta)}, \quad \frac{\partial G}{\partial s_u} = \frac{q_u}{2} + \frac{\epsilon\delta E-\epsilon E_u-t\delta-s_u}{2\delta(1-\delta)}$
With product remanufacturing PARTIAL upgrades	
$\frac{\partial \Pi}{\partial \phi} = -q\tau$	$\frac{\partial \Pi}{\partial t} = -q \quad \frac{\partial \Pi}{\partial s_u} = q_u \quad \frac{\partial \Pi}{s_r} = q_r$
$\frac{\partial C}{\partial \phi} = \frac{-q\tau}{2}$	$\frac{\partial C}{\partial t} = -\frac{q}{2} \quad \frac{\partial C}{\partial s_u} = \frac{q_u}{2} \quad \frac{\partial C}{\partial s_r} = \frac{q_r}{2}$
$\frac{\partial TE}{\partial \phi} = -q\xi - \frac{\tau(E-\phi\xi-E_u-\xi)}{1-\delta}$	$\frac{\partial TE}{\partial t} = -\frac{E-E_u}{2(1-\delta)} \quad \frac{\partial TE}{\partial s_u} = \frac{E_u-E_R}{2\delta\beta} - \frac{E-E_u}{2(1-\delta)} \quad \frac{\partial TE}{\partial s_r} = -\frac{E_u-E_R-\beta E_u}{2\delta\beta(1-\beta)}$
$\frac{\partial G}{\partial \phi} = \frac{q(-3\tau+2\epsilon\xi)}{2} + \frac{\epsilon\tau(E-\phi\xi-E_u-\xi)}{2(1-\delta)}$	$\frac{\partial G}{\partial t} = -\frac{3q}{2} + \frac{\epsilon(E-E_u)}{2(1-\delta)} \quad \frac{\partial G}{\partial s_u} = \frac{3q_u}{2} - \frac{\epsilon(E_u-E_R)}{2\delta\beta} + \frac{\epsilon(E-E_u)}{2(1-\delta)}$
	$\frac{\partial G}{\partial s_r} = \frac{3q_r}{2} + \frac{\epsilon(E_u-E_R-\beta E_u)}{2\delta\beta(1-\beta)}$

Table 10 Comparative Statics of Social welfare and its components with respect to policy levers. q_i **represents respective quantities in presence of respective policies**

expected an elevated taxation would contribute to reduced profits, consumer surplus and environmental footprint. Social welfare may increase if the reduced environmental footprint justifies reduced economical parameters. Subsidy on remanufacturing or upgrade serves as a compensatory mechanism catering for economical losses and hence result in increase in profits and consumer surplus. However, it is not straightforward to observe if the subsidy structure lead to diminished environmental footprint. Please observe that the respective condition that governs the relation of subsidy with the total environmental footprint is same that governs relation between environmental footprint and recycling cost in table 9 such that when increasing recycling cost reduces environmental footprint, an increasing subsidy is detrimental to the environment. When remanufactured products are offered in both upgraded and non-upgraded form, the relation of respective subsidy structure with environmental footprint depends on the innovation levels and (E, E_u, E_R). A low innovation would guarantee that the environmental footprint increases with subsidy on upgrade and decreases with subsidy on remanufacturing. A higher environmental footprint associated with new products as compared to upgraded products would mean that any subsidy on upgrade would lead to a decrease in total environmental footprint. On a similar note, if the environmental footprint associated with upgrade is sufficiently high in comparison with remanufacturing without upgrade footprint or the industry follows a high rate of innovation, the subsidy on remanufacturing would contribute to lower environmental footprint. The overall social welfare would be balanced by its environmental and economical components. The social welfare may increase due to increasing profits and consumer surplus even though if the environmental footprint is also rising with subsidy structure.

3.5. Equilibrium Analysis

The study of firm's problem has enhanced our insights about the role of each parameter towards reduced total environmental footprint and high social welfare. In this section, we extend this discussion and study how the optimal policy parameters are set. We solve this problem as a stackelberg game or more commonly known as leader/follower game similar to (Atasu et al. 2009, 2013, Drake 2015) where follower's problem is solved and its decisions are incorporated into the leader's (policy maker) problem and the values for optimal policy levers is obtained. The value of optimal parameters lead us to optimal prices and quantities. In our case, the policy maker selects between either a recovery target based policy along the same lines as WEEE legislations in the European Union or develop an incentive structure based on taxation/subsidy.

3.5.1. Recovery Target based Policy In this policy, a policy maker assigns a recovery target (ϕ). A firm recovers a quantity (ϕq) remanufactures the products according to the demands and recycle the product in accordance with the prevalent environmental legislations. Recall ($e_d - e_{rc} = \xi$) which defines difference between the environmental footprint of disposal in comparison with recycling. The higher the difference, the more are the incentives for promoting recycling. The policy maker solves the following problem:

$$\max_{\phi} G_R = \Pi_R + C_R - \epsilon T E_R \tag{21}$$

where ϵ is a conversion parameter that translates the environmental footprint into monetary cost

Proposition 11. • *G_R is concave in ϕ iff $3\tau < 4\epsilon\xi$.*

- *With policy where upgraded products are partially or fully offered, the optimal recovery target is given as:*

$$\phi^* = \Big(\beta_u(c_o+\tau)(3\tau-2\epsilon\xi)(1-\beta)-(3\tau-2\xi\epsilon)(1-\delta-k\beta_u)+2\epsilon\tau(E-E_u-\xi))\Big)/\tau(4\epsilon\xi-3\tau) \tag{22}$$

- *If there is no upgrade with remanufacturing, the optimal recovery target is given as:*

$$\phi^{*\mathcal{R}} = \phi^* + \Big(\beta(2\epsilon\xi-3\tau)(\delta+c_o-c-\beta_u c_o-\beta_u\tau)+2\epsilon\tau(E_u-E_R)\Big)/\tau(4\epsilon\xi-3\tau) \tag{23}$$

- $\partial\phi^*/\partial\beta > 0$ *iff* $2\epsilon\xi > 3\tau$,$\partial\phi^{*\mathcal{R}}/\partial\beta > 0$,$2\epsilon\xi > 3\tau$ *and* $\delta + c_o - c > 0$

  $\partial(\phi^*, \phi^{*\mathcal{R}})/\partial\beta_u > 0$ *iff* $3\tau > 2\epsilon\xi$,

  $\partial(\phi^*, \phi^{*\mathcal{R}})/\partial k > 0$ *iff* $3\tau > 2\epsilon\xi$

  and $\partial(\phi^*, \phi^{*\mathcal{R}})/\partial E > 0$,$\partial\phi^*/\partial E_u < 0$,$\partial\phi^{*\mathcal{R}}/\partial E_R < 0$

This problem is concave if the monetary value of the environmental cost associated with disposal is sufficiently high to warrant recycling a feasible practice. Similarly this parameter ξ is a key parameter required for optimal mandatory recovery target. If this value is too small or in other words there is a limited environmental advantage associated with recycling, there is no need for a policy maker's intervention. Similarly, if this value is too high i.e,($e_d >> e_{rc}$), a policy maker is better off implementing maximum possible value for mandatory recycling rate. Between these extremes, the optimal value of recovery target can be calculated by equation 22 with partial or full product upgrade and is given by equation 23 for no upgrade. A recovery target with in presence of no upgrade strategy can be higher than the recovery target with upgrade strategy if ($E_u >> E_R$) or/and ($2\epsilon\xi > 3\tau$)& ($\delta + c_o - c - \beta_u c_o - \beta_u\tau > 0$).

Now we study how innovation, reusability and reusability cost influence this decision. An increasing degree of innovation combined with low recycling cost would lead to an increased recovery target. This is because rapid innovation diminish incentives for remanufacturing leading to high environmental footprint due to improper disposal which a firm responds by increasing limit on mandatory recycling. Alternatively, if the recycling cost is high in comparison with the monetary environment cost associated with the disposal, clearly there is little incentive for a policy maker to curb environmental costs and as innovation increases, decreases the opportunity for remanufacturing (which is already low due to high recycling cost). It leads the policy maker to reduce mandatory recovery rates as recycling does not warrant significantly reduced environmental footprint. Similarly, an increase in reusability level is accorded by the policy maker with a decrease in mandatory recycling target. Increase in reusability level comes up with higher manufacturing cost which is translated to new products production resulting in lower environmental footprint from new products. Although these products are replaced by remanufactured products which may lead to overall higher total environmental footprint; the policy maker slashes down the recovery target to release financial pressure on the new product production as a reward for reusability investments. It is pretty intuitive to see that an increase in reusability investment cost (k) is compensated by the policymaker with a decrease in recovery target. However, if the recycling cost is too high $3\tau > 2\epsilon\xi$ we observe an increasing trend in the mandatory recycling rate with increase in reusability levels or reusability cost. This is surprising because a good behaviour namely increasing reusability level is responded with increasing recovery target and that too when recycling fail to impose itself as an attractive strategy due to high cost. This mostly happens when the environmental footprint associated with new products are high and the policy maker takes advantage of high reusability levels by diverting maximum products to remanufacturing (with or without upgrade). A higher recovery level on one hand curbs some environmental footprint from new products but at the same time increases demand for remanufactured products with upgrades and hence balancing out the decline in new product sales by a jump in product updates.

As far as the effect of environmental footprint on recovery rate is concerned, a firm increases the recycling rate, if the environmental footprint from production is high. It decreases the recycling rate if the environmental footprint from upgraded products are increasing because in that case there is no need of incentivizing product upgrades and recovery. Surprisingly, it is independent of the environmental footprint associated with the remanufactured products. This is because that the recovery target translates into cost addition of the new production. Due to cannibalization, this recovery target which influences new product prices also change the quantity of remanufactured products with upgrade. But a remanufactured product without un upgrade does not directly interact with the new products so it is not influenced by the recovery target. Another important observation is made about recycling cost. Generally, a high recycling cost leads to lower mandatory recovery rates due to two reasons (i) Remanufacturing levels increase due to cannibalization (ii) Financial incentive is provided on new product sales. However, if the recycling cost becomes too high one may witness an increase in recovery target with increasing recycling cost.

3.5.2. Tax/Subsidy Policy Our second policy is based on incentives structure which is similar in practice to SHAR laws in Japan or some states in United States. The policy maker recovers a tax on per unit sales of the new products and use this money to subsidize remanufacturing. The subsidy is awarded on both remanufacturing with and without upgrades. Therefore, a policy maker solves the following problem,

$$\max_{t,s_u,s_r} G_T = \Pi_T + C_T - (\epsilon T E_T + B_T) \tag{24}$$

PROPOSITION 12. *The optimal taxation and subsidy levels and their comparative statics are presented in table 11*

Irrespective of the firm's strategy about product upgradability i.e, regardless of the fact that firm partially or totally upgrades its products or does not upgrade at all, the optimal policy parameters will remain the same in this policy. This is different from the recovery target based policy where recovery target changes if upgrade option is activated.

t	$-1+c_o+\beta(c-c_o)+k\beta_u+2\epsilon E$
s_u	$\delta-\beta(c-c_o)-(c_o+\tau)(1-\beta_u+\beta\beta_u)-2\epsilon E_u$
s_r	$\delta(1-\beta)-(c_o+\tau)(1-\beta_u)-2\epsilon E_R$

$$\partial t/\partial\beta>0, \partial t/\partial\beta_u>0,\ \partial t/\partial k>0, \partial t/\partial\tau=0, \partial t/\partial E>0$$

$$\partial s_u/\partial\beta<0, \partial s_u/\partial\beta_u>0,\ \partial s_u/\partial k=0, \partial s_u/\partial\tau<0, \partial s_u/\partial E_u<0$$

$$\partial s_r/\partial\beta<0, \partial s_r/\partial\beta_u>0,\ \partial s_r/\partial k=0, \partial s_r/\partial\tau<0, \partial s_r/\partial E_R<0$$

Table 11 Optimal Policy Parameters for Tax/Subsidy Policy

Moreover, in presence of taxation/subsidy based scheme, the optimal policy parameters are monotone with respect to the innovation,reusability and other cost, market and environmental parameters. An increasing innovation rate is responded with an elevated taxation and reduced subsidy levels. A higher innovation has reduced incentives for remanufacturing which leads to higher environmental footprint owing to landfilling. The policy maker could have responded by elevating subsidy levels prompting product reuse but since an increased innovation means consumer depreciation for remanufactured products without upgrade and higher manufacturing cost for remanufactured products with upgrade, the policy maker realizes that an increase in subsidy is unlikely to cause any environmental benefits. Therefore, a policy maker responds by a high taxation level in an effort to curb the environmental footprint from new products to curb down total environmental footprint. It is not surprising that an increasing reusability level leads to higher taxes and subsidies. A higher reusability ensures higher incentives for remanufacturing which the policy maker complement by raising the subsidies facilitating more product reuse. The policy maker is therefore strategic rewarding long terms investments rather than short term needs of the firm. A higher taxation level can be explained for two reasons. First, taxation level is raised to collect funds for subsidy so that less and less of the policy cost is diverted to taxpayers.

Secondly, with the increase in product reuse there is less concern for firm's profitability and consumer surplus, therefore, a policy maker takes advantage by exerting pressure on new products production in order to control the environmental footprint from new products.

A high cost requirement for incorporating reusability is translated into higher taxation levels but does not affect subsidies. The reason behind raising taxation is to offset total environmental effect by reducing footprint from new product production. Similarly, a higher recycling cost translates into lower subsidies but does not have any effect on taxation. The intuition behind lower subsidies stems from the fact that higher recycling cost itself makes the product costly to recycle so the alternative methods such as reuse are already preferred by the firm. Finally it is pretty intuitive to note that an increase in environmental footprint will be complemented by an elevated taxation or reduced subsidy level on the said product.

Compare the subsidy incentives for remanufacturing with or without upgrade. Since, remanufacturing involve more reuse and has more environmental benefits, a unit subsidy on remanufacturing is expected to exceed unit subsidy on remanufacturing with upgrade. A contrary case is also plausible which requires the consumer valuation for remanufacturing to exceed a certain threshold i.e,$s_u \geq s_r$ iff $\delta > (c - c_o + \tau\beta_u + c_o\beta_u) + 2\epsilon(E_u - E_R)/\beta$. Interestingly, a low innovation level makes this condition implausible to satisfy. Product upgrades offer competition to both remanufactured and new products therefore, a policy maker offer a greater subsidy to product upgrade in order to substitute more of the new products with upgraded ones and mitigate the environmental footprint with new products although this leads to diminished incentives for product remanufacturing. This only happens at low innovation because at high innovation product upgrade becomes an activity with higher environmental footprint therefore diluting some of the environmental benefits it offers.

3.5.3. Comparison of Policies The relative merits and demerits of each of these policies with respect to each other attracts attention of policy makers. Unfortunately, due to complicated nature, the comparison of these policies along components of environmental and economical criteria is difficult to tackle analytically and does not offer any qualitative insights. Therefore, we resolve to numerical methods to generate some insights. Moreover, we find that there is no pareto dominance of one policy by the other i.e, both policies can outperform the other.

Therefore, with a focus on the case where remanufactured products are offered with both upgraded and non upgraded version, we compare the total environmental footprint of the both policies over a wide range of parameters. We fix $c = 0.5, c_o = 0.3, k = 0.3$ whereas the other parameters vary over a range as $E\{0.4, 0.7\}$,$E_u\{0.05, 0.E\}$,$E_R\{0.05, 0.E_u\}$,$\xi\{0.03, 0.5\}$,$\epsilon\{0.05, 0.5\}$,$\beta\{0.1, 0.5\}$,$\beta_u\{0.1, 0.5\}$ and $\tau\{0.01, 0.2\}$. We remain interested in the cases where the environmental footprint associated with both policies intersect. Figure 3 presents three different cases that capture low and high environmental footprint and low and high levels of innovation and reusability.

Recovery target based policy tends to dominate the taxation/subsidy policy when the recycling cost is sufficiently low. This behaviour is consistent for a varying set of environmental and economical parameters. This provides an evidence in the support of conventionally held beliefs that a subsidy structure on recycling would promote product take back significantly reducing the environmental footprint. We observe that a lower recycling cost always, in most of the cases, ensure a better performance for a recovery target based legislations in comparison with tax/subsidy scheme. This dominance is established even in the scenarios where environmental footprint with improper disposal is low.

Next, we compare the environmental footprint associated with both schemes with respect to level of innovation. As we already discussed in previous sections that increasing level of

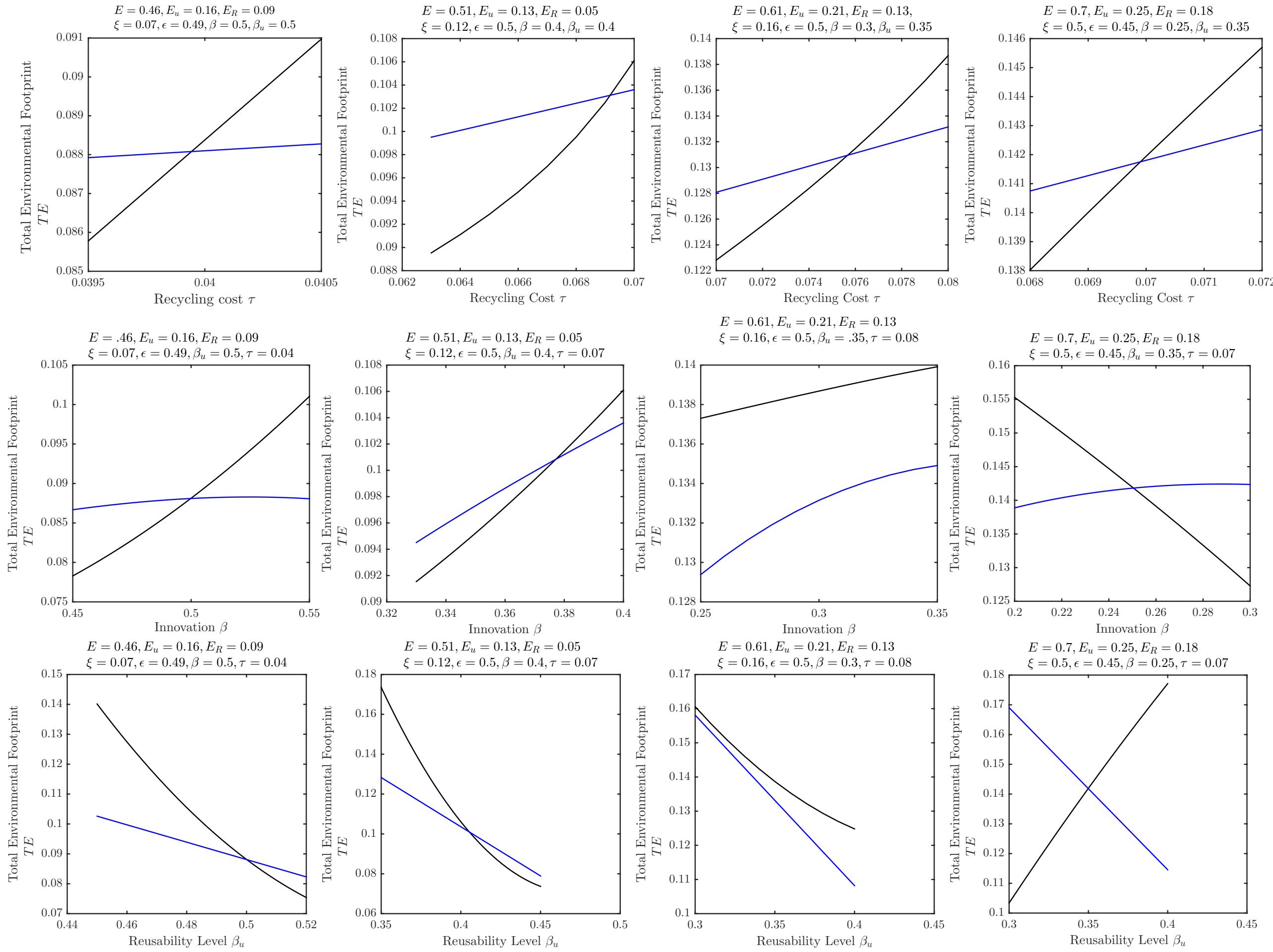

Figure 3 **Comparison of Recover Target with Tax/Subsidy policy. Black line represent recovery target based policy while blue represents taxation policy**

innovation could mean lower environmental footprint. This case is represented by one of our cases. We observe that when the environmental footprint associated with product is low and the reusability levels are moderate to high; a lower level of innovation would lead a recovery target based regulation dominate taxation/subsidy policy. A lower innovation often reduces incentives for remanufacturing (with or without upgrade). A recovery target based policy which only has a single policy parameter caters for this diminished incentives by an increase in recovery target which not only curbs the environmental footprint associated with new products but also increases incentives for product remanufacturing. Since, a taxation/subsidy policy posses three policy levers; the taxation reduces with decreasing innovation while subsidy structure is used to incentivize remanufacturing. This leads to the overall dominance of recovery target based scheme on lower levels of innovation. A converse phenomenon takes over when the environmental footprint decreases with innovation making recovery target based policy to dominate the other at higher level of innovation.

Observe the graph with reusability which captures the opposite picture to the level of innovation. It can be inferred from the graphs that when the environmental footprint increases with innovation it decreases with the level of reusability and vice versa. As expected, a taxation/subsidy scheme dominates the recovery target scheme on lower levels of reusability because it offers a better incentive structure to promote product remanufacturing. However, if the environmental footprint associated with new products is too high i.e, the environmental footprint from virgin material use is quite high; the environmental footprint from upgrade and production of non reusable components during remanufacturing tend to offset the benefits of increased remanufacturing. Thus, a recovery target based policy dominates a taxation/subsidy scheme for higher levels of reusability.

We run another comprehensive test to compute the instances where one policy dominates the other. Considering the case of partial upgrade, we take $c = 0.5$,$c_o = 0.3$,$\delta = 0.6$. We take a range of $\beta = \{0.1, 0.5\}$, $k = \{0; 05, c_o\}$ and $\beta_u = \{0.1, 0.5\}$, $\tau = \{0.01, 0.2\}$, $\epsilon = \{0.05, 0.5\}$,$e_d = \{0.03, 0.2\}$ and $e_m = \{0.01, 0.2\}$. The use impact from the products are assumed to be 20% of manufacturing impact while the impact from remanufacturing and recycling are considered to be 5% of manufacturing and disposal impact respectively. This leads to 6.653×10^8 iterations which take 10 days of computation time. We evaluate 2.35×10^6 instances where a recovery target based policy is feasible (all quantities are non-negative and $\phi < 1$). We find only 43 instances where a taxation/subsidy policy dominates a mandatory recycling rate policy. We acknowledge that this result may not be conclusive yet it provides ample evidence to tilt the balance in the favour of mandatory recycling rate based policy which is not only cost neutral but also use a single policy instrument in comparison with the other policy; yet it manages to dominate the other in numerous examples.

3.6. Conclusion

In this paper, we investigate the effects of innovation and design incentives such as recycling cost and reusability on environmental footprint of a monopolistic firm. First, we show that contrary to the popular opinion, these parameters do not enjoy a simple and monotone relationship with the environmental footprint. Furthermore, we extend our discussion including two popular product recovery policies and investigate how the policy levers adjust to our parameters of interest namely innovation, reusability and recycling cost. We find that although the policy levers associated with taxation/subsidy based policy offer a simple straightforward response to our parameters but the relation of recovery target with our parameters of interest is not straightforward and unidirectional which though adds complexity but provides adaptability to recovery target based policy. We extend our discussion by presenting a stackelberg game between a social welfare maximizing policy maker and profit maximizing firm and study the optimal policy parameters. Next, present our insights extracted from the numerical results of comparison of the two policies. Furthermore, we show that a recovery target based policy may dominate the taxation/subsidy schemes at a lower recycling cost,lower level of innovation and higher reusability if the environmental footprint from new products is not extravagantly high.

Appendix3:Proofs

The equation 19 can be derived as under: The environmental footprint associated with the products include their footprint during production,use, remanufacturing,recycling and disposal which is given as:

$$e_m q+\beta q_u e_m+(1-\beta)(1-\beta_u) q_u e_m+(1-\beta_u) q_R e_m+\beta_u q_R e_{rm}+(1-\beta)\beta_u e_{rm} q_u+e_u(q+q_u+q_R)$$
$$+\beta q_u e_{rc}+(1-\beta)(1-\beta_u) q_u e_{rc}+(1-\beta_u) q_R e_{rc}+(q_c-q_u-q_R) e_{rc}+(q-q_c) e_d+(q_R+q_u) e_d$$

Taking $q_c = q_u + q_r$ for the case of no legislation and taxation/subsidy policy and taking $q_c = \phi q$ will lead us to the results presented in equation 19

Proof Lemma 2 (i) $E > E_u > E_R$ can be obtained by simple comparison

$E - E_u = (1-\beta)\beta_u(e_m - e_{rm} + e_{rc}) + \xi > 0$ and $E_u - E_R = \beta\beta_u(e_m - e_{rm} + e_{rc}) > 0$. (ii) Similarly, we obtain, $E - \phi\xi - E_u - \xi = -\phi\xi + \beta_u(1-\beta)(e_m - e_{rm} + e_{rc})$. And the one pertaining to new and remanufactured products $(E-\phi\xi)-(E_R+\xi) = -\phi\xi+\beta_u(e_m-e_{rm}+e_{rc})$. Solving these inequalities will lead us the the conditions presented in lemma.

Proof of Proposition 9

We take the optimal quantities presented in table 7 and plug these in equation 19 to get total environmental footprint for each policy. A simple differentiation and simplification lead to results presented in table 9.

Proof of Proposition 10

Equation 18 present environmental and economical components of our social welfare function. Profit is represented by equation 17,environmental footprint by 19 and consumer surplus by 20 We plug optimal quantities for each policy back in these equations. A simple differentiation lead to the results presented in table 10.

Proof of Proposition 11

The policy maker solves equation 21. There is one variable and no constraint which suggest that SOC is negative iff $4\epsilon\xi > 3\tau$. Therefore, FOC is sufficient and we solve FOC to obtain the results presented in proposition 11.

Proof of Proposition 12

We solve the optimization problem presented in equation 24. We have three variables with out any constraint which suggest all three principal minors of hessian matrix should be investigated.

$$H = \begin{bmatrix} (4\,\delta-4)^{-1} & (4\,\delta-4)^{-1} & 0 \\ (4\,\delta-4)^{-1} & 1/4\,\frac{\delta\,\beta-\delta+1}{(\delta-1)\delta\,\beta} & 1/4\,\frac{1}{\delta\,\beta} \\ 0 & 1/4\,\frac{1}{\delta\,\beta} & 1/4\,\frac{1}{\delta\,\beta\,(\beta-1)} \end{bmatrix}$$

Therefore, $H_1 = -1/4(1-\delta) < 0$, $H_2 = 1/16\delta\beta(1-\delta) > 0$ and $H_3 = -1/64\beta\delta^2(1-\delta)(1-\beta) < 0$. Since, the hessian is negative semi definite therefore FOCs are sufficient. The solution of FOCs give the optimal policy parameters given in table 11. The comparative statics can be performed with simple differentiation.

4. Robust Product Portfolio Selection and Allocation Decisions with Environmental Legislations

4.1. Introduction

With the increase in global competition, the firms seek cost efficient off-shored facilities and suppliers to retain competitive advantage. Although offshoring does expand, firm's competitive advantage by offering cost efficient options, there are some challenges that can significantly impact a firm's capability to serve its supplier base. They include unreliability of supplier, uncertain lead times, capacity constraints and supply chain disruptions (Kleindorfer and Saad 2005). These issues can be addressed through introduction of multi sourcing strategy. With this strategy, instead of reliance over a single supplier; the firms seek a number of suppliers for the same product/component. With this practice, a firm is able to mitigate the associated risks with supply chain disruptions etc. Multi sourcing strategy has been demonstrated to produce effective results in addressing issues with uncertainties in lead times (Ramasesh et al. 1991), capacity constraints (Yazlali and Erhun 2009), supplier unreliability Dada et al. (2003) and supply chain disruptions Tomlin (2006).

The introduction of multi-sourcing ensures the availability of an alternative source of component should there arise any unforeseen incidents in the supply chain. However, in presence of multi-sourcing strategy, there may be a set of available product configurations and the firm is required to select a subset of product configurations that are most suited to serve its customer base. The extant literature on multi-sourcing has taken into account cases where a customer may or may not differentiate among these product configurations. The literature on Newsvendor models with partial substitution represent the former case. However, it is also plausible that these products are fully substitutable and the customers lack the ability to distinguis among them. Yet, the firms differentiate and tarde off the characteristics of these product configurations to weigh out options for its portfolio selection.

Such characteristics include respective costs, lead times, supplier reliability and associated risks. We extend this discussion with the argument that prevalent legislative regimes may significantly alter the firm's preference order of product configurations. We capture the effects of two different legislative regimes (a) compliance based regulatory standards (b) recovery legislations. Compliance based regulatory standards may disqualify certain product configurations from entry to a certain market. Recovery legislations, on the other hand, introduce dimension of recyclability/reusability of the products that is required to be taken into account alongwith respective costs.

Presently, such compliance regulations are mostly driven with environmental and health concerns and have potential of inflicting severel consequences for the producing firms. In 2001, 1.3 Mn game consoles of Sony were confiscated in the Netherlands because their cables exceeded the maximum allowable concentration of Cadmium which costed SONY 130 MN $. Similarly, with the introduction of ROHS directive in the European Union, the supplies were suspended for Apple iSight camera and Palm Inc Treo 650 cellular device. Therefore, compliance based regulations have produced set-backs to the firms and have forced them to discontinue their sales in the market. With the increasing environmental concerns, there are two important directives enacted in the European union that restrict use of certain metals and chemicals in the electronic products. REACH (Registration, Evaluation, Authorizition and Restriction of Chemicals)Reach (2006) and ROHS RoHs (2003) (Restriction on Hazardous Substance) are two fundamental directives enforced in European Union in 2006 and 2003 respectively. While the former stresses on registration and phase wise removal of hazardous chemicals in a number of products; the latter's scope is restricted to electrical and electronic products. It sets maximum limits on six hazardous chemicals namely(lead, mercury, cadmium, hexavalent chromium,PBB,PBDE). With the expansion of ROHS's directive scope; a wider range of products being reviewed to be added to its jurisdiction. An addition to the list of hazardous chemicals is also under consideration. For instance, ROHS 2 RoHs (2011) adds more product categories for ROHS directive. Similarly, in a letter to World Trade Organizition dated Dec 17'2014, European Union adds four more chemicals in its restricted list which will be effective from 2019 (TUVRheinland 2015).

The scope of compliance based regulations is not limited to environmental and health concerns. It also encompasses broader and more complicated political, social and cultural aspects. Dodd Frank Reform Act on conflict minerals adds constraints on US based firms from sourcing minerals from conflict zones in central Africa (Fein 2010). Amnesty International which is one of the proponent of this act has said that Apple and Samsung may have violated this act (Wilson 2016). California is contemplating a ban on leather products sourced from Kangaroo hides. Similarly, the leather products from pig-skin are banned in some gulf states. Similarly, derivatives sourced from cows is a source of contention in India.

Such restrictions are not globally consistent such as the enforcement of ROHS directive is restricted to the European Union. Similarly, the countries may have their own set of preferences with regard to phase out removal of hazardous chemicals. For instance, Japan's green procurement practices act referred as JPSSI is considered to be more restrictive than ROHS . Australia where mining and metallurgy makes a significant economic contribution is lenient on such legislations. Similarly, Environmental Protection Agency (EPA) in US believes that global emission of lead-tin solder is less than tin-silver solder. In addition to that there are other directives such as ELV (End of Life Vehicle) ELV (2000) restricting the use of heavy metals and ensuring recycling standards in the vehicles.

A firm may pursue an " aggressive standardization" strategy developing a product that qualify to the most stringent set of regulatory requirements. A number of global firms practise this strategy. However, a standard product will not come without a significant cost addition which might make the firm vulnerable in presence of local low cost local competitors in developing countries. Goodman and Robertson (2006) reported compliance costs for ROHS directive to be around 1-4% of a firm's turnover that could inflate the prices by 10-20%. This underscores the limitations of "aggressive standardization" specially for the firms with slim profit margins and in competition with local manufacturers. Alternatively, a firm may opt for multi sourcing strategy allowing it to develop a product portfolio comprising a number of product configurations where each configuration has been developed in accordance with the compliance requirements of the market, it is expected to satisfy.

Compliance regulations are not the only set of environmental regulations that operate in European Union and other markets. There is another set of regulations called "take back" laws which are introduced to address the growing E-Waste regulations. Our dissertation is entirely focussed on the take back laws also known as recovery legislations and we have already included a detailed discussion about them in the previous two chapters. Some of these markets may be governed with recovery legislations which require the firms to retrieve and recycle a fraction of their sales. In presence of these take back laws, the recyclability of the product configurations or the cost incurred to recycle a certain product configuration appear to be a key parameter in our problem. The firms are expected to trade off the cost of the production with the recycling cost of these products in order to select their product portfolio. For this reason, there may be more than one product configuration for each market.

Another important consideration is the absence of complete knowledge about sourcing options/components. Since, such multiple sourcing options are sought offshore, there can be incoherence between the supplier and the firm leading to uncertainty associated with cost parameters. Therefore, for any product portfolio option, we consider two sources of uncertainty; (a) uncertainty associated with production cost of a product option (b) uncertainty with the recycling cost of the product option in presence of recovery legislations. This recycling cost depends on recyclability levels of individual components and incomplete information about them lead to uncertain recovery costs.

Our contribution is the formulation of a robust model that accommodates uncertainties and (i) offer optimal product portfolio selection decision in presence of compliance and recovery legislations (ii) offer product allocation decisions specifying the quantity of each product configuration to be supplied to each market. Our model therefore aids in development of a robust product portfolio that can accommodate for uncertainties associated with the cost parameters. In section 4.2, we present our model. We start with a mixed integer linear programming based model that does not take into account the uncertainties associated with the costs. Next, we present our robust model that accommodates level of uncertainty associated with the cost parameters in presence of deterministic demands. Later, we relax the assumption of deterministic demands and introduce stochastic formulation of demands and accommodates expected stockout/overstock costs. Finally, we add more complexity to the model by considering uncertainty associated with the probability distribution of the demand and thereby present a distributionally robust demand formulation model . We show that our model can be solved with large scale problems in reasonable time and underscore the importance of robust approach with numerical experiments.r

4.2. Model

In this section, we highlight the key features and characteristics of our model which solve a multi-product multiple markets based problem. It selects the optimal product configurations alongwith allocation quantities that are required to be supplied to each market.

If m represent the number of components in each product configuration and n represent the component options the firm have for each component. Then there is (m^n) possible set of available product configurations. If a certain component does not comply the regulatory standards of any market, all the available product configurations comprising that component become ineligible for that market. A product configuration cost can be obtained with the addition of component cost. We also assume that there is a fixed cost associated with the selection of product configuration to eliminate the trivial outcome where all product configurations are active in the supply chain. All costs and sources of uncertainty are associated with the product configuration.

We present the notations of the problem as under:

Let i represent set of available product configurations and j represents the markets.

Let $\mathcal{D}_j$ represent the demand associated with each market.

Let ϕ_j represent the recovery target for each market.

Let c_i represent the manufacturing cost for each product configuration. This cost may be computed by simple summation of all components cost.

Let r_i represent the recycling cost for each product configuration option.

Let f_i represent the fixed cost of a certain product configuration. This fixed cost includes installation of facility for assembly.

Let L_{ij} (binary) captures the compliance obligation. $L_{i,j} = 1$ if a certain product configuration and zero otherwise.

Let y_i (binary) represent the binary decision variable for product selection. With $y_i = 1$ if product configuration i is active and zero otherwise.

Let q_{ij} represents the quantity of product configuration i to be supplied in market j.

Let R_{ij} represents the quantity of product configuration i to be recovered from market j.

Let p represent the price of the product which we assume to be equal across all markets.

4.2.1. Deterministic Model First we formulate the deterministic model where the demands are deterministic and we assume that the cost parameters associated with production and recovery are known to certainty. Under this formulation,

Fixed Cost of Installation of Product

$$\sum_{i=1}^{I} f_i.y_i$$

Production Cost

$$\sum_{j=1}^{J}\sum_{i=1}^{I} c_i.q_{ij}$$

Revenue from Sales

$$\sum_{j=1}^{J} \mathcal{D}_j.p$$

Recovery Costs

$$\sum_{j=1}^{J}\sum_{i=1}^{I} R_{ij}r_i$$

Hence, the optmization model can be presented as:

$$\max_{y_i,q_{ij}} \Pi = \sum_{j=1}^{J} \mathcal{D}_j.p - \sum_{i=1}^{I} f_i.y_i - \sum_{j=1}^{J}\sum_{i=1}^{I} c_i.q_{ij} - \sum_{j=1}^{J}\sum_{i=1}^{I} R_{ij}r_i$$

$$\text{s.t} \sum_{i=1}^{I} q_{ij} = \mathcal{D}_j \qquad \sum_{i=1}^{I} R_{ij} = \phi_j.\mathcal{D}_j \qquad q_{ij} \leq L_{ij}.\mathcal{M} \qquad q_{ij} \leq y_i\mathcal{M} \quad (25)$$

This is the deterministic formulation of the problem. The profit is given by the revenue generated by sales of products minus cost of production, fixed cost of selection and installation of the product and recovery costs. The first constraint in the model highlights the deterministic demands so that production is equivalent to demands. The second constraint specifies that the total recovered quantity in any market should be equal to the recovery target multiplied with the total sales. The third merely enforces the fact that compliance obligations will be fulfilled i.e, a product configuration will not be supplied to the market if it does not satisfy the compliance requirements. $\mathcal{M}$ is just a very large number.

4.2.2. Incorporating Cost uncertainty Deterministic Demand The previous section presents the deterministic formulation which allows us to analyze key trade offs decisions.In this section, we extend the previous model by accommodating uncertainty associated with the underlying cost parameters. We capture the effects of uncertainties and present a robust optimization based model. Here, two sources of uncertainties are considered:

1. Uncertainties associated with manufacturing cost of the product.
2. Uncertainties associated with recycling cost of the product.

We consider that the cost associated with manufacturing and recovery are subjected to some level of uncertainty due to lack of complete knowledge about product characteristics and processes used for production. Acquisition literature in closed loop supply chain resonates with our assumption acknowledges the uncertainties associated with product recovery cost (Hahler and Fleischmann 2013, Teunter and Flapper 2011).

Therefore, we capture two sources of uncertainties one associated with product manufacturing cost and the other associated with product recovery costs. There are three ways, robust optimization model generally accommodate uncertainty sets (a) box uncertainty set (b) ellipsoidal uncertainty set (c) budgeted uncertainty set. We opt for budgeted uncertainty set as it offers lesser degree of conservatism as compared to box uncertainty while maintaining the linear formulation unlike ellipsoidal uncertainty set. More specifically, we capture the uncertainty associated with costs following the approach of (Bertsimas and Sim 2004). We consider the production cost for each product configuration and recovery cost associated with it is uncertain but bounded and is given by the interval $\{c_i + \hat{c}_i, c_i - \hat{c}_i\}$

and $\{r_i + \hat{r}_i, r_i - \hat{r}_i\}$. Furthermore, in order to cater with the level of conservatism, it is assumed that among the product configurations that are shipped in a market j there is only a subset which is subject of cost uncertainties. We introduce parameters Γ_j and Λ_j associated with production and recycling costs respectively. These parameters capture a decision maker's level of conservatism and can be adjusted accordingly. For every market j Γ_j represent the maximum number of product configurations that are supplied in market j and whose **manufacturing cost** is subjected to uncertainty. On a similar note, Λ_j represent the maximum number of product configurations that are supplied in the market j and with **recovery cost** subject to uncertainty.

For a certain market j, we consider the following non-linear formulation

$$\sum_{i=1}^{I} q_{ij}c_i + \max \sum_{i=1}^{I} Q_{ij}\hat{c}_i + (\Gamma_j - \lceil \Gamma_j \rceil).\hat{c}_{it}Q_{ij}$$
$$\text{s.t} - Q_{ij} \leq q_{ij} \leq Q_{ij}$$

This equals the objective function of the following linear program

$$\max \sum \hat{c}_i |q_{ij}| z_{ij}$$
$$\text{s.t} \sum z_{ij} \leq \Gamma_j$$
$$0 \leq z_{ij} \leq 1$$

By using dual formulation, for every market, we obtain

$$\sum_{i=1}^{I} c_i.q_{ij} \; + \; z_j\Gamma_j \; + \; \sum_{i=1}^{I} \eta_{ij} \qquad \text{s.t}, z_j \; + \; \eta_{ij} \; \geq \; \hat{c}_i.Q_{ij} \qquad - \; Q_{ij} \; \leq \; q_{ij} \; \leq \; Q_{ij} \tag{26}$$

z_j, η_{ij} and Q_{ij} are the dual variables associated with the formulation. Readers may go through proposition 1 and theorem 1 of (Bertsimas and Sim 2004) for the detailed proof.

In a very similar way, obtain the linear formulation for the uncertainties associated with the recovery cost for each market. This is given as,

$$\sum_{i=1}^{I} r_i.R_{ij} \ + \ \lambda_j \Lambda_j \ + \ \sum_{i=1}^{I} \zeta_{ij} \qquad \text{s.t} \lambda_j \ + \ \zeta_{ij} \ \geq \ \hat{r}_i.\mathcal{R}_{ij} \qquad - \ \mathcal{R}_{ij} \ \leq \ R_{ij} \ \leq \ \mathcal{R}_{ij} \quad (27)$$

λ_j, ζ_{ij} and $\mathcal{R}_{ij}$ are the dual variables of our linear formulation.

Robust Model

With deterministic demands and uncertainties associated with (i) manufacturing cost (ii) recovery cost; the linearized robust optimization based model is given as:

$$\max_{y_i, q_{ij}} \Pi \sum_{j=1}^{J} p.\mathcal{D}_j - \sum_{i=1}^{I} f_i.y_i - \sum_{j=1}^{J} \Big(\sum_{i=1}^{I} c_i.q_{ij} + z_j \Gamma_j + \sum_{i=1}^{I} \eta_{ij} \Big) - \sum_{j=1}^{J} \Big(\sum_{i=1}^{I} r_i.R_{ij} + \lambda_j \Lambda_j + \sum_{i=1}^{I} \zeta_{ij} \Big)$$

$$\text{s.t} \sum_{i=1}^{I} q_{ij} = \mathcal{D}_j \qquad \sum_{i=1}^{I} R_{ij} = \phi_j.\mathcal{D}_j \qquad q_{ij} \leq L_{ij}.\mathcal{M}$$

$$z_j + \eta_{ij} \geq \hat{c}_i.Q_{ij} \qquad -Q_{ij} \leq q_{ij} \leq Q_{ij} \qquad \lambda_j + \zeta_{ij} \geq \hat{r}_i.\mathcal{R}_{ij} \qquad -\mathcal{R}_{ij} \leq R_{ij} \leq \mathcal{R}_{ij} \quad (28)$$

This presents the robust optimization based model which incorporates the effects of bounded uncertainty sets associated with the cost parameters. This model presents a list of product configurations along with their optimal quantities for each market. Γ_j and Λ_j are decision maker's selected parameters that trade off conservatism against profit. A high value of these two would suggest a highly conservative solution. There is a fixed cost associated with each product configuration which prevents the trivial case where all product configurations will be selected. However, an upper limit on the number of products in the product portfolio can also be induced:

$$\sum_{i=1}^{I} y_i \leq \mathcal{K}, \quad \text{where } \mathcal{K} \text{ restricts the number of product} \qquad (29)$$

4.2.3. Incorporating Cost uncertainties with Stochastic Demands The assumption about the deterministic knowledge of the demands in each market is not coherent with reality. Therefore, we proceed our robust optimization model with the stochastic formulation of the demand. We assume that the demand follows a known probability distribution with a known mean and standard deviation. The knowledge of the probability distribution can be easily drafted by enlisting demand scenarios with a probability and demand value associated with each scenario. Let there are k available demand scenarios and $\mathcal{P}_k$ capture the value of probability associated with each probability along with $\mathcal{D}_{jk}$ value of demands. Then, for each market j the expected demand will be given as $\sum_{k=1}^{K} \mathcal{P}_k.\mathcal{D}_{jk}$.

In presence of stochastic demands, it no longer remains possible to exactly meet the demands and therefore there are overstock/stockout costs that are required to be accommodated.

Let O_{ijk} represent the overstock quantity of a certain product configuration in a market j and o_i represent the overstock cost. Similarly, U_{jk} represents the under-stock quantity in market j with u_j being the associated cost, then the stochastic formulation of demand with robust model is given as:

Fixed Cost of Installation of Product

$$\sum_{i=1}^{I} f_i.y_i$$

Production Cost

$$\sum_{i=1}^{I}\sum_{j=1}^{J} c_i.q_{ij} \;+\; \sum_{j=1}^{J} z_j\Gamma_j \;+\; \sum_{i=1}^{I}\sum_{j=1}^{J} \eta_{ij} \quad \text{s.t,} z_j \;+\; \eta_{ij} \;\geq\; \hat{c}_i.Q_{ij} \qquad -\; Q_{ij} \;\leq\; q_{ij} \;\leq\; Q_{ij}$$

Revenue from Sales

$$\sum_{k=1}^{K}\sum_{j=1}^{J} \mathcal{P}_k \sum_{i=1}^{I} \Big(q_{ij} - O_{ijk}\Big)p$$

Expected Over-Stock Costs

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\mathcal{P}_k\Big(\sum_{i=1}^{I}O_{ijk}.o_i\Big) \qquad \text{where,} \quad \sum_{i=1}^{I}O_{ijk} \geq (\sum_{i=1}^{I}q_{ij} - \mathcal{D}_{jk})$$

Expected Stock-Out Costs

$$\sum_{k=1}^{K}\mathcal{P}_k\Big(U_{jk}.u\Big) \qquad \text{where,} \quad U_{jk} \geq (\mathcal{D}_{jk} - \sum_{i=1}^{I}q_{ij})$$

Expected Recovery Costs

$$\sum_{i=1}^{I}r_i.R_{ijk} \; + \; \lambda_j\Lambda_j \; + \; \sum_{i=1}^{I}\zeta_{ij} \qquad \text{s.t}\lambda_j \; + \; \zeta_{ijk} \; \geq \; \hat{r}_i.\mathcal{R}_{ij} \qquad - \; \mathcal{R}_{ijk} \; \leq \; R_{ijk} \; \leq \; \mathcal{R}_{ijk}$$

$$\text{where,} \quad \sum_{i=0}^{I}R_{ijk} \geq \phi_j\sum_{i=1}^{I}(q_{ij} - O_{ijk)})$$

The optimization model encapsulates the revenues generated from sale minus costs of production and installation of products along with expected costs associated with stockout/ overstock and product recovery.

$$\max_{q_{ij},y_i}\Pi = -\sum_{i=1}^{I}f_i.y_i - (\sum_{i=1}^{I}\sum_{j=1}^{J}c_iq_{ij} + \sum_{j=1}^{J}z_j\Gamma_j + \sum_{i=1}^{I}\sum_{i=1}^{J}\eta_{ij})$$
$$+\sum_{k=1}^{K}\mathcal{P}_k\Big(\sum_{j=1}^{J}\sum_{i=1}^{I}(q_{ij}-O_{ijk})p - \sum_{j=1}^{J}U_{jk}.u - \sum_{j=1}^{J}\sum_{i=1}^{I}O_{ijk}o_i - \sum_{i=1}^{I}\sum_{j=1}^{J}r_i.R_{ijk} - \sum_{j=1}^{J}\lambda_j\Lambda_j - \sum_{i=1}^{I}\sum_{j=1}^{J}\zeta_{ij}\Big) \tag{30}$$

The constraints are given as:

$$\text{s.t} \quad z_j + \eta_{ij} \geq \hat{c}_iQ_{ij} \qquad -Q_{ij} \leq q_{ij} \leq Q_{ij} \tag{31}$$

$$\sum_{i=1}^{I}O_{ijk} \geq \sum_{i=1}^{I}q_{ij} - \mathcal{D}_{jk} \tag{32}$$

$$U_{jk} \geq (\mathcal{D}_{jk} - \sum_{i=1}^{I}q_{ij}) \tag{33}$$

$$\sum_{i=1}^{I} R_{ijk} \geq \phi_j \sum_{i=1}^{I} (q_{ij} - O_{ijk}) \quad (34)$$

$$\lambda_j + \zeta_{ij} \geq \hat{r}_i.\mathcal{R}_{ijk} \qquad -\mathcal{R}_{ij} \leq R_{ij} \leq \mathcal{R}_{ijk} \quad (35)$$

$$q_{ij} \leq L_{ij}.M \qquad q_{ij} \leq y_i.M \quad (36)$$

4.2.4. Uncertainty with Demands: Distributionaly Robust model With stochastic formulation of demand, a complete knowledge about the probability distribution of the demand is assumed which may not lean towards realistic settings where there is only partial information about the demand distribution. Therefore, a set of uncertainty set is expected to be associated with the demand scenarios and probabilities attached to them. A robust approach is required to cope up with the uncertainties associated with demands. One way is to solve the problem for the worst case scenario however this will lead to overly conservative results. We therefore, use distributionally robust approach where we make a trade-off between worst case outcome and profitability by selecting production quantities which are robust against the variability in probability distributions.

We take the approach presented by (Liao et al. 2013) who use distributionally robust approach for call centre scheduling . We make a distinction with (Liao et al. 2013) where uncertainty is presented in one of the constraints whereas we have the element of uncertainty in our objective function.

Consider $\mathcal{P}_k$ as the probability associated with each scenario. In absence of complete information about probability distribution $\mathcal{P}_k$ is an uncertain quantity given as $\mathcal{P}_k = \mathrm{p}_k + \xi$. There is a bound on the presence of probability given as:

$$\beta \geq \sum \frac{|\, \mathcal{P}_k - \mathrm{p}_k \,|}{\omega_k}$$

We find another definition for $\mathcal{P}_k$ given by:

$$\delta_k = \frac{\mathcal{P}_k - \mathrm{p}_k}{\omega_k}$$

where ω_k is a parameter.

Consider equation 28, we simplify,

$$\mathbb{R}_{jk} = \Big(\sum_{i=1}^{I}(q_{ij} - O_{ijk})p - U_{jk}.u - \sum_{i=1}^{I} O_{ijk}o_i - \sum_{i=1}^{I} r_i.R_{ijk} - \lambda_j\Lambda_j - \sum_{i=1}^{I}\zeta_{ij}\Big)$$

Now, the optimization problem can be written as:

$$\max - \sum_{i=1}^{I} f_i.y_i - \max(\sum_{i=1}^{I}\sum_{j=1}^{J} c_i q_{ij} + \sum_{j=1}^{J} z_j\Gamma_j + \sum_{i=1}^{I}\sum_{i=1}^{J}\eta_{ij}) + \max\min_{\mathcal{P}_k}\mathcal{P}_k\sum_{j=1}^{J}\mathbb{R}_{jk} \tag{37}$$

We focus on the solution of max-min problem given as $\max\min_{\mathcal{P}_k}\mathcal{P}_k\sum_{j=0}^{J}\mathbb{R}_{jk}$

This problem is equivalent to:

$$\begin{aligned}\max\sum_{k=1}^{K}\mathrm{p}_k\sum_{j=1}^{J}\mathbb{R}_{jk} + \sum\max\min\omega_k\delta_k\sum_{j=1}^{J}\mathbb{R}_{jk}\\ \text{s.t}\quad \sum_{k=1}^{K}\omega_k\delta_k = 0\\ \text{s.t}\quad \delta_k \geq \frac{-\mathrm{p}_k}{\omega_k}\\ \text{s.t}\quad \sum_{k=1}^{K}\mid\delta_k\mid\leq\beta\end{aligned}$$

With the partial dualization, it can be written as:

$$\max\mathrm{p}_k\sum_{j=1}^{J}\mathbb{R}_{jk} + \max\min\sum\omega_k\delta_k\sum_{j=1}^{J}\mathbb{R}_{jk} + \sum v\omega_k\delta_k + \sum w_k(\delta_k + \mathrm{p}_k/\omega_k)\quad \text{s.t}\sum\mid\delta_k\mid\leq\beta \tag{38}$$

which can be simplified as:

$$\max\mathrm{p}_k\sum_{j=1}^{J}\mathbb{R}_k + \max\min_{\delta_k}\sum\omega_k\sum_{j=1}^{J}(\mathbb{R}_{jk} + v + w_k)\delta_k + \sum w_k\mathrm{p}_k\quad \text{s.t,}\sum\mid\delta_k\mid\leq\beta$$

Now, we write dual of the inner min-max problem of the linear programming problem.

The primal problem is given as:

$$\max\min_{\delta_k}\sum\omega_k\sum_{j=1}^{J}(\mathbb{R}_{jk} + v + w_k)\delta_k + \sum_{k=1}^{K} w_k\mathrm{p}_k\quad \text{s.t,}\sum\mid\delta_k\mid\leq\beta$$

The dual problem is given as:

$$\max \quad \beta\epsilon \quad \text{s.t,} \quad \omega_k(\sum_{j=1}^{J} \mathbb{R}_{jk} + v + w_k) \leq \epsilon \tag{39}$$

This will lead us to the formulation of robust optimization model where uncertainties associated with cost parameters have been incorporated using the work of (Bertsimas and Sim 2004) and uncertainties associated with probability distribution are taken into account through a distributionally robust model similar to the approach of (Liao et al. 2013)

4.3. Numerical Experiment

Having formulated the model, the next step is to examine the performance of the model. We examine the performance of our model based on two set of criteria (i) computational efficiency of the model i.e, to see if the model is capable of solving large scale industrial problems (ii) significance and relevance of the model i.e, if there is any significance of introducing a robust approach and accommodate concerns about uncertainty. The former is measured by mere calculation of computational time while the latter can be analyzed by (a) if the product selection and allocation decisions change with the introduction of robust approach (b) if there is significant financial consequence, provided robust approach is not introduced.

A large scale problem of a firm serving 50 markets is studied. The firm develops its portfolio by optimally selecting a subset among 3000 available product configurations. These product configurations are differentiated based on their costs, uncertainties associated with the costs and compliance requirements. Therefore, a firm selects best configurations and allocates them in the markets considering the legislative structure. In order to eliminate the trivial case of selecting a large number of product configurations in its portfolio, fixed costs are associated with each product configuration. We also include the case where the portfolio size is restricted by a constraint. Binary random numbers are used to define compliance obligation of a configuration with the market. Random numbers over a range are used to define cost parameters. We associate a small level of uncertainty for a product configuration with high cost, assuming that higher cost is due to more advanced and thorough manufacturing operations.

We perform this experiment with (i) Deterministic demands (ii) Stochastic demands (iii) With demand uncertainty and report the findings as under:

4.3.1. Robust Optimization Model with Deterministic Demands This 3000 product configuration 50 market problem is solved with deterministic demand and the average computation time for this problem in presence of deterministic demands is 30 mins with 2.4 Ghz Intel i5 processor with 8 GB RAM. The solution selects three product configurations$P_{1114}, P_{2500}, P_{2613}$ with the profit 240125. Next, we restrict the product portfolio size limiting it to two products by imposing a constraint given by equation 29. The computation time for this formulation rises to 60 mins and a profit decline of around 30% is observed. Moreover, ta complete change in product portfolio is noted with the inductees P_{130}, P_{1135} replacing the other products.

Next, we demonstrate the significance of our approach solving a model with deterministic cost parameters. We plug this solution into simulation model where the actual cost parameters turn out to be random numbers within a small range $5-10\%$. The profit is plotted in black line in part (a) of figure 4. Next, we repeat the experiment inserting the solution obtained with a robust approach into the simulations. The expected profit is plotted in blue in the same figure. Observe that plot with robust solution is distributed over a significantly narrower range. This suggests that by undertaking a robust solution, the firm can avoid a large number of worst case outcomes.

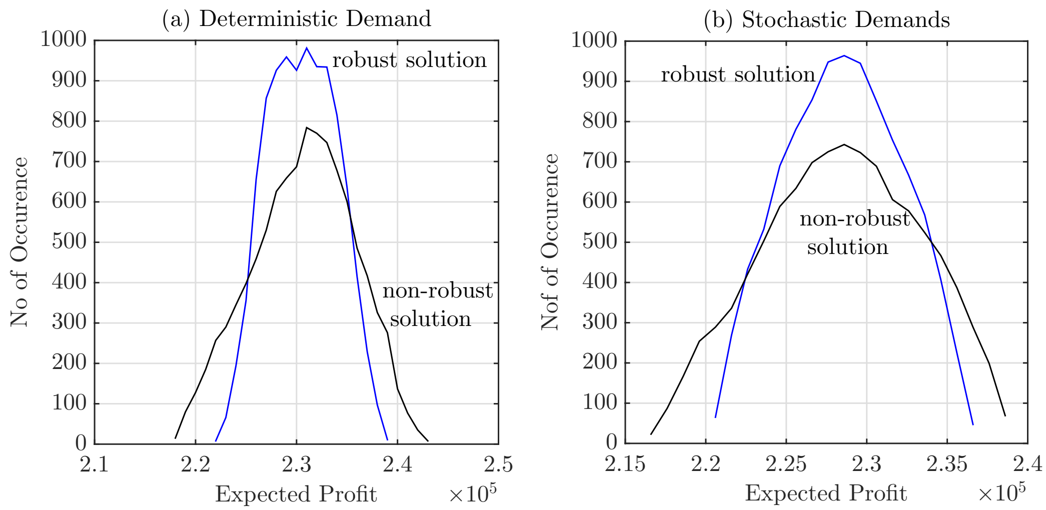

Figure 4 **Numerical result of expected profit distribution**

4.3.2. Robust Optimization Model with Stochastic Formulation of Demands Now, we consider the case of stochastic demands. We solve the problem with robust approach and find that the average computation time ranges between $60-240$ mins depending on the number of demand scenarios. The constraint with respect to restriction in portfolio size yields 38% profit decline and takes 90 mins.

Next, we solve the problem with robust approach and for the case where uncertainties associated with cost parameters are overlooked and plot them in part(b) of figure 4. Note that the significance of robust approach is amplified in this case, as with stochastic demands overlooking cost uncertainty may yield far adverse consequences than the case with deterministic demands. The expected profit in this case is dispersed over a wide range with high likelihood of worse financial outcomes. The blue line demonstrates that selection of robust approach can significantly contain this range avoiding worse cases.

4.3.3. Distributionally Robust Demand Formulation In this step, we enhance the level of complexity of our problem taking into account uncertainties associated with demand distributions. A large scale problem with this setting takes $180 - 900$ mins of computation time.

Next, we take the solution which has taken into account uncertainties associated with costs and demands and take the case where effects of uncertainties associated with neither are considered. Note that if both sources of uncertainty are overlooked, far adverse economical consequences can be expected as the profits distribute over a wider range. The robust model not only contains the distribution of profit in a narrower range but visibly performs far better than the model which does not take into out the effects of uncertainty.

Therefore, we demonstrate the significance of using a robust approach and show that it is both relevant and significant for the firm's performance.

4.4. Conclusion

To the best of our understanding, we present the first study that combine the compliance based legislation and recovery legislations and study their effects on supply chain. We start with a simpler model and gradually increase its complexity which allow us to capture the real world settings. Apart from presenting a robust model that retains linearity and thus is capable of tackling large scale real problems under uncertainty; we are able to demonstrate that introduction of compliance based regulations may completely change product configuration selection decisions. This effect is amplified in presence of uncertainty with relevant cost and market parameters. It stresses that portfolio diversification becomes more imeprative if the relevent parameters are not known with certainty.

5. Conclusion

This dissertation provides an overview of the environmental regulations and explain how they influence operational decisions. Since, introduction of environmental regulations is a costly exercise, it is important for the policy makers to estimate the optimal response and ensure that the proposed regulations lead to the desired outcomes both on environmental as well as economical frontiers.

To conduct this research, we used analytical modeling techniques based on optimization theory. We used game theoretic model based on stackelberg game and model the interaction between a regulator and a monopolistic firm in presence of different legislative schemes. Furthermore, we also develop a robust optimization based model accommodating the uncertainties associated with the recovery costs and demands and solve for optimal product selection and allocation decisions.

The literature in the area of recovery legislations is growing but there are few papers that encapsulate it as a game between policy maker and a firm and we contribute to the extant literature by throwing light on how optimal policy parameters are set and how do they respond to changes in firm's cost and market parameters. Yet we are the first who study the effect of internal competition referred as "demand cannibalization" from remanufactured product which is an important feature and can change the insights from single period models.

The study provides a broader and clearer picture of the take back schemes allowing a policy maker to understand it from the perspective of the firm and more importantly cautioning the policy maker about how under some cases ambitious policy instruments may lead to unintended and undesirable consequences. From the firm's perspective this study provides a better understanding of the policy maker's intervention and devising appropriate tools to respond to such interventions. It also stirs the consideration of uncertainties associated with cost and market parameters and how their impact is amplified in presence of the regulations. In order to reach a goal of reduced environmental footprint, it is important for both firms and policy makers to understand and address each other concerns.

5.1. Key Findings and Contribution

This dissertation contributes to the growing literature in closed loop supply chains and in particular the one which investigates the influence of environmental regulations and take back schemes in the following ways:

1. The game theoretic model enhances our understanding about the key trade off decisions and capture better picture incorporating the effect of cannibalization for reuse decisions.
2. A mixed legislative policy where recovery targets are combined with taxation/subsidy schemes dominates the other two policies. This policy not only leads to higher social surplus and reduced environmental footprint but also leads to better economical incentives i.e, higher profitability and consumer surplus than taxation/subsidy based policy.
3. Under pure taxation/subsidy based scheme, a firm is more likely to retain a single market structure.
4. Furthermore, a taxation/subsidy and mixed approach align the incentives for the policy maker and the firm for the adoption of marketing channel.
5. Contrary to popular beliefs innovation and reusability may lead to unintended environmental consequences i.e, innovation may lead to lower environmental footprint and reusability may lead to higher environmental footprint. This effect is captured with a lifecycle based environmental assessment on a steady state model that captures product cannibalization. It is noted that such an effect could not have been captured without considering internal competition between a product and its remanufactured version.

6. To the best of our understanding, chapter 3 presents very first robust optimization based model dealing with product selection issues under compliance obligations.
7. A small degree of uncertainty associated with costs or market parameters may completely change product portfolio in addition to influencing the allocation decisions.
8. Numerical experiments show that there can be significant monetary consequences for the firm if the uncertainties are not accommodated in the model.

5.2. Limitations and Future Research

The limitations and future research are discussed in the end of each chapter. In general, the scope of this research is limited to a monopolistic firm. A discussion on competing firms is missing and may enrich our managerial insights; however, even a duopolistic competition would increase the product interactions on two different levels and perhaps one will have to resolve to numerical techniques for the solution.

In chapter 1, the market selection strategy is exogenized and more comprehensive analysis might endogenize it entailing We exogenized marketing strategy and a more comprehensive analysis selection of marketing strategy as a response to the policy instruments.

The discussion in chapter 2 could be enriched with the study of innovation levels and reusability as decision variables. It will be interesting to analyze the influence of policy instruments on a firm's long term decision of incremental innovation reusability levels.

As far as Chapter 3 is concerned, two natural extensions include, (i) accommodating uncertainty associated with a product configuration compliance of such regulatory standards (ii) study of optimal product configuration decisions such as studying the issue of component commonality and modular versus integral configurations can also lead to many interesting managerial insights.

References

Agency, Environmental Protection. 2016. Facts and figures on e-waste and recycling. URL `http://www.epa.gov/recycle`.

Atasu, Atalay, V Daniel R Guide, Luk N Wassenhove. 2008a. Product reuse economics in closed-loop supply chain research. *Production and Operations Management* **17**(5) 483–496.

Atasu, Atalay, Öznur Özdemir, Luk N Van Wassenhove. 2013. Stakeholder perspectives on e-waste take-back legislation. *Production and Operations Management* **22**(2) 382–396.

Atasu, Atalay, Miklos Sarvary, Luk N Van Wassenhove. 2008b. Remanufacturing as a marketing strategy. *Management Science* **54**(10) 1731–1746.

Atasu, Atalay, Luk N Van Wassenhove, Miklos Sarvary. 2009. Efficient take-back legislation. *Production and Operations Management* **18**(3) 243–258.

Atasu, Atalay, Luk N Wassenhove. 2012. An operations perspective on product take-back legislation for e-waste: Theory, practice, and research needs. *Production and Operations Management* **21**(3) 407–422.

Australian Bureau of Statistics. 2013. Electronic and electrical waste. URL `http://www.abs.gov.au/ausstats/abs@.nsf/Products/4602.0.55.005~2013~Main+Features~Electronic+and+Electrical+Waste?OpenDocument`.

Australian Recycler MRI. 2014. Australian Recycling Rates. URL `http://www.mri.com.au/recycling-fees.shtml`.

Basel Convention. 2011. Basel convention on controlling transboundary movement of hazardous waste. URL `http://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx`.

Bertsimas, Dimitris, Melvyn Sim. 2004. The price of robustness. *Operations research* **52**(1) 35–53.

Boyaci, T, Vedat Verter, Michael R Galbreth. 2015. Design for reusability and product reuse under radical innovation. *Working Paper, available online https://www.dropbox.com/s/8shdgxl3ietyvyb/RadicalInnovationsJuly2015WP.pdf?dl=0* .

BusinessWeek. 2005. Remanufacturing: The original recycling. URL `http://www.businessweek.com/stories/2005-12-29/remanufacturing-the-original-recycling`.

California EPRI. 2012. Epri calculates annual cost of charging an ipad. URL http://www.epri.com/Press-Releases/Pages/EPRI-Calculates-Annual-Cost-of-Charging-an-iPad-at-$1-36.aspx.

California State Board of Equalization. 2014. California e waste recycling act. URL http://www.boe.ca.gov/pdf/pub95.pdf.

Corbett, Charles J, Robert D Klassen. 2006. Extending the horizons: environmental excellence as key to improving operations. *Manufacturing & Service Operations Management* **8**(1) 5–22.

Dada, Maqbool, Nicholas C Petruzzi, Leroy B Schwarz, et al. 2003. *A newsvendor model with unreliable suppliers*. University of Illinois at Urbana-Champaign Champaign, Illinois, USA.

Drake, David. 2015. Carbon tariffs: Effects in settings with technology choice and foreign production cost advantage. *Harvard Business School Technology & Operations Mgt. Unit Working Paper* (13-021).

Drake, David F, Stefan Spinler. 2013. Om forum-sustainable operations management: An enduring stream or a passing fancy? *Manufacturing & Service Operations Management* **15**(4) 689–700.

EEA. 2012. Policy instruments. URL http://www.eea.europa.eu/themes/policy.

Electronics, Take-Back. 2016. Facts and figures on e-waste and recycling. URL http://www.electronicstakeback.com/wp-content/uploads/Facts_and_Figures_on_EWaste_and_Recycling1.pdf.

ELV, EU. 2000. Directive 2000/53/ec of the european parliament and of the council, "on end-of life vehicles". *Official Journal of the European Union, L* **53** 1–22.

Energy, Solid. 2008. *Environmental Report*. Solid Energy New Zealand.

EPA. 2015. Reduce, reuse, recycle. URL http://www2.epa.gov/recycle/reducing-and-reusing-basics.

Esenduran, Gökçe, Eda Kemahlıoğlu-Ziya. 2015. A comparison of product take-back compliance schemes. *Production and Operations Management* **24**(1) 71–88.

Esenduran, Gökçe, Eda Kemahlıoğlu-Ziya, Jayashankar M Swaminathan. 2015. Take-back legislation: Consequences for remanufacturing and environment. *Decision Sciences* .

Eskeland, Gunnar S, Shantayanan Devarajan. 1996. Taxing bads by taxing goods. *Pollution control with presumptive charges. World Bank* .

European Commission. 2014. Electronics sales and E Waste data. URL http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/key_waste_streams/waste_electrical_electronic_equipment_weee.

Fabrellas, Begona. 2015. First national target for weee preparation for reuse:. URL http://www.rreuse.org/wp-content/uploads/150427_FINAL_Targets-Preparation-for-re-use-in-Spain.pdf.

Fein, Melanie L. 2010. Dodd-frank wall street reform and consumer protection act .

Ferguson, Mark E, L Beril Toktay. 2006. The effect of competition on recovery strategies. *Production and operations management* **15**(3) 351–368.

Galbreth, Michael R, Tamer Boyacı, Vedat Verter. 2013. Product reuse in innovative industries. *Production and Operations Management* **22**(4) 1011–1033.

Gartner. 2015. Gartner electronics sale report. URL http://www.gartner.com/newsroom/id/2954317.

Ghose, Anindya, Rahul Telang, Ramayya Krishnan. 2005. Effect of electronic secondary markets on the supply chain. *Journal of Management Information Systems* **22**(2) 91–120.

Goodman, Paul, Chris Robertson. 2006. Review of directive 2002/95/ec (rohs) categories 8 and 9-final report. *Leatherhead, Surrey, UK: ERA Technology Ltd* .

Greenstone, Michael, John A List, Chad Syverson. 2012. The effects of environmental regulation on the competitiveness of us manufacturing. Tech. rep., National Bureau of Economic Research.

Guide, V Daniel R, Terry P Harrison, Luk N Van Wassenhove. 2003. The challenge of closed-loop supply chains. *Interfaces* **33**(6) 3–6.

Guide, V Daniel R, Luk N Van Wassenhove. 2009. Or forum-the evolution of closed-loop supply chain research. *Operations Research* **57**(1) 10–18.

Hahler, Stefan, Moritz Fleischmann. 2013. The value of acquisition price differentiation in reverse logistics. *Journal of Business Economics* **83**(1) 1–28.

ICF International. 2011. Electronics waste management in the united states through 2009. Tech. Rep. EPA 530-R-11-002, U.S. Environmental Protection Agency Office of Resource Conservation and Recovery. URL http://www.epa.gov/wastes/conserve/materials/ecycling/docs/fullbaselinereport2011.pdf.

Jacobs, Brian W, Ravi Subramanian. 2012. Sharing responsibility for product recovery across the supply chain. *Production and Operations Management* **21**(1) 85–100.

Jaffe, Adam B, Steven R Peterson, Paul R Portney, Robert N Stavins. 1995. Environmental regulation and the competitiveness of us manufacturing: what does the evidence tell us? *Journal of Economic literature* 132–163.

Jain, Siddharth. 2011. A comparative assessment of the carbon footprint of amd fusion products with the previous generation products.

Kang, Hai-Yong, Julie M Schoenung. 2006. End-of-life personal computer systems in california: Analysis of emissions and infrastructure needed to recycle in the future. *Electronics and the Environment, 2006. Proceedings of the 2006 IEEE International Symposium on*. IEEE, 321–325.

Karakayali, Ibrahim, T Boyaci, Vedat Verter, Luk N Van Wassenhove. 2012. On the incorporation of remanufacturing in recovery targets. Tech. rep., Working paper, available online: http://people. mcgill. ca/files/tamer. boyaci/RecoveryTargetsWP. pdf.

Kinnaman, Thomas C., Hide-Fumi Yokoo. 2011. Economic policies to address the environmental consequences of global reuse. *American Economic Review* **101**(3) 71–76.

Kleindorfer, Paul R, Germaine H Saad. 2005. Managing disruption risks in supply chains. *Production and operations management* **14**(1) 53–68.

Kleindorfer, Paul R, Kalyan Singhal, Luk N Wassenhove. 2005. Sustainable operations management. *Production and operations management* **14**(4) 482–492.

Krass, Dmitry, Timur Nedorezov, Anton Ovchinnikov. 2013. Environmental taxes and the choice of green technology. *Production and Operations Management* **22**(5) 1035–1055.

Kuehr, Ruediger, Eric Williams. 2003. *Computers and the Environment: Understanding and Managing their Impacts: Understanding and Managing Their Impacts*, vol. 14. Springer Science & Business Media.

Liao, S, Christian Van Delft, J-P Vial. 2013. Distributionally robust workforce scheduling in call centres with uncertain arrival rates. *Optimization Methods and Software* **28**(3) 501–522.

Mitra, Supriya, Scott Webster. 2008. Competition in remanufacturing and the effects of government subsidies. *International Journal of Production Economics* **111**(2) 287–298.

National Center for Environmental Economics. 2015. Economic incentives. URL `http://yosemite.epa.gov/EE%5Cepa%5Ceed.nsf/webpages/EconomicIncentives.html`.

OECD Publishing. 2001. *Extended Producer Responsibility: A Guidance Manual for Governments*. Organisation for Economic Co-operation and Development.

Oraiopoulos, Nektarios, Mark E Ferguson, L Beril Toktay. 2012. Relicensing as a secondary market strategy. *Management Science* **58**(5) 1022–1037.

Ovchinnikov, Anton, Vered Blass, Gal Raz. 2014. Economic and environmental assessment of remanufacturing strategies for product+ service firms. *Production and Operations Management* **23**(5) 744–761.

Plambeck, Erica, Qiong Wang. 2009. Effects of e-waste regulation on new product introduction. *Management Science* **55**(3) 333–347.

Porter, Michael. 1996. America's green strategy. *Business and the Environment. Earthscan, London* 33–35.

Ramasesh, Ranga V, J Keith Ord, Jack C Hayya, Andrew Pan. 1991. Sole versus dual sourcing in stochastic lead-time (s, q) inventory models. *Management Science* **37**(4) 428–443.

Raz, Gal. 2015. Economical and environmental assessment of remanufacturing in competitive setting. *Working Paper* .

Raz, Gal, Cheryl T Druehl, Vered Blass. 2013. Design for the environment: Life-cycle approach using a newsvendor model. *Production and Operations Management* **22**(4) 940–957.

Reach, EU. 2006. Regulation (ec) no 1907/2006 of the european parliament and of the council,concerning the registration, evaluation, authorisation and restriction of chemicals (reach). *Official Journal of the European Union, L* **396** 1–849.

RoHs, EU. 2003. Directive 2002/95/ec,restriction of the use of certain hazardous substances in electrical and electronic equipment. *Official Journal of the European Union, L* **37** 19–23.

RoHs, EU. 2011. Directive 2011/65/eu of the european parliament and of the council,restriction of the use of certain hazardous substances in electrical and electronic equipment. *Official Journal of the European Union, L* **174** 88–108.

Sharpe, M. 2005. Climbing the e-waste mountain. *Journal of Environmental Monitoring* **7**(10) 933–936.

Sloma, Marcin. 2013. Carbon footprint of electronic devices. *Electron Technology Conference 2013*. International Society for Optics and Photonics, 890225–890225.

Souza, Gilvan C. 2013. Closed-loop supply chains: A critical review, and future research*. *Decision Sciences* **44**(1) 7–38.

Teunter, Ruud H, Simme Douwe P Flapper. 2011. Optimal core acquisition and remanufacturing policies under uncertain core quality fractions. *European Journal of Operational Research* **210**(2) 241–248.

Toffel, Michael W. 2004. Strategic management of product recovery. *California management review* **46**(2) 120–141.

Tomlin, Brian. 2006. On the value of mitigation and contingency strategies for managing supply chain disruption risks. *Management Science* **52**(5) 639–657.

Toyasaki, Fuminori, Tamer Boyacı, Vedat Verter. 2011. An analysis of monopolistic and competitive take-back schemes for weee recycling. *Production and Operations Management* **20**(6) 805–823.

TUVRheinland. 2015. Draft commission directive amending annex ii to rohs directive. URL `http://www.tuv.com/en/usa/about_us/regulations_and_standard_updates/latest_regulations_us/latest_regulation_content_us_231820.html`.

Walls, Margaret. 2006. Extended producer responsibility and product design: Economic theory and selected case studies .

Waste Diversion Ontario. 2005. Why a tv recycling fee? URL `http://www.wdo.ca/blog/why-tv-recycling-fee/`.

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

West, Sarah E, Ann Wolverton. 2005. Market-based policies for pollution control in latin america. *Environmental Issues in Latin America and the Caribbean*. Springer, 121–146.

Wilson, Tom. 2016. Apple inc, samsung electronics co may be using cobalt dug by children in congo: Amnesty international. URL `http://business.financialpost.com/fp-tech-desk/apple-inc-samsung-electronics-co-may-be-using-cobalt-dug-by-children-in-congo-amnesty-internationa`
`__lsa=985a-f057`.

Yazlali, Özgür, Feryal Erhun. 2009. Dual-supply inventory problem with capacity limits on order sizes and unrestricted ordering costs. *IIE Transactions* **41**(8) 716–729.

Zhang, Y, John K Gershenson. 2003. An initial study of direct relationships between life-cycle modularity and life-cycle cost. *Concurrent Engineering* **11**(2) 121–128.

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ÉCOLE DOCTORALE
Sciences de l'homme et de la société (SHS)

Titre : Trois essais sur les effets des législations environnemental sur les chaîne d'approvisionnement

Mots clés : Législation des récupération, réutilisation des produits, économie circulaire optimisation robuste, jeu stackelberg

Résumé : Cette thèse est consacrée à l'étude des législations environnementales et leurs effets sur la chaîne d'approvisionnement. Plus précisément, nous nous intéressons à la législation basée sur le recyclage du produit mais aussi sur les normes de conformité (ROHS). Nous étudions le potentiel de réutilisation ainsi que les aspects environnementaux et économiques de différents systèmes de législation. La solution se présente sous forme d'une combinaison de politiques de récupération qui mène à de meilleurs résultats sur le plan écologique ainsi que sur le plan économique

Dans la deuxième partie de la thèse, Nous étudions la performance comparative des régimes à base sur la législation de récupération avec des problématiques d'innovation et de conception de produits. La politique de réutilisation des produits peut aggraver l'environnement si le cadre de la régulation n'est pas bien défini. Dans la dernière partie, une étude est menée sur le choix des produits dans une chaine d'approvisionnement avec des législations basées sur la récupération et et sur la conformité des produits. Nous intégrons les effets de l'incertitude associée à la demande du marché et les paramètres de coût de récupération. Une méthode d'optimisation robuste pour la sélection et distribution des produits est présentée.

Title: Three essays on the effects of Environmental Regulations on supply chain practices

Keywords : Recovery Legislations, Product reuse, Closed loop supply chain, Environmental footprint, Stackelberg game, Robust Optimization

Abstract: Climate change and global temperature rise has made environmental legislations a focal point of discussion. This dissertation is devoted to the study of environmental legislations and their effect on supply chain practices. More precisely, our center of interest is the product recovery based legislation along with compliance based regulations. We explore the reuse potential and the environmental and economical aspects of different product recovery based legislation schemes by modeling a stackelberg game between a social welfare maximizing policy maker and a profit maximizing monopolistic firm and find that a combination of existing recovery policies i.e., a recovery target in combination with incentive structure such as taxation/subsidy may lead to better outcomes not only from environmental perspective but also from economical aspects. In Chapter 2, we extend the discussion comparative performance of the recovery legislation based schemes in presence of innovation and product design issues and show how unintended environmental outcomes may appear if the policy framework is not adequately designed. In Chapter 3, we capture the effect of recovery legislations and compliance based legislations on product selection when a firm serves a number of markets. We incorporate the effects of uncertainty associated with market demands and recovery cost parameters and present a robust optimization based method for product selection and allocation decisions.