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Product system implications at end-of-life: An Economic and environmental assessment

Mark Krystofik

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PRODUCT SYSTEM IMPLICATIONS AT END-OF-LIFE:
AN ECONOMIC AND ENVIRONMENTAL ASSESSMENT

by

MARK KRYSTOFIK

A DISSERTATION
Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Sustainability
Department of Sustainability
Golisano Institute for Sustainability
Rochester Institute of Technology
May 2013

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Mark Krystofik
Product system implications at end-of-life: an economic and environmental assessment

By

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SUSTAINABILITY PROGRAM
ROCHESTER INSTITUTE OF TECHNOLOGY
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ABSTRACT
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Name of Candidate Mark Krystofik
Title Product system implications at end-of-life: an economic and environmental assessment

While there are many opportunities to make adjustments in how products are produced and consumed to reduce environmental impact, this dissertation focuses on product reuse and proposes a framework to evaluate the economic and environmental effects of proposed interventions in the product system that encourage end-of-life product to be guided toward environmentally preferred reuse or recycling paths. A novel aspect of the approach requires characterizing the product system structure to distinguish between those interventions that maintain the interaction dynamics amongst product system actors (producers, consumers and government), and those that alter the product system structure, enabling unintended consequences. The consumer printing sector serves as the backdrop to demonstrate our framework over three essays. This sector was chosen because inkjet cartridges have a variety of end-of-life paths available in the United States, but the majority is still routed to the municipal waste stream after a single use. The first essay utilizes Life Cycle Assessment to quantify the environmental impact of an inkjet cartridge compared to remanufactured and multiple refilling alternatives. Results confirm that inkjet cartridge reuse provides environmental improvement over new inkjet cartridges. However, inclusion of how consumers go about purchasing and
disposing of inkjet cartridges in the functional unit revealed changes in consumer behavior can have more bearing on environmental impact than what product alternative was purchased. The second essay uses economic modeling to show that it is possible to raise social welfare and maintain the original manufacturer’s profit by strengthening the firm’s intellectual property rights in exchange for the firm implementing greener physical product attributes. The third essay considers the economic and environmental effects of a product take-back regulation that may encourage recycling in a collective implementation or remanufacturing of the durable printer in an individual producer implementation. While take-back only applies to the printer market, we investigate the spillover effects to the cartridge market that resides within our product system model. While a collective take-back scheme minimizes environmental harm, welfare is also minimized. Whereas, under an individual take-back scheme, environmentally preferred remanufacturing of returned durable products may lead to a reduction in environmental harm while increasing welfare.
ACKNOWLEDGMENTS

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Last, but certainly not least, I would like to thank my family for their support and sacrifices over the past four years while I pursued my PhD. My wife Mary has been the primary bearer of the financial burden, and primary caregiver allowing me to focus on my studies. You have all my love and gratitude.
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I. INTRODUCTION

Research in sustainable consumption and production aims to promote social and economic development within the carrying capacity of ecosystems by a) improving efficiency of production processes, b) moving toward sustainable use of resources, and c) reducing resource degradation, pollution and waste. The research in this area is focused on eco-efficiency strategies on the production side, encouraging more efficient deployment of products and services during the use phase, and reducing consumption volumes while maintaining quality of life, promoting end-of-life products toward reuse or recycling paths, or switching to greener products on the consumption side [1]. This research has provided valuable insight into understanding the role each actor (i.e., consumer, producer and government) plays within a product market, and has identified factors responsible for attributing to current environmental impacts.

However, this research field struggles with evaluating the overall effects that independent actor intervention recommendations will have in the product market(s) due in part to complex interactions that exist between these actors, but also since some recommended environmentally motivated interventions typically lead to an altered product system structure, which may make findings from previous modeling (based on the original product structure) invalid. This dissertation proposes a system-level analysis framework to evaluate economic and environmental implications of recommended actor interventions. For interventions that maintain the product system structure (PSS), the framework allows for economic and environmental comparison of pre and post intervention conditions. Whereas for interventions that disrupt the product system
structure, our approach suggests revised characterization of the product system structure is necessary to identify avenues that can lead to unintended consequences.

**Figure 1.1** Structure, conduct and performance approach as presented by Figure 1.1. Carlton and Perloff [2].

Our PSS concept takes a systems approach by first determining the environmental impacts for a specific product of interest throughout its lifecycle and identifying opportunities for environmental improvement. Each intervention opportunity can then be evaluated to determine if the proposed intervention would alter the ways the individual actors interact in the product market(s). Our PSS concept is much like the *structure-conduct-performance* approach (Figure 1.1 adapted from Figure 1.1 Carlton and Perloff [2]) commonly used in the field of industrial organization to understand economic performance, except we also include environmental performance. We specifically
identify key observations to consider for each of the boxes shown in Figure 1.1 to determine the PSS for the product markets studied in this dissertation. An intervention in the form of information the Environmental Protection Agency posts on their web site that mentions ways for people to reduce the environmental impact of their lifestyle choices is of the type that maintains the product system structure. An intervention of this type enables voluntary actions and does not necessarily change the way producers and consumers interact. However, an intervention in the form of a regulation or policy instrument (e.g., tax on a “brown” good and/or subsidy on a “green” good) alters the free market playing field and rules of engagement. This altered product system structure may prompt responses from firms and/or consumers that could not be anticipated in the original product structured before the regulation. If we think of a product system structure as a card game with defined rules, and card players have knowledge of different strategies available to play the game, then the regulation would be like a new rule introduced to the game. The new rule changes the card game, and an effective strategy under the old rules may become completely ineffective in the new game.

Rapid technological progress in electronic products (e.g., cellular phones, personal computers, printers and multifunction devices) has provided society with many benefits, such as enhanced productivity, communication and information processing. However, consumer desire for faster and better devices, results in new production and premature abandonment of functional, but outdated electronic products. Gains in production output efficiency have been accompanied with side-effects in the form of negative environmental externalities, such as eutrophication from fertilizer use and livestock production, ozone depletion from halocarbon refrigerants, pollution and GHG emissions.
emissions from all sectors of the economy that disrupt ecological recycling and threaten the Earth’s life support functions. But unlike natural systems where residues are welcome additions to interconnected food webs, discarded products are often not returned to industrial systems as efficiently as residues are returned to natural systems. Since industrial systems are not interconnected as in natural systems, discarded products may be routed to a variety of end-of-life paths, such as reuse, repair, refurbishment, remanufacture, recycling, incineration, and landfill. From a systems level approach, slowing overall consumption of material and energy intensive products combined with efficient processing of discarded products back into the production of new products that better fit changing needs of our evolving society is in alignment with sustainable development.

This dissertation looks to fill a gap in the literature by combining a variety of analysis tools, including economic welfare modeling, life cycle assessment (LCA), and systematic operational analysis to ascertain the economic and environmental impacts of actor intervention opportunities, with specific focus upon actor engagements defined by the product system structure. Our case study focused on the inkjet cartridge market. Inkjet cartridges were considered because the majority (65% to 75%) is routed to disposal after a single use in North America [3], even though there are a variety of end-of-life routes that could provide environmental benefits. But due to a tie-in sales strategy prevalent in the inkjet printer/cartridge markets, both product markets were considered using our PSS framework. Chapter 2 uses embodied energy as a proxy for environmental impact in comparing new, remanufactured and refilled inkjet cartridges, and maps environmental impact of discard paths. As expected, reuse alternatives can provide
environmental improvement in the product market, and informing consumers of these findings may encourage some consumers to alter their purchase choices and discard methods. More importantly, the analysis revealed that consumers could drive much more environmental improvement by changing the manner cartridges (or alternatives) were purchased (e.g., reduce consumer travel to a retail store) rather than altering their cartridge purchasing decisions. Maintaining the mix and volume of cartridge and alternatives consumed in the market should not prompt a response from producers, as would be expected if consumers dramatically substituted reused cartridge alternatives for new cartridges. Hence, sharing these findings from the LCA study to the general public would be an intervention that maintains the product system structure.

Investigation into the reasons for cartridges to be routed toward less environmentally preferred end-of-life routes, revealed an important connection to the printer market. Original manufacturers (OMs) use a tie-in strategy, where printers are offered on the market at a low price to increase demand for highly profitable replacement cartridges. Under this strategy, the OM is motivated to sell single use cartridges, and actively takes step to prevent independent firms from providing high quality remanufactured cartridges that would reduce the number of new replacement ink cartridges sold by the OM. The OM utilizes a combination of intellectual property rights and physical product attributes incorporated into the design in order to deter independent firms from remanufacturing the original manufacturer’s product. The contribution of Chapter 3 is to combine the economics of green design literature with the literatures regarding raising rivals’ costs and the economics of intellectual property rights to show that a regulator could raise social welfare by strengthening the OMs’ intellectual property
rights in exchange for an increase in remanufacturability built into products by OMs. While motivated by observations seen in the printer-cartridge markets, the analysis performed in Chapter 3 is general and broadly applicable. The basic idea is that an OM can protect profit from independent (aftermarket) manufacturers by either reducing the remanufacturability of its product or by enjoying relatively strong intellectual property rights. These strategies can differ in social impact, however, as reducing remanufacturability raises consumption of single-use products and therefore increases the flow of virgin materials to production and the flow of consumer waste to landfills. As opposed to recommending government install a new policy to influence OMs to increase remanufacturability of their products that would change the structure of the product system, this chapter looks at the economic and environmental impacts of selectively fine tuning an existing government policy mechanism, the intellectual property right system. Given that our product system structure for our case study encompasses both the inkjet printer market and replacement inkjet cartridge markets, Chapter 4 investigates economic and environmental impacts across both markets for a product take-back regulation for the durable printer, much like the WEEE Directive in Europe. Our findings that the economic and environmental impacts are dependent on whether the durable product take-back is implemented as a collective or individual producer responsibility scheme is consistent with the literature [4-6]. One novelty of our approach is that these impacts are examined across both the durable and consumables markets as defined by our product system structure. We find that environmental damage is reduced under collective durable product take-back, but welfare is lower than prior to the take-back requirement, and lower than when the firm remanufactures under the individual durable product take-back
scheme. The economic and environmental impacts under the individual scheme are dependent upon the cost savings the firm can achieve from reusing returned durable product, and the environmental benefit achieved from reuse. On a per durable product basis, individual take-back with the OM remanufacturing can range from a little worse to much better than the collective scheme from an environmental damage perspective. We find social welfare is improved the most under individual take-back with the OM remanufacturing, but the results depend upon the environmental savings that can be achieved from remanufacturing.
II. WHEN CONSUMER BEHAVIOR DICTATES LIFE-CYCLE PERFORMANCE BEYOND THE USES PHASE: CASE STUDY OF INKJET CARTRIDGE END-OF-LIFE MANAGEMENT

2.1 Introduction

Public awareness of environmental issues has left consumers wondering what lifestyle changes they can initiate to lessen the environmental impacts associated with consumption. Aside from just consuming less, consumers may reduce their environmental footprint by switching to product alternatives with lower life cycle environmental impacts. Markets have responded with “greener” product offerings; but higher prices and performance concerns discourage wide-spread adoption. One example is remanufactured products, which have the stigma of being a “used” product, but are considered to be greener, since some remanufactured products require less energy and virgin materials than their new counterparts [7, 8]. Additionally, the lower price of remanufactured products may make them desirable to consumers. A remanufactured product is more likely to be a suitable replacement when the consumer values cost and function over other product attributes, like aesthetics. An example of this preference is consumer printer cartridges, which can be refilled for reuse or remanufactured for direct savings to the consumer without significant loss of quality or need to maintain appearance. However, remanufactured and refilled printer cartridges satisfy just 20% of market demand in the United States [9]. This low percentage can be attributed to market dynamics and a lack of clear guidance for consumers. Since printer original equipment manufacturers (OEMs or OMs) use a business model that relies on sales of new inkjet...
cartridges, OEMs are motivated to protect their revenue stream by discouraging cartridge reuse alternatives provided by independent remanufacturing and refilling firms.

The disparity between new and reused or remanufactured cartridges will likely grow as the market expands. In 2006, 479 million new inkjet cartridges, 85% of the total cartridge market were shipped to North America [3]. The inkjet printer market is projected to see 5.8% compound annual growth in the United States through 2014 [10]. Increasingly, inkjet printers are preferred over laser printer alternatives, due to performance and cost. Printed page yield for a laser printer cartridge have ranges of the order of 1,000 to 50,000 pages (at 5% coverage), whereas the range for an inkjet cartridge is typically from 100 to 2,000 pages. The technologies also diverge in price, resulting in a market segmented between high volume users selecting laser printing technology and home and small business users selecting inkjet technology. Due to cartridge construction differences laser cartridges must have internal components replaced during a remanufacturing cycle to provide acceptable performance, whereas an inkjet cartridge may be refilled multiple times before degradation in printing is noticeable [11]. This inherent durability of inkjet cartridges and the associated profit potential of refilling have prompted inkjet cartridge refilling services to enter the retail landscape, including national retailers Wal-Mart and Walgreens.

While laser and inkjet cartridges provide a similar function in a printing system, their similarities end there, preventing previous laser cartridge LCA research from painting a clear picture of the environmental impacts associated with end-of-life paths and reuse options for inkjet cartridges that were not considered in a 1996 inkjet cartridge LCA [12]. Results for these studies are summarized in Table 2.1, with an expanded
description of each study in the Appendix. This body of work has revealed several findings that are relevant for the inkjet cartridge case. In 2002, Berglind and Eriksson demonstrated environmental savings could be achieved from multiple laser cartridge remanufacturing cycles, while bringing attention to the impact of paper and printer electricity, noting that 95% of the electricity consumed by the printer during the cartridge use cycle occurred while the printer was idle [13]. A 2004 study conducted by First Environment proposed a methodology for dealing with quality and page yield difference between a new Hewlett-Packard (HP) laser cartridge and three very different remanufactured versions in the marketplace at that time [14]. This study was also refreshed in 2008 by Four Elements Consulting, but included a detailed sensitivity analysis [15]. This literature does not address the scenario of multiple use cycles that may be achieved from refilling one original inkjet cartridge. No study to our knowledge connects this consumer-driven EOL pathway to potential environmental benefits.
### Table 2.1 Comparison of LCA parameters and key results for previous cartridge assessments

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cartridge</td>
<td>OEM</td>
<td>OEM</td>
<td>Rem</td>
<td>OEM</td>
</tr>
<tr>
<td>Paper</td>
<td>OEM</td>
<td>OEM</td>
<td>Rem</td>
<td>OEM</td>
</tr>
<tr>
<td>GWP100</td>
<td>%</td>
<td>kg CO2 eq</td>
<td>kg CO2 eq</td>
<td>kg CO2 eq</td>
</tr>
<tr>
<td>Production</td>
<td>85%</td>
<td>9.533</td>
<td>5.867</td>
<td>31.033</td>
</tr>
<tr>
<td>Use</td>
<td>13%</td>
<td>0.031</td>
<td>5%</td>
<td>0.019</td>
</tr>
<tr>
<td>EOL</td>
<td>2%</td>
<td>0.041</td>
<td>73%</td>
<td>0.438</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>9.533</td>
<td>5.867</td>
<td>31.033</td>
</tr>
<tr>
<td>Recycle</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Waste-to-Energy</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Note: “OEM” refers to a new cartridge and “Rem” refers to a remanufactured cartridge. The three remanufactured cartridge scenarios considered in the 2004 study were 1) a baseline remanufacturing cycle assumed to be representative of the remanufacturing industry in North America denoted as Rem-Base, 2) a “drill and fill” operation where an empty OEM cartridge is just drilled in order to remove residual and waste toner in the cartridge and then filled with replacement toner, and 3) a remanufactured cartridge produced by an international remanufacturer with improved quality and reliability than the baseline version.
The purpose of this study is to provide a consumer-oriented comparison of the environmental tradeoffs associated with retail refilling and remanufactured inkjet cartridge alternatives as compared to purchasing new OEM inkjet cartridges. Since a consumer’s inkjet cartridge purchase options at any point in time are dependent upon actions taken in previous time periods, our study specifically focuses on: 1) consumer decisions at cartridge end-of-life (EOL), 2) the processing an EOL inkjet cartridge undergoes before returning to the market as a reused (e.g., remanufactured or refilled) alternative, and 3) how consumers purchase inkjet cartridges. Sensitivity and scenario analyses are used to explore assumptions and parameter uncertainties while incorporating observations and data from the inkjet cartridge market to describe the inkjet cartridge alternatives typically found in the U.S. market. Previous LCA results in the print industry suggest consumer behavior during the use phase as the best opportunity for environmental savings from the reduction of paper consumption [16]. Our study fills a gap in existing literature by investigating consumer behavior pertaining to the mode of transportation and manner in which consumers purchase cartridges (i.e., multiple cartridge purchases vs. one-by-one purchasing). Understanding conditions where cartridge reuse can provide environmental savings without sacrificing benefit consumers receive from printed output is explored in this study.

2.2 Inkjet cartridge LCA

2.2.1 Methodology and framework

This LCA study was conducted with guidance from the International Organization for Standardization’s (ISO’s) 14040 and 14044 standards[17]. The LCA was applied to
a monochrome (i.e., black ink) inkjet cartridge produced by Hewlett-Packard, the leader in the consumer inkjet printing market, and was chosen for several reasons:

1. The HP 60 inkjet cartridge was designed so that it could utilize plastic recycled from previously used HP inkjet cartridges; an innovative process widely promoted by Hewlett-Packard [18].

2. Unlike previous generation inkjet cartridges that specify the amount of ink in the cartridge, the HP 60 cartridge instead identifies an expected page yield of up to 200 one-sided pages at 5% ink coverage.

3. The HP 60 cartridge is representative of a recent trend in the industry of providing the consumer two replacement inkjet cartridge options, HP 60 and HP 60XL. The HP 60XL is a high yield version cartridge with up to 600 one-sided pages of expected output. The HP 60 has a lower price than the HP 60XL, but a higher price per page printed as seen in Table 2.2.

<table>
<thead>
<tr>
<th>Model</th>
<th>Yield</th>
<th>Price</th>
<th>Price per Printed Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP 60</td>
<td>Up to 200 pp</td>
<td>$14.99</td>
<td>$0.075</td>
</tr>
<tr>
<td>HP 60XL</td>
<td>Up to 600 pp</td>
<td>$34.99</td>
<td>$0.058</td>
</tr>
</tbody>
</table>

2.2.2 Goal and scope

The main goal of the study is evaluate environmental impacts of EOL pathways available to consumers for an inkjet cartridge and determine to what extent the consumer behaviors influence these impacts. Results from this LCA are intended to be used to inform and guide consumers in comparing EOL pathways and inkjet cartridge reuse alternatives. To achieve this goal, specific objectives of the study were to:

1. Determine the life cycle inventory for a representative inkjet cartridge.
2. Compare the life cycle impact of this representative inkjet cartridge with related alternatives available to a US consumer, namely, cartridge refilling performed by a retailer, and purchasing a remanufactured cartridge at a retailer. This comparison will also identify environmental “hotspots” associated with how consumers achieve printed output by the inkjet cartridge options they choose, including the transport mode and manner in which cartridges are purchased. Each scenario includes sensitivity analysis on parameters with high uncertainty to identify conditions under which the environmental preference of inkjet cartridge options may change.

3. Compare the environmental impact of alternative potential waste management options (i.e., recycle, donation and disposal) for each cartridge option at the end of the use stage.

2.2.3 Functional unit

The function of an inkjet cartridge is to enable a user to print output, and it is only one part of a printing system, which includes a printer, print media, a computer or other device used to transmit the data to be printed. Although there may be differences between the quality and quantity of pages printed across each cartridge alternative, the baseline assumption was that the quality and quantity of pages printed would be identical for each cartridge alternative. Although previous comparative life cycle assessment studies listed in Table 2.1 for printer cartridges typically use “pages printed” or a variation thereof for the functional unit, basing results on cartridge use cycles allows for more direct focus on impacts specific to the inkjet cartridge EOL route chosen by the consumer, regardless of use. Previous studies, which all assume 100 pages of printed
output, also introduce a metric of “usability” for the printed output, and their results show that perceived quality differences in printed output can have a substantial influence on the life cycle impact. To be conservative, our study assumes that each inkjet cartridge alternative provides sufficient quality so that all 100 pages of printed output are usable. This assumption reflects the market, where reputable remanufacturers and retailers offering refill services offer a money back guarantee [19, 20]. Since multiple reuse cycles achieved from refilling by a retailer was of specific interest, the functional unit was defined as “five use cycles.” This functional unit enables comparison of five new cartridges, one new cartridge reused four subsequent times, or any combination that provides functionality of five cartridge uses.

### 2.2.4 Processes and assumptions

Figure 1 shows the processes included for the comparative life cycle assessment of five inkjet cartridge use cycles when a consumer has the choice of purchasing a new or remanufactured cartridge upon their first visit to the retail store. After a use cycle, only a new (or previously refilled) inkjet cartridge may be routed for refilling up to a maximum of four times. Every EOL pathway, except disposing of an empty inkjet cartridge into the municipal waste stream (MSW), requires the consumer to undertake a transportation activity. For consistency, each consumer transport activity is held constant across compared scenarios. After an inkjet cartridge use cycle, the consumer chooses an EOL route for the spent cartridge, independent of the choice for which inkjet cartridge alternative to purchase, except for when the consumer chooses the “Refill” EOL route. Assumptions and specific details for blocks shown in Figure 2.1 are as follows:
OEM Cartridge

To generate a baseline for comparing cartridge EOL alternatives, a new HP 60 inkjet cartridge was disassembled and then modeled using life cycle inventory data available in the ecoinvent v2.2 database [21] in SimaPro 7.3 [22]. Since the exact origin of each component/material could not be verified, European data electricity was assumed and no additional transportation operations were added to account for each component/material to travel from its manufacturing origin to the final cartridge assembly location. The disassembled inkjet cartridge was categorized into the following seven subassemblies/named components:
• **Housing** - The inkjet cartridge housing is composed of 85% polyethylene terephthalate (PET) and 15% glass fiber formed into two pieces (ink well and top cover) through injection molding. The ink well is the primary structure used in additional processing steps to mount components and sub-assemblies in producing a finished inkjet cartridge. The top cover is used near the end of the production process to seal the ink within the cartridge. The entire subassembly weight was used for injection molding processing.

• **Circuitry** – the inkjet circuitry is made of a network of conductors that connect to the print head and interface to circuitry residing in the printer. This circuitry is similar to a ribbon cable that may be found to connect a monitor to the motherboard of a laptop computer, with connections similar to those found in integrated circuits where the cable connects to the print head. The circuitry was estimated to contain copper, gold, ethylvinylacetate foil, integrated circuit and ribbon cable, all materials available in the ecoinvent database. Processing was estimated using production efforts for transistor manufacturing.

• **Label** – A printed label is applied with adhesive to the inkjet cartridge in one of the final production steps. A LDPE film material, adhesive and printing operation that best represented the OEM label from the inkjet cartridge under study was selected from the ecoinvent database. Printing of the label was estimated using “production of carton board boxes, offset printing” in the ecoinvent database.
• **Polyurethane foam** – a block of polyurethane foam is used inside the inkjet cartridge housing for the ink delivery system; the cartridge was weighed post use, so some portion of dried ink contained in the foam increased its weight.

• **Print head** – The thermal inkjet print head integrated into the inkjet cartridge is a sophisticated device that enables ink to move from the holding tank onto print media. Over time, the print head has evolved to contain the passive thermal inkjet heater circuitry with simple metal oxide semiconductor (MOS) transistor drive circuitry incorporated on the same substrate similar to an integrated circuit [23]. Due to proprietary nature of the print head design and manufacture, we chose to represent the print head as an integrated circuit from the ecoinvent database as a reasonable proxy.

• **Ink** – the ink found in OEM inkjet cartridges is formulated to work in unison with the printer, paper and specific cartridge design to provide optimal printing performance. OEM ink formulations are proprietary, highly protected trade secrets. However, a comparable ink formulation was used in this study [24, 25]; primarily consisting of deionized water, followed by the addition of various solvents and carbon black for color.

• **Packaging** – The packaging represented in this study is reflective of Hewlett-Packard packaging which included 1) a postage-paid return and recycling envelope (which was discontinued in 2008) so that the consumer could send their empty inkjet cartridge to the OEM’s designated recycling center, 2) a low density polyethylene (LDPE)/foil wrapper around the cartridge, 3) an instruction sheet, 4) a printed paper board box to display the product, 5) and a
representative portion of the corrugated case packaging was allocated to an individual cartridge. Processing steps for packaging was assumed to be represented in the inkjet assembly processing. Since packaging represents a significant portion (47%) of the total weight of a new packaged inkjet cartridge, manufacturers continue to refine inkjet cartridge packaging.

Manufacturing processing required to produce an inkjet cartridge involve a wide range of activities from plastic injection molding, electronic manufacturing and highly accurate robotic assembly. This wide variety made it difficult to select a reasonable proxy available in ecoinvent. Inkjet cartridge manufacturing was estimated using a steel processing block in ecoinvent by substituting PET for steel. Since steel production involves processes similar to injection molding and utilizes a similar amount of automation, this choice seemed reasonable.

_Barge and Truck transport_

An inkjet cartridge may be produced at any one of four Hewlett-Packard inkjet cartridge manufacturing locations (Singapore, Malaysia, Puerto Rico and Ireland). Each location was equally weighted in calculating transport distances for a cartridge to be shipped to Rochester, NY USA. It was assumed that cartridges produced in Singapore and Malaysia were shipped via ocean freighters to a port in Los Angeles and then transported via large truck to Rochester, and cartridges produced in Puerto Rico and Ireland were shipped via ocean freighters to a port in New York City and then transported via large truck to Rochester.
Retailer shelf

Since the focus of the study is aimed to inform consumers, the infrastructure and operation of a retailer offering OEM and remanufactured inkjet cartridges for sale was not included in the study.

Purchase decision

This block represents the consumer’s decision process for determining which inkjet cartridge alternative to purchase, and does not consist of any actions that contribute to environmental impact in itself. But the manner in which a consumer purchases cartridges may have a profound effect upon environmental impact. In our study, five cartridge use cycles could be achieved in many ways, such as by a consumer purchasing five OEM inkjet cartridges in one trip to a retailer, or purchasing an OEM cartridge in the first trip to a retailer, followed by four subsequent trips to get the empty OEM cartridge refilled. Our base case assumes consumers purchase cartridges one at a time. Purchasing multiple cartridges at one time and varying combinations of cartridges and alternatives are considered in sensitivity analysis.

Consumer transport

The base case assumes that the consumer travels 4 kilometers to a retailer to either purchase a new or remanufactured cartridge, or to have their existing cartridge refilled, an assumption based on a LCA that investigated retail DVD rental locations in Ann Arbor, Michigan USA [26]. The base case assumes the consumer uses an automobile to make a dedicated visit to a retailer to purchase a single cartridge or refill a cartridge. The consumer purchase decision will affect the number of consumer transports required to achieve the functional unit. But the mode of travel selected by the consumer and the
degree to which transport impacts are allocated to the cartridge will also affect environmental impact and are considered in sensitivity analysis.

Use

Since our study explores EOL routes and reuse options for inkjet cartridges, the base case scenario excludes use phase impacts which have been adequately addressed by previous laser cartridge LCA studies summarized in Table 2.1 and expanded in the Appendix. However, in order to compare our findings with these previous printer cartridge LCA studies, we have also considered a scenario that includes use phase impacts. For this scenario, use phase includes 100 pages (8.5” x 11” size) of output at 5% ink coverage using uncoated 20 lb. copy paper and electricity required for printing. The representative printer (Hewlett-Packard Deskjet F-4280) consumes 17 watts when printing, and we estimated 4 minutes were required to print 100 pages. The US Waste scenario in the ecoinvent database was selected as the waste treatment option.

Retail inkjet cartridge refill

Though there are several avenues to refill an inkjet cartridge, such as home refilling and cartridge exchange services, this study is focused on retail refilling since it is a rapidly growing service with widespread availability in the United States [27, 28]. Unlike a cartridge exchange service where cartridge ownership is transferred, retail refilling allows for the consumer to retain ownership and track how many times a given cartridge has been refilled. A retail refill was modeled assuming a commercially available inkjet cartridge refilling machine was used to refill a cartridge. Materials and energy required to refill a cartridge were included, but materials and processes required to build and transport the refilling machine to the retailer were excluded.
**Remanufactured inkjet cartridge**

A remanufactured inkjet cartridge is an inkjet cartridge that has undergone processing by a third party that includes filling the cartridge with ink and packaging comparable to packaging of a new OEM inkjet cartridge. A remanufactured cartridge can vary in environmental impact due to numerous factors, some of which have been considered in previous printer cartridge LCA studies detailed in the Appendix. Our base assumption assures that the remanufactured cartridge performs on par with an OEM cartridge. However, differences amongst remanufacturers will ensure variability in environmental impact for any given remanufactured cartridge (that satisfies our performance assumption) on the market at any point in time. Based upon market observations and industry data [29], there are three sources of variability in remanufactured cartridge environmental impact investigated in this study: spent cartridge travel distance, spent cartridge quality, and remanufacturer efficiency. Specifically, two spent cartridge travel distances (500 and 2,300 miles), two input cartridge quality levels (virgin and mixed), and three remanufacturing efficiencies, expressed as the number of cartridges required to produce one remanufactured cartridge (1.09 representing high efficiency, 2.33 representing moderate efficiency, and 3.57 representing low efficiency) are examined. Spent cartridge collection operations are modeled by a collector traveling 300 miles with a small truck, and then the remaining travel distance is modeled using a large truck. A “virgin” cartridge is an OEM cartridge that has undergone one use cycle, where the “mixed” cartridge quality designation consists of a blend of 25% virgin and 75% non-virgin cartridges. In the United States, consolidation has resulted in a small number of large volume cartridge remanufacturing facilities. We assume the base
remanufactured cartridge in our study is produced by a highly efficient remanufacturer from a virgin cartridge that traveled 2,300 miles to the remanufacturing facility. The transport distance by large truck that a remanufactured cartridge travels to a retailer in Rochester, NY USA is fixed at 1,273 miles.

**MSW and Recycling**

Municipal solid waste (MSW) was modeled using the US Waste scenario in the ecoinvent database. Inkjet cartridge recycling assumed that only the plastic housing (primarily PET) was recovered and used in the production of new OEM inkjet cartridges.

### 2.2.5 Impact assessment

Impact assessment was carried out in SimaPro 7.3 LCA software using Cumulative Energy Demand (CED) version 1.07 and Global Warming Potential (GWP) over 100 years using IPCC 2007 GWP 100a. CED and GWP were chosen as representative proxies for environmental impact for three reasons: (1) no activity related to inkjet cartridges considered in this study poses human health risks beyond those indicated by CED and GWP100, (2) preliminary screening using other impact assessment methodologies (e.g., TRACI) were found to trend as CED and GWP100 categories, and (3) GWP allows us to compare our findings with previous printer cartridge LCA studies that reported results using GWP impact assessment (although some previous studies use GWP100a based on IPCC assessment reports prior to 2007). Results are shown using either GWP100 or CED when the two assessment methods track similarly, and when these indices differ, results are presented with both assessment methods.
2.2.6 Sensitivity analysis

LCI and LCIA results were interpreted based on the goal and scope of the study to compare inkjet cartridge EOL routes and reuse options compared to OEM cartridges to achieve five use cycles using environmental indicators of interest. A sensitivity analysis was performed on key assumptions pertaining to consumer purchasing manner, consumer transport, recycled PET content in an OEM cartridge, and inkjet cartridge remanufacturing as follows:

*Consumer purchasing manner*

Under one at a time purchasing, three cases were compared: five OEM cartridges, one OEM cartridge refilled four times, and five remanufactured cartridges. But five inkjet cartridge use cycles may be attained by varying the amount of inkjet cartridges (or alternatives) purchased at one time. Hence there are several combinations of OEM and reuse cartridge alternatives that a consumer may select that still satisfy the functional unit of five inkjet cartridge use cycles while requiring less than five consumer transport activities. We specifically consider combinations of OEM cartridge and refill purchases.

*Consumer transport*

The base case assumes the consumer uses an automobile to make a dedicated visit to a retailer to purchase a single cartridge or refill a cartridge. Alternate modes of transportation, reducing the percent of the transport impact allocated to the cartridge (i.e., performing multiple tasks on the same trip), and reducing transport distance may enable consumers to reduce environmental impact associated with cartridge EOL decisions and reuse alternatives. Alternate consumer transport scenarios were investigated to demonstrate environmental savings that a consumer could achieve, such as a walking or
bicycling (0% allocation), combining inkjet cartridge purchase or refill with weekly shopping (50% allocation), and choosing to purchase a cartridge as part of an existing commute for a job (10% allocation).

Recycled PET content of OEM inkjet cartridge

The base case assumed OEM inkjet cartridges were manufactured with 100% virgin PET. But some OEM inkjet manufacturers incorporate recycled PET into inkjet cartridges production [30]. Five levels of recycled PET content in the representative inkjet cartridge were evaluated.

Inkjet cartridge remanufacturing

The base case assumed a remanufactured cartridge was produced by a highly efficient remanufacturer from a virgin inkjet cartridge that traveled 2,300 miles. The “best” remanufacturing case has the spent cartridge traveling 500 miles. The “worst” remanufacturing case pertains to a remanufactured cartridge produced by a lowly efficient remanufacturer from a mixed stream of spent cartridges that traveled 2,300 miles.

2.3 Results and discussion

The HP 60 inkjet cartridge bill of materials and processing data shown in Table 2.3 reflect the base case assumption of 100% virgin material used in the production of an inkjet cartridge. Transportation from different manufacturing locations to their typical US port by barge and ground truck transportation to Rochester, NY is shown in Table 2.4.
### Table 2.3 Bill of materials and processes for the manufacture of one OEM inkjet cartridge

<table>
<thead>
<tr>
<th>BOM Level</th>
<th>Assembly / Material</th>
<th>Ecoinvent Material/Process Used</th>
<th>Amount (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Housing / Polyethylene terephthalate (PET)</td>
<td>Polyethylene terephthalate, granulate, bottle grade, at plant/RER</td>
<td>23.64</td>
</tr>
<tr>
<td>1.1</td>
<td></td>
<td></td>
<td>20.09</td>
</tr>
<tr>
<td>1.2</td>
<td></td>
<td>Glass fibre, at plant/RER</td>
<td>3.55</td>
</tr>
<tr>
<td></td>
<td>Process</td>
<td>Injection moulding/RER</td>
<td>23.64</td>
</tr>
<tr>
<td>2</td>
<td>Inkjet circuitry / Flexible printed circuit board</td>
<td>Copper, secondary, at refinery/RER</td>
<td>0.1</td>
</tr>
<tr>
<td>2.1</td>
<td></td>
<td></td>
<td>0.015</td>
</tr>
<tr>
<td>2.2</td>
<td></td>
<td>Gold, secondary, at precious metal refinery/SE</td>
<td>0.001</td>
</tr>
<tr>
<td>2.3</td>
<td></td>
<td>Ethylvinylacetate, foil, at plant/RER</td>
<td>0.03</td>
</tr>
<tr>
<td>2.4</td>
<td></td>
<td>Integrated circuit, IC, logic type, at plant/GLO</td>
<td>0.004</td>
</tr>
<tr>
<td>2.5</td>
<td></td>
<td>Cable, ribbon cable, 20-pin, with plugs, at plant/GLO</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>Process</td>
<td>Production efforts, transistors/GLO</td>
<td>0.1</td>
</tr>
<tr>
<td>3</td>
<td>Cartridge label / low density polyethylene (LDPE)</td>
<td>Packaging film, LDPE, at plant/RER</td>
<td>0.05</td>
</tr>
<tr>
<td>3.1</td>
<td></td>
<td></td>
<td>0.045</td>
</tr>
<tr>
<td>3.2</td>
<td></td>
<td>Adhesive for metals, at plant/DE</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>Process</td>
<td>Production of carton board boxes, offset printing</td>
<td>0.05</td>
</tr>
<tr>
<td>4</td>
<td>Ink delivery system / foam</td>
<td>Polyurethane, rigid foam, at plant/RER</td>
<td>1.34</td>
</tr>
<tr>
<td>4.1</td>
<td></td>
<td></td>
<td>1.34</td>
</tr>
<tr>
<td>5</td>
<td>Print head / semiconductor</td>
<td>Adapted from Integrated circuit, IC, logic type, at plant/GLO (removed epoxies and lead)</td>
<td>0.11</td>
</tr>
<tr>
<td>5.1</td>
<td></td>
<td></td>
<td>0.11</td>
</tr>
<tr>
<td>6</td>
<td>Ink / Solvent-based ink</td>
<td>Water, deionised, at plant/CH</td>
<td>15</td>
</tr>
<tr>
<td>6.1</td>
<td></td>
<td></td>
<td>11.7</td>
</tr>
<tr>
<td>6.2</td>
<td></td>
<td>Pentane, at plant/RER</td>
<td>1.05</td>
</tr>
<tr>
<td>6.3</td>
<td></td>
<td>N-methyl-2-pyrrolidone, at plant/RER</td>
<td>1.05</td>
</tr>
<tr>
<td>6.4</td>
<td></td>
<td>Carbon black, at plant/GLO</td>
<td>1.05</td>
</tr>
<tr>
<td>6.5</td>
<td></td>
<td>Butane-1,4-diol, at plant/RER</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>Inkjet packaging / multiple materials:</td>
<td>Packaging film, LDPE, at plant/RER</td>
<td>35.12</td>
</tr>
<tr>
<td>7.1</td>
<td>Low density polyethylene</td>
<td></td>
<td>0.19</td>
</tr>
<tr>
<td>7.2</td>
<td>Paperboard</td>
<td>Corrugated board, recycling fibre, double wall, at plant/RER</td>
<td>17.66</td>
</tr>
<tr>
<td>7.3</td>
<td></td>
<td>Corrugated board base paper, wellenstoff, at plant/RER</td>
<td>24.58</td>
</tr>
<tr>
<td>7.4</td>
<td>Paper</td>
<td>Paper, woodfree, coated, at integrated mill/RER</td>
<td>5.63</td>
</tr>
<tr>
<td>7.5</td>
<td>Pigments</td>
<td>Pigments, paper production, unspecified, at plant/RER</td>
<td>1.8</td>
</tr>
<tr>
<td>7.6</td>
<td>Foil</td>
<td>Sealing tape, aluminum/PE, 50 mm wide, at plant/RER</td>
<td>1.16</td>
</tr>
<tr>
<td>8</td>
<td>Cartridge assembly</td>
<td>Adapted from average metal working Steel/RER (substituted 0.23 kg PET for steel)</td>
<td>75.36</td>
</tr>
</tbody>
</table>

### Table 2.4 Cartridge transportation estimates

<table>
<thead>
<tr>
<th>Transportation Activity</th>
<th>Mode</th>
<th>Amount (kg-km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer to US Ports</td>
<td>Transport, barge/RER</td>
<td>679</td>
</tr>
<tr>
<td>US Ports to Rochester, NY</td>
<td>Transport, lorry &gt;16t, fleet average/RER</td>
<td>181</td>
</tr>
</tbody>
</table>
**Objective 1: determine hot spots in the life cycle**

From Table 2.3, the print head only represents 0.15% (0.11 out of 75 grams) of the packaged HP 60 inkjet cartridge, but is responsible for 20% of the cartridge CED, as shown in Figure 2.2. This finding is understandable, since the print head was modeled as an integrated circuit in ecoinvent. On the other hand, ink contributes 20% (15 out of 75 grams) by mass of a packaged OEM cartridge from Table 2.3, but only 3.2% toward CED. These findings support our initial hypothesis that maximizing print head life through refilling or remanufacturing may enable users to reduce the environmental impact associated with inkjet cartridge consumption.

**Figure 2.2** Cumulative energy demand (MJ) (a) contribution by component and production processing (b) compared to component weight.

**Objective 2: comparison of inkjet cartridge versions - OEM, refilled and remanufactured**

Table 2.5 summarizes the GWP impact results on a per use cycle basis, excluding impacts from the consumer transport activity, so that a comparison of each cartridge alternative (i.e., OEM, Remanufacture and Refill) can be compared with previous cartridge LCA studies summarized in Table 2.1. In order to report on a per use cycle
basis, total impacts for each alternative (i.e., OEM, Remanufacture and Refill) were summed and then divided by five. Since previous results varied in assumptions regarding the use phase, impact results for each alternative in Table 2.5 are presented using our base case, which excludes cartridge use phase impacts, as well as an alternate scenario that includes use as defined in section 2.2.4. The GWP impacts of the OEM cartridge (excluding use phase) from Table 2.5 compare similarly with the 1996 inkjet cartridge impact results found in Table 2.1[12]. In our study, the contribution from the use phase is 0.38 kg CO2 eq per use cycle across all alternatives, which accounts for 36% to 57% of total kg CO2 eq. This is not the case for the 2004 and 2008 studies, which range from 60% to 96% of total kg CO2 eq [14, 15] due to the inclusion of a “usability” metric for printed output. The refill case offered the lowest environmental impact, with a 76% reduction to GWP impact when use phase is excluded and a 37% reduction to GWP impact even when considering cartridge use and the associated power use and paper consumption impacts. Next, the baseline remanufacturing case provided an 18% savings in GWP impact including use phase and a 36% savings in GWP impact excluding use phase compared to the OEM alternative.

### Table 2.5 Cartridge LCA global warming potential impact results per use cycle

<table>
<thead>
<tr>
<th>Study</th>
<th>[2012 Inkjet Cartridge]</th>
<th>OEM</th>
<th>OEM</th>
<th>Remanufacture</th>
<th>Remanufacture</th>
<th>Refill</th>
<th>Refill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>None</td>
<td>100 pp</td>
<td>None</td>
<td>100 pp</td>
<td>None</td>
<td>100 pp</td>
<td>None</td>
</tr>
<tr>
<td>GWP100 kg CO2 eq</td>
<td></td>
<td>0.43 82%</td>
<td>0.43 40%</td>
<td>0.26 78%</td>
<td>0.26 30%</td>
<td>0.11 86%</td>
<td>0.11 16%</td>
</tr>
<tr>
<td>Production</td>
<td>0.06 11%</td>
<td>0.06 5%</td>
<td>0.05 14%</td>
<td>0.05 5%</td>
<td>0.01 9%</td>
<td>0.01 2%</td>
<td></td>
</tr>
<tr>
<td>Distribution</td>
<td>0 0%</td>
<td>0.38 36%</td>
<td>0 0%</td>
<td>0.38 43%</td>
<td>0 0%</td>
<td>0.38 57%</td>
<td></td>
</tr>
<tr>
<td>Use</td>
<td>0.04 7%</td>
<td>0.20 19%</td>
<td>0.03 8%</td>
<td>0.19 22%</td>
<td>0.01 6%</td>
<td>0.17 26%</td>
<td></td>
</tr>
<tr>
<td>EOL</td>
<td>0.52 100%</td>
<td>1.07 100%</td>
<td>0.33 100%</td>
<td>0.88 100%</td>
<td>0.13 100%</td>
<td>0.67 100%</td>
<td></td>
</tr>
</tbody>
</table>

These findings indicate that refilling used cartridges or purchasing remanufactured cartridges both offer environmental improvement compared to
purchasing new OEM cartridges, when assessed on the basis of one use cycle. When evaluating options on the basis of the functional unit of five inkjet cartridge use cycles, the analysis must also comprehend consumer transport activities between use cycles – particularly travel to a retailer to either refill an existing cartridge or purchase a new one. The manner and mode by which consumers purchase cartridges have not been addressed by the previous cartridge LCA studies summarized in Table 2.1. Since an 8-kilometer trip by automobile, fully allocated to the purchase of one inkjet cartridge accounts for 1.44 kg CO2 eq for GWP (25 MJ for CED), variability in the consumer transport activity can substantially influence results. Figure 2.3 illustrates how results are influenced by select assumptions that affect mode of travel, allocation percent, and manner (i.e., number of trips) for the consumer transport activity can have on the results. Results in Figure 2.3 are divided between one OEM cartridge that is refilled four consecutive time (and the degree to which trips to a retailer are allocated to the cartridge) and five OEM cartridges (either purchased consecutively in 5 trips or all at once in 1 trip), the latter assuming that 100% of the transport activity is allocable to the cartridge. For our base assumptions, refilling is the best cartridge option for one at a time purchasers making dedicated trips by automobile at 138 MJ. This refilling option can be reduced to as low as 13 MJ when one at a time purchasers chose an impact-free (0% allocated) transportation method, like walking or biking to the retailer. In the case of 5 OEM cartridges, the minimum total impact possible is 50 MJ, which includes the OEM processes and no (or 0%) transportation impact. Including the transportation in the 5 OEM cartridge case scenarios results in impact from 175 MJ for the base assumption of 5 trips and 75 MJ for a single trip. Notably, a consumer that buys five OEM cartridges all
at once is equivalent to a consumer selecting refilling one at a time with transport allocated at 50%.

![Graph showing CED (MJ)](image)

**Figure 2.3** Cumulative Energy Demand (CED) per five cartridge use cycles. Left: one OEM cartridge refilled consecutively four times, with increasing percentages of transportation impact allocated to the cartridge life cycle; Right: five OEM cartridges purchased consecutively in five trips or all at once in a single trip. Results are highly sensitive to consumer transport assumptions.

If consumers purchase inkjet cartridges one at a time, then our results show refilling provides the lowest environmental impact, regardless of other consumer transport factors. However, removal of the one at a time purchasing constraint enables a consumer to achieve additional environmental improvement by reducing the number of trips required to obtain the functional unit of five cartridge use cycles. Since the impact for a refill is approximately 11% of the CED value for a fully allocated trip to a retailer.
by automobile, the environmental savings from reducing the number of consumer transport activities overwhelms savings provided from refilling. If the allocation percentage associated with getting a refill for an 8 km trip is less than 11% (i.e., 89% of the trip impact can be allocated to other activities like grocery shopping, leisure activities, or work commutes), then refilling will provide more environmental savings than eliminating one trip. This demonstrates that results are extremely sensitive to consumer transport decisions.

So far we have looked at either purchasing all OEM cartridges or refilling one OEM cartridge four subsequent times. But five inkjet cartridge use cycles may be obtained in other combinations, like purchasing multiple OEM cartridges at a time with subsequent refills in another retailer visit. Figure 2.4 considers the CED for combinations of OEM cartridges and refills that achieve five use cycles with consumer transports fully allocated to the cartridge life cycles. Here we see that reducing the environmental impacts of the consumer transport activity outperforms the environmental savings that can be achieved by refilling.
Objective 3: EOL routes

Consumers also have a variety of ways to discard an inkjet cartridge. Remanufacture and refill routes considered in this study may result in an inkjet cartridge seeing one or more additional use cycles. However, market data indicate that typical EOL routes of landfill, incineration, recycle, and municipal solid waste are more utilized than those that lead to inkjet cartridge reuse. Figures 2.5 and 2.6 illustrate the CED and GWP contribution of each EOL route compared to impacts for a single OEM cartridge delivered to a retailer in Rochester, NY, USA.
Figure 2.5 CED contribution for each EOL route relative to the (A) total CED value for producing one OEM cartridge available for purchase in Rochester, NY. (B) Shows the additional burden for municipal solid waste routes and (C) shows the variable benefit attainable from recycling PET at average (8%, comparable to MSW recycling) and best rates (100% closed loop), remanufacturing the entire cartridge under Worst-, Base-, and Best-case scenarios, and refilling the cartridge up to four times not including consumer transport.
Figure 2.6 GWP contribution for each EOL route relative to the (A) total GWP value for one OEM cartridge available for purchase in Rochester, NY. (B) shows the additional burden for municipal solid waste routes and (C) shows the variable benefit attainable from recycling PET at average (8%, comparable to MSW recycling) and best rates (100% closed loop), remanufacturing the entire cartridge under Worst-, Base-, and Best-case scenarios, and refilling the cartridge up to four times not including consumer transport.

**Landfill, incineration and municipal solid waste**

The contribution of these EOL routes to total CED are relatively small, compared to the manufacture of new cartridges, with increasing impact observed in (1) incineration (0.18%), (2) US Waste (0.20%) and (3) landfill (0.35%), respectively, although the maximum difference between any of these EOL routes is only 0.2%. On the other hand, the contribution of these EOL routes for the GWP100 impact assessment method range
from 8% to 12% with US Waste now having the lowest impact and landfill the greatest, due to the potential for methane emissions.

Recycling

Recycled PET from spent inkjet cartridges and water bottles is used in the production of OEM inkjet cartridges [30] and provides a credit of approximately 1.49 MJ, which is 15% of the CED for the OEM cartridge. This credit from closed loop recycling is much higher than the 0.12 MJ credit that would be achieved if PET was recycled at 8.2% from the U.S. municipal waste stream [31]. Similarly, recycling an inkjet cartridge provides a credit of up to 0.05 kg CO2 eq (10%) for the GWP impact assessment method. Table 2.6 expands on the GWP and CED impact performance for cartridges with 0%, 30%, 50%, 70% and 100% recycled PET content. More than 70% of an HP 60 cartridge body (by weight) is currently recycled content from used HP cartridges and other sources such as water bottles [32]. At 70% recycled PET content, there is only modest environmental improvement for both GWP and CED.

Table 2.6 GWP and CED impact savings by recycled PET in OEM cartridge

<table>
<thead>
<tr>
<th>Recycled PET not including use phase and customer transport</th>
<th>GWP 100a (kg CO2 eq)</th>
<th>GWP Savings</th>
<th>CED (MJ)</th>
<th>CED Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin PET OEM Inkjet</td>
<td>0.48</td>
<td>N/A</td>
<td>9.90</td>
<td>N/A</td>
</tr>
<tr>
<td>30% Recycled PET OEM Inkjet</td>
<td>0.47</td>
<td>3.5%</td>
<td>9.40</td>
<td>5.4%</td>
</tr>
<tr>
<td>50% Recycled PET OEM Inkjet</td>
<td>0.46</td>
<td>5.4%</td>
<td>9.12</td>
<td>7.9%</td>
</tr>
<tr>
<td>70% Recycled PET OEM Inkjet</td>
<td>0.45</td>
<td>7.2%</td>
<td>8.83</td>
<td>10.8%</td>
</tr>
<tr>
<td>100% Recycled PET OEM Inkjet</td>
<td>0.43</td>
<td>10.1%</td>
<td>8.41</td>
<td>15.0%</td>
</tr>
</tbody>
</table>
Remanufacture

The maximum theoretical reduction in environmental impact from reuse may be represented by \[1-(1/(1+n))\] x 100%, where “n” reflects the number of reuse cycles [33]. For one inkjet cartridge remanufacturing cycle the maximum theoretical reduction in CED would be 4.95 MJ (50% x 9.9 MJ), provided there were no additional actions done to the inkjet cartridge to enable another reuse cycle. But a remanufactured cartridge can vary in environmental impact due to numerous factors. Three sources of variability in remanufactured cartridge environmental impact investigated in this study were spent cartridge travel distance (500 and 2,300 miles), spent cartridge quality (virgin and mixed input), and remanufacturer efficiency (high, moderate and low). Figure 2.7 illustrates the effect on GWP from each of these sources of variability. From Figure 2.7, it is obvious that remanufacturing efficiency has the greatest effect on GWP impact for a remanufactured cartridge, followed with spent cartridge input type having a slightly greater effect than cartridge travel distance. Although it is impossible to characterize the remanufacturing cartridge market due its dynamic nature, consolidation in the inkjet cartridge remanufacturing sector serving the US is more likely to result in large remanufacturers that leverage their market power to claim high quality cartridges as input to their highly efficient operations. A large remanufacturer of this type would produce an inkjet cartridge with a value of 0.33 kg CO2 eq, labeled as “Base” on Figure 2.7. The base case is only marginally higher than the “Best” case of a highly efficient remanufacturer processing the virgin cartridges that traveled 500 miles at a value of 0.3265 kg CO2 eq. This result suggests that environmental improvement obtained from increased efficiency through consolidation may lead to aggregate environmental
improvement in the sector, since environmental gains from improved efficiency outperform environmental impacts from increased cartridge travel distance.

Figure 2.7 GWP impact for remanufacturing inkjet cartridges disaggregated by remanufacturer efficiency (low and high), input cartridge quality (virgin and mixed) and spent cartridge travel distance (500 and 2,300 miles). Remanufacturing efficiency considers the number of input cartridges required to produce one remanufactured cartridge (1.09 representing high efficiency and 3.57 representing low efficiency).

Notably, the worst case remanufacturing case provides a 14% improvement compared to the benefit from recycling PET from a spent cartridge. However, from a GWP impact assessment perspective, the worst case remanufactured cartridge case provides a 33% improvement over recycling. Where economically motivated consolidation in the cartridge remanufacturing sector may lead to environmental benefits,
profit motivated collection firms of spent cartridges may route less desirable cartridges to remanufacturers instead of incurring a cost associated with recycling them at the onset. Spent cartridges of this type may accrue environmental impact from transportation and a failed remanufacturing attempt.

Refill

From Figures 2.5 and 2.6, a single refill cycle offers a greater reduction in environmental impact than any of the remanufacturing scenarios. The first reuse cycle from refilling provides a reduction in CED of 4.6 MJ, just 7% less than the theoretical maximum reduction of 4.95 MJ. As expected, subsequent refills provide further environmental benefit, with four refills providing a reduction of 7.37 MJ. Even though refilling provides the best opportunity to reduce environmental impact by extending the usable life of an inkjet cartridge, the sensitivity of these findings to the consumer transport activity suggest that maximizing environmental savings from reducing consumer transport impacts should be examined first. Recall that a fully allocated consumer transport activity to purchase an inkjet cartridge alternative is approximately 2.5 times the CED (3 times the GWP) impact of an OEM cartridge.

2.4 Conclusions and recommendations

Consistent with conventional wisdom, we find reuse of an inkjet cartridge can provide an environmental benefit over a new OEM inkjet cartridge. In exploring inkjet cartridge reuse, we investigated two options readily available to US consumers, (1) purchasing a remanufactured inkjet cartridge, and (2) inkjet cartridge refilling at a local retailer. The latter alternative enables a consumer to reuse an inkjet cartridge multiple times, whereas a spent inkjet cartridge typically undergoes one remanufacturing cycle.
With a functional unit of five inkjet cartridge use cycles, results were highly sensitive to how a consumer went about purchasing an inkjet cartridge use cycle and the associated transportation activity and impact. Based on these findings, broader implications are discussed below.

**Sequential Purchasers**

For those consumers that purchase and use one inkjet cartridge at a time, and then repeat the cycle; refilling an OEM cartridge four consecutive times provides the best alternative for reducing environmental impact associated with inkjet cartridge consumption. Although inkjet cartridge refilling cycles offer the greatest opportunity for environmental improvement, refilling may not appeal to all consumers. For those consumers that don’t want to retain and refill cartridges, substituting remanufactured cartridges for OEM cartridges will provide environmental improvement, but at more modest levels. Further improvement in environmental performance may be obtained through choosing a mode of travel with lower impacts.

**Multiple Cartridge Purchasers**

Consumers that already minimize the environmental impact associated with consumer transport by purchasing multiple cartridges in a single trip to a retailer should not pursue refilling if doing so leads to a net increase in environmental impact from additional travel. However, substituting cartridge refills in place of OEM cartridges will yield environmental savings when holding consumer transport constant. A consumer that purchases two cartridges at a time could achieve an environmental benefit by taking two empty OEM cartridges to a retailer and getting both refilled as opposed to purchasing two more OEM or remanufactured cartridges.
The recommendation of what should be done with a spent inkjet cartridge is less obvious, since traditional EOL routes vary for GWP and CED impact categories. However, our findings suggest the following guidelines:

**OEM Cartridge**

A spent OEM cartridge is a preferred input (i.e., “virgin” cartridge) for both inkjet cartridge remanufacturers and consumers that want to pursue cartridge refilling. Consistent with our findings, a cartridge of this type should be directed to an EOL route that leads to reuse.

**Remanufactured Cartridge**

Since inkjet cartridge remanufacturers have a strong preference for virgin OEM cartridges, previously remanufactured cartridges should be directed to cartridge recycling as the first best option. Even though the results indicate additional environmental savings may be achieved by the worst case remanufacturer that have some non-virgin cartridges in their input stream, environmental impact incurred from less desirable cartridges being sent to remanufacturers is likely to result in more cumulative environmental harm than if the cartridge was directed to an efficient recycling path.

**Refilled Cartridge**

A spent cartridge that has been successfully refilled four times, or has failed prematurely, should be directed to cartridge recycling as in the recommendation for a previously remanufactured cartridge above. Since all recycling routes do not have the same environmental impact, care should be taken by consumers in selecting a recycling route. Although OEMs accept their own cartridges for recycling, previously remanufactured or refilled cartridges are excluded.
from voluntary recycling by OEMs. Consumers desiring to recycle spent remanufactured cartridges often drop them off at a retailer for recycling, which requires transport. Since recycling of PET from cartridges provides a 10% GWP reduction in impact (15% CED reduction) in the most optimistic case, the environmental harm from the consumer transport activity may erode or exceed environmental savings of inkjet cartridge recycling.

Since consumer decisions related to the manner of purchase/disposal and mode of travel have a significant effect on environmental impact for achieving 5 use cycles, it is worthwhile to investigate observations from the US market that may influence consumer travel. HP estimates that if all inkjet cartridges returned using return envelopes in 2008 were instead returned via consumers taking empty cartridges to retailer Staples for consolidated shipping to HP’s recycling center, 600,000 pounds of shipping materials would be eliminated [34]. While reduced packaging and consolidated shipping offers environmental benefits over cartridges returned using return envelopes, the method consumers choose to route their empty cartridges to stores may cut into these environmental benefits, or even make the in-store return option result in worse environmental performance. As seen from analysis performed here, consumer travel to (and from) a retailer represents the largest portion of environmental impact for an inkjet cartridge use cycle. Assuming the number of returned cartridges remains the same, if HP’s decision to eliminate return envelopes with new cartridge packaging results in more consumer trips to a retailer, then it is likely that environmental performance of the Staples return system may be worse than the return envelope system.
Staples policy for cartridge recycling may further promote additional consumer trips to Staples stores even for consumers that utilize Staples mail order services. For instance, Staples return policy provides a store credit of $2 (limit of ten cartridges per month) for each cartridge brought to a Staples store for recycling, but no financial credit for cartridges returned for recycling through parcel delivery [35].

Market changes may also encourage more consumer travel related to inkjet cartridge use. As stated earlier, OEMs have expanded cartridge offerings to include low and high yield alternatives. If a consumer purchased low yield cartridges (e.g., HP 60) which provides one-third the rated output of a high yield cartridge (e.g., HP 60XL), consumer transport could increase three fold over the high yield alternative. Aside from an increased likelihood of consumer transport, printing systems with low yield inkjet cartridges have worse carbon footprint performance on a per image printed basis than printing systems using high yield inkjet cartridges [36]. Locating a more durable print head within the inkjet printer and switching the inkjet cartridges to ink tanks would reduce “resource consumption during product manufacturing by 40%, air emissions by 67%, solid waste generation by 95%, and wastewater by 92% per page printed” [37].

Given the complexity of understanding and modeling consumer purchase and disposal decision making for inkjet cartridge alternatives, future research is required to investigate the trade-offs in convenience, cost and environmental impact associated with each purchase and disposal option. Understanding how consumers perceive these trade-offs may illuminate opportunities to design and implement incentives to shift consumers toward purchase and disposal options with lower environmental impacts. While focused
specifically on cartridge systems here, these outcomes are applicable to other examples of consumer decisions across the “green” product space.
III. INTELLECTUAL PROPERTY RIGHTS AND GREEN PRODUCT DESIGN

3.1 Introduction

There is increasing industrial and academic interest in remanufacturing as a more sustainable production process compared to those that utilize virgin materials or even recycled materials. The general purpose of this paper is to better understand why current market incentives do not seem strong enough to generate socially optimal rates of remanufacturing activity and what, therefore, could be done to strengthen incentives. To achieve this goal, we propose combining economic literatures regarding green design, “raising rivals’ costs,” and intellectual property rights. Our specific contribution is to show within such a framework that it is possible to raise social welfare and maintain the original manufacturer’s profit by strengthening the firm’s intellectual property rights in exchange for implementing greener physical product attributes. This possibility arises since a firm may choose a level of physical product attributes in its product that is less than socially optimal. The firm is constrained by the regulator in selecting the level of intellectual property rights necessary to deter independent firms from entering the market with a remanufactured version of the firm’s product. While granting stronger intellectual property rights might reduce social welfare, ceteris paribus, our model shows how the reduction in environmental impact from greater remanufacturing can raise welfare by more than stronger intellectual property rights might reduce welfare.

A novel and counterintuitive aspect of our approach leverages an intellectual property rights policy focused to encourage innovation to also affect environmental quality. This unconventional approach was pursued because intellectual property may be used by an original manufacturer (OM) to deter independent firms from bringing an
environmentally preferred remanufactured version of the OM’s product to market. Although establishment of a new policy to encourage remanufacturing is another option, our approach minimizes unintended economic and environmental consequences that may result from alterations to the structure, conduct and performance of product markets due to a new policy intervention.

Remanufacturing involves recovering value from end-of-life products to manufacture like-new products. Since remanufacturing enables reused value-added components to see one or more additional use cycles, remanufacturing retains the embodied energy of reused components and is often environmentally preferential when compared to energy recovery, material recycling, or reusing components in products with less demanding specifications (i.e., downcycling)\[8, 38\].\(^1\) Extending lifespan via remanufacturing may also reduce greenhouse gas emissions. These environmental benefits from remanufacturing may be complemented by economic benefits. For instance, Giuntini and Gaudette\[39\] find that remanufactured products incur costs that are typically 40 to 65 percent less than costs incurred for new products, but only sell for 30 to 40 percent less than similar new products, indicating that there are incentives for both producers and consumers to engage in the remanufactured product market. And as Ferrer and Ayres\[40\] suggest, developing a more robust remanufacturing sector can have positive economy-wide impacts in terms of raising the demand for labor and for all other goods. Geyer \textit{et al.}\[38\] note that Kodak’s single-use camera core was designed with components with a durability level to endure six consumer use cycles. Since Kodak was able to effectively recover spent single-use cameras, remanufacturing proved to be more

\(^1\) See Geyer \textit{et al.}\[38\]. See also Gutowski \textit{et al.}\[8\], as they provide a review of life cycle assessment studies with emphasis on energy savings. They find that remanufacturing usually outperforms new products in terms of energy savings, except when improvements in current models of durable energy consuming products have significantly reduced energy consumption during use compared with remanufactured versions of less efficient products, such as refrigerators.
profitable than new production while providing environmental benefits. Maslennikova and Foley [41] observe that Xerox continues to utilize a modular design strategy for most of its products that allows the firm to collect and profitably remanufacture products. Xerox was able to transform a potential disposal cost associated with 160,000 Xerox machines recovered from customers in Europe (in 1997) into a net savings of $80 million by reprocessing these machines [41].

Notwithstanding the opportunities that remanufacturing presents—and that some firms and consumers have captured—there remains a significant flow of remanufacturable materials heading to landfills each year. For instance, one industry report estimates that approximately 50% of more than 562 million computer printer cartridges consumed annually in the US are thrown away, most ending up in landfills [3]. Various reasons for possible gaps between privately optimal and socially optimal consumer and firm decision-making regarding remanufacturability are considered in the literature. Several researchers focus upon the level of remanufacturability an original manufacturer (OM) selects to design into its products in various market structures. Ferguson [42] notes that even though remanufacturing may be cost-efficient relative to producing a new product, most firms appear to either ignore or actively deter any remanufacturing and reuse of their product. Since OMs are not guaranteed that consumers will route discarded products to either recycling centers or the municipal waste stream, an unwanted product transferred by a consumer to an independent remanufacturer may re-enter the market as a differentiated product that competes with the OM’s product. Hence, any actions an OM takes to improve the remanufacturability of its

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2 Maslennikova and Foley [41] page 228.
product may enable independent remanufacturers to free-ride on the OM’s investment. Debo et al. [43] consider an infinite time horizon model where a monopolist must select the product’s remanufacturability level for a heterogeneous consumer market where the new product and remanufactured product are considered as differentiated products. They expand their model to consider competition from independent remanufacturers that collect the monopolist’s product from period one and offer a remanufactured version in the next period. In this setting, increased competition in the remanufactured product market forces reduced prices for remanufactured product and for used remanufacturable product. This result then motivates the OM to reduce the product’s remanufacturability, leading Debo et al. [43] to suggest that “any legislator encouraging competition for remanufactured products should take into account that the level of remanufacturability of the new product will decrease with competition”. Most recently, Bernard [44] presents a model in which OMs provide an interchangeable remanufacturable component part used in a durable product with an expected lifetime that exceeds the lifetime of the remanufacturable component. Hence, consumers that purchase the product will require at least one replacement component part before the durable product wears out. Bernard finds that when the two OMs collude on the level of remanufacturability, the OMs internalize their free-riding ability by choosing the level of remanufacturability that maximizes joint profit. Even though collusion by the OMs does not eliminate independent remanufacturers’ ability to free-ride on investments made in the level of remanufacturability embedded into the component part by the OMs, the collusive case has the OMs remanufacturing more components and lower quality independent remanufacturers producing less, resulting in an increase in both producer and consumer
surplus. These results provide optimism that government policy instruments can help align strategic firm objectives with social welfare.

Identifying precisely where in the product life cycle government policy instruments should be optimally applied is also an active area of research focus. In particular, several researchers have looked into policy instruments that could be used to encourage upstream producers to design environmentally-preferred products (i.e. “green design”), and encourage downstream consumers to recycle discarded products. Fullerton and Wu [45] were the first to provide a general equilibrium model to consider the effectiveness of different policy instruments for promoting recycling of products by consumers and encouraging producers to design products to be more recyclable. They find that if consumers bear the full social cost to dispose products, consumers will signal producers to reduce product packaging and improve the recyclability of products brought to the market. If consumers don’t pay to dispose unwanted products, then a tax on producers’ use of packaging and a subsidy for recyclable designs will achieve the social optimum. Calcott and Walls [46] consider policy instruments to encourage green design when consumers have recycling options of (1) free curbside recycling, (2) taking a recyclable product to a recycling center for payment, and (3) disposing recyclable product in the municipal waste stream. They find that a deposit-refund scheme combined with an advanced disposal fee can lead to a second-best outcome as long as unclaimed consumer deposits are not awarded to producers. And in a recent econometric study, Rehfeld et al. [47] find that downstream policy pressure has a positive effect on environmental product innovations at the 1% level of statistical significance. In particular, if the OM has a financial obligation of dealing with its product after consumer
use (or is interested in remanufacturing its products), the manufacturer is more likely to initiate product and process design decisions that influence recycling and waste treatment costs.

Observations in the above literature suggest that there are two additional concepts that may be fruitfully brought to bear upon our understanding of the green design problem per se: the concept of “raising rivals’ costs” and the conceptual structure of intellectual property rights. Salop and Scheffman [48, 49] introduced the concept of raising rivals’ costs, wherein a firm with market power may use cost-raising strategies to increase its profits by disadvantaging its rivals (competitors) in a dominant firm and competitive fringe market. In their model, an increase in the incremental costs to rival firms will shift up the rival firms’ supply curves. Assuming the dominant firm keeps its output the same and the rival firms have relatively elastic supply curves, the market price will shift up to a level equal to the increase in the rival firms’ incremental costs. The dominant firm’s profits will increase as long as its own average costs increase by less than the increase in the rival firms’ incremental costs; more generally, they find that a dominant firm’s exercise of cost-raising strategies has an ambiguous effect upon prices, fringe profit and welfare. Landes and Posner [50] explore the implications of the Salop and Scheffman model in the context of intellectual property rights assignments. In their model, the dominant firm can utilize its intellectual property right strength to curb the fringe’s output by raising rivals’ marginal costs.

While stronger intellectual property rights raise the dominant firm’s fixed costs, by the logic from Salop and Scheffman, the net benefits to the dominant firm from stronger intellectual property rights can be positive.

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4 We note that in the Landes and Posner [50] model, the strength of intellectual property rights is exogenous to the dominant firm.
As noted at the outset, the contribution of the present paper is to combine the economics of green design literature with the above two literatures regarding raising rivals’ costs and the economics of intellectual property rights to show that a regulator could raise social welfare by strengthening the OMs’ intellectual property rights in exchange for an increase in remanufacturability built into products by OMs. The basic idea is that an OM can protect profit from independent (aftermarket) manufacturers by either reducing the remanufacturability of its product or by enjoying relatively strong intellectual property rights. These strategies can differ in social impact, however, as reducing remanufacturability raises consumption of single-use products and therefore increases the flow of virgin materials to production and the flow of consumer waste to landfills. These natural resource input flows and waste output flows may be greater than socially optimal. As Bernard [44] emphasizes, public policy in this context must incentivize OMs to raise the remanufacturability of their products. Our results complement Bernard’s findings by showing that strengthening the OMs’ intellectual property rights—a policy lever that is already in place—provides a compelling incentive for enhancing remanufacturability.

Our paper proceeds as follows: In Section 3.2, we set forth the basic model, showing how an OM’s decision concerning the degree of remanufacturability and the independent (aftermarket) remanufacturers’ reaction to the degree of remanufacturability can be modulated by the regulator’s award of greater intellectual property right strength. We introduce representative functional forms and parameters in Section 3.3 so that the model can be solved and its properties illustrated. Comparative statics follow, showing how different specifications for strengthening intellectual property rights might affect the
firms’ costs, firms’ profits, and social welfare differentially. Section 3.4 concludes with
discussion of the results and directions for future research.

3.2 Theoretical model

Although there are many strategies an OM may implement to deter independent
firms from remanufacturing the OM’s product after a use cycle by consumers, we are
specifically interested in those strategies the OM may employ that affect the built
product. The built product may contain technical barriers in the form of physical product
attributes intended to deter independent remanufacturers. For instance, a typical toner
cartridge used in a laser printer has a housing comprised of two plastic pieces that are
joined together using a zig-zag ultrasonic welding operation by the OM that results in the
toner cartridge housing or other components being damaged / destroyed during
disassembly [51]. This type of physical product attribute increases the unit cost of
remanufacturing the toner cartridge, for both the OM and independent remanufacturers.

Physical product attributes embedded in a product are denoted by \( \rho \) in our model, where \( \rho \)
is defined such that \( 0 \leq \rho \leq 1 \). When \( \rho \) is equal to zero the product does not have any
physical attributes that deter remanufacturing, while when \( \rho \) is equal to one, the amount
of physical product attributes contained in the product make remanufacturing impossible.
It is important to clarify how our use of \( \rho \) differs from previous literature that consider \( \rho \)
defined as a product’s level of recyclability [45, 46] and \( q \) defined as a product’s level of
remanufacturability[43, 44]. Calcott and Walls [46] and Fullerton and Wu [45] use \( \rho \) as a
scalar index to represent a product’s level of recyclability, where \( \rho \) can be thought of as
representing the fraction of the weight of the product that can be recycled; as \( \rho \) increases,
the product becomes more recyclable. In their case, \( \rho \) is considered to be a non-material
input (e.g., a fixed cost) and average costs of the product are increasing with \( \rho \). Since we consider \( \rho \) as a cost-raising strategy in the form of a physical feature introduced into the product, \( \rho \) has a fixed cost component that increases in \( \rho \) and a unit cost component that also increases in \( \rho \). That is, if an OM chooses to implement a technical barrier in the product to deter independent remanufacturers, the strategy will result in the OM incurring a fixed cost component (e.g., additional labor during the product design stage) while the physical product attribute added to the product increases unit costs. Our use of \( \rho \) is related to level of remanufacturability, \( q \), used by Debo et al. [43] and Bernard [44]. Increases in \( \rho \) and \( q \) both result in increased fixed costs and increased unit costs of new production for the OM, but increased \( q \) results in lower remanufacturing costs whereas increased \( \rho \) results in higher remanufacturing costs. This is because \( \rho \) is a cost-raising strategy. A toner cartridge designed with fasteners that are easily removed to enable worn internal component repair or replacement would have a lower value for \( \rho \) than a toner cartridge with the zig-zag ultrasonic welding joining method.

As an alternative to physical product attributes (\( \rho \)) introduced into its product, an OM may select a level of intellectual property to embed in its product. Intellectual property may take on many forms, including trade secrets, industrial know how, proprietary software, patents, trademarks and copyrights. An individual may seek protection for some intellectual property by appealing to the appropriate government agency. For instance, the United States federal government has laws that relate to patents, copyrights and trademarks. A valid patent gives the patent owner (the OM in our case) exclusive rights to produce and sell products covered by the patent claims for a specified duration under the governing intellectual property rights system. An
independent remanufacturer desiring to remanufacture the OM’s product would (1) be required to pay the OM a license fee, or (2) incur costs to “design around” the patent claims, or (3) risk a patent infringement lawsuit. In our model, we follow Landes and Posner [50] by representing intellectual property embedded in a product by variable \( z \), where \( 0 \leq z \leq 1 \). A product without any intellectual property designation would have a level of \( z \) equal to zero, whereas a product with \( z \) equal to one would fully protect the OM from competition in the product market—protection from private firms offering a new product that violates intellectual property rights of the OM’s product and by independent remanufacturers. Unlike \( \rho \) that results in increased costs to remanufacture by either the OM or an independent remanufacturer, the level of \( z \) embedded in a product by the OM raises the costs of independent remanufacturers and competing firms in the new product market. Hence, as we show below, a profit-seeking OM would select the level of \( z \) (and \( \rho \)) to embed in its product by equating the marginal benefit of \( z \) (resp., \( \rho \)) equal to the marginal cost of \( z \) (resp., \( \rho \)). These privately optimal rates may diverge from socially optimal rates.

It is important to pause and recognize that there may be several reasons why an OM and its design engineers may prefer certain physical product attributes and intellectual property structures that are independent of how they affect the product’s remanufacturability level. For instance, ultrasonic welding of plastic halves for toner cartridges likely provides a more robust, tamperproof fastening method than screws, possibly reducing the OM’s product liability risk. Similarly, intellectual property embedded into a product may enable the product to have enhanced features desired by consumers, and may enable the OM to use a proprietary production process with a variety
of benefits. In what follows, our goal is to show how such design decisions (captured in the abstract by variables $\rho$ and $z$) nevertheless do affect the product’s remanufacturability and, consequently, social welfare.

We consider an OM that manufactures a product and is considered a monopoly in the first period but faces competition in the second period from fringe firms offering a remanufactured version of the OM’s new product. Without loss of generality, we normalize the number of fringe firms in the market to one. Consumed products in the first period (commonly referred to as “cores”) become available inputs to both the dominant OM and the fringe to produce remanufactured versions of the new product still in production. We assume consumers drop off cores to the OM and fringe firms, and receive no payment for returning a core. Such could be the case under a product take-back law, or a deposit-refund scheme. The parameters and decision variables for our model are defined in Table 1.
Table 3.1 Parameters and decision variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>The level of physical product attributes in the product to deter independent firms from remanufacturing the OM’s product</td>
</tr>
<tr>
<td>$z$</td>
<td>The level of intellectual property rights in the product</td>
</tr>
<tr>
<td>$Q_{1}$</td>
<td>Quantity of new products by the OM in period one</td>
</tr>
<tr>
<td>$P_{1}$</td>
<td>New product price in period one</td>
</tr>
<tr>
<td>$c(z, \rho, Q)$</td>
<td>OM’s cost function for new product output $Q$ for embedded levels of $z$ and $\rho$</td>
</tr>
<tr>
<td>$F(z)$</td>
<td>OM’s fixed cost per unit of $z$</td>
</tr>
<tr>
<td>$G(\rho)$</td>
<td>OM’s fixed cost per unit of $\rho$</td>
</tr>
<tr>
<td>$Q_{o,n,2}$</td>
<td>Quantity of new products by the OM in period two</td>
</tr>
<tr>
<td>$P_{o,n,2}$</td>
<td>New product price in period two</td>
</tr>
<tr>
<td>$Q_{o,r,2}$</td>
<td>Quantity of remanufactured products by the OM in period two</td>
</tr>
<tr>
<td>$P_{o,r,2} = P_{f}$</td>
<td>Price for a remanufactured product</td>
</tr>
<tr>
<td>$Q_{f}(\rho, z)$</td>
<td>Quantity of remanufactured products by a fringe firm in period two</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Willingness-to-pay for a remanufactured product</td>
</tr>
<tr>
<td>$c_{o,r,2}(z, \rho, Q_{o,r,2})$</td>
<td>OM’s cost to remanufacture for output $Q_{o,r,2}$ with levels of $z$ and $\rho$</td>
</tr>
<tr>
<td>$c_{f}(z, \rho, Q_{f}(\rho, z))$</td>
<td>Fringe firm’s cost to remanufacture output $Q_{f}(\rho, z)$ by using the OM’s product as an input with embedded levels of $z$ and $\rho$</td>
</tr>
<tr>
<td>$Q_{MSW}$</td>
<td>Quantity of product routed to the municipal solid waste stream</td>
</tr>
<tr>
<td>$D(Q_{MSW}(\rho, z))$</td>
<td>Environmental harm associated with the product that enter the municipal waste stream instead of being remanufactured</td>
</tr>
</tbody>
</table>

In the two-period model, the dominant firm’s (OM’s) optimization problem is to maximize profit: \[ \max \pi = \pi_1 + \pi_2 \text{ where } \]

\[ \pi_1 = P_{1}(Q_{1}) * Q_{1} - c(z, \rho, Q_{1}) - F(z) - G(\rho) \text{ and } \]

\[ \pi_2 = [P_{o,n,2}(Q_{o,n,2}, Q_{o,r,2} + Q_{f}(\rho, z); \delta)] * (Q_{o,n,2}) + \]

\[ \ast [P_{o,r,2}(Q_{o,n,2}, Q_{o,r,2} + Q_{f}(\rho, z); \delta)] * (Q_{o,r,2}) - \]

\[ c(z, \rho, Q_{o,n,2}) - c_{o,r,2}(z, \rho, Q_{o,r,2}) \]
As detailed in Table 3.1, the subscripts on $Q$ and $c$ denote (a) the OM by $O$, (b) $n$ for new product and $r$ for remanufactured product, and (c) period by $1$ or $2$. In the first period, the OM does not encounter any competition and acts as a monopoly. In the second period, the OM acts like a dominant firm with a competitive fringe supplying the market with remanufactured versions of the OM’s product that have been used in period one and then reclaimed by third-party firms. The OM is able to sell its new product and a remanufactured version of its product in the second period. Recognizing that a remanufactured product is differentiated from a new product, we assume each consumer’s willingness-to-pay for a remanufactured product is a fraction $\delta$ of their willingness to pay for a new product, where $0 < \delta < 1$.[52] This assumption tells us that we have a vertical differentiated product market where consumers prefer a new product to a remanufactured product for the same price. However, we assume that consumers are not able to discern the firm’s choice of $\rho$ and $z$ in the product, and consumers face a marginal cost of disposal equal to zero.

For simplicity, the sum of the competitive fringe output may be represented by one firm with profit function

$$\pi_f = P_f * Q_f(\rho, z) - c_f(z, \rho, Q_f(\rho, z))$$

where $P_f = P_{o,r,2}$ if (as we assume) consumers have the same willingness to pay for a remanufactured product regardless of the firm that remanufacturers the product. We assume the OM’s cost to remanufacture its own product is less than the cost for a fringe firm to remanufacture the product. The rationale supporting this assumption is that the OM has access to proprietary information pertaining to the design of the product, brand recognition and a first-mover advantage over a fringe firm such that the OM will have a
lower cost for remanufacturing than a fringe firm for any given $\rho$ and $z$. We assume this is the case even if a fringe firm has cost advantages in specific categories such as core collection, being able to pay lower wages, or having lower overhead costs, providing the OM and fringe firm remanufactured product is of the same quality.

We follow Salop and Scheffman [49] in having the OM choose price/output jointly with cost-raising variables $\rho$ and $z$.\(^5\) Our $Q_f(\rho, z)$ is analogous to Salop and Scheffman’s [49] $y(p, \alpha)$ or $S(p, \alpha)$ function. We assume $Q_{o,r,2} + Q_f \leq Q_1$ (i.e., what is remanufactured in period 2 cannot exceed what was produced in period 1). We have the following first-order conditions:

\[
\frac{\partial \pi_o}{\partial Q_1} = P_1 + \frac{dP}{dQ_1} Q_1 - \frac{\partial c(z, \rho, Q_1)}{\partial Q_1} = 0
\]  \hspace{1cm} (3.1)

\[
\frac{\partial \pi_o}{\partial Q_{o,n,2}} = MR_{o,n,2} - \frac{\partial c(z, \rho, Q_{o,n,2})}{\partial Q_{o,n,2}} = 0
\]  \hspace{1cm} (3.2)

\[
\frac{\partial \pi_o}{\partial Q_{o,r,2}} = MR_{o,r,2} - \frac{\partial c_{o,r,2}(z, \rho, Q_{o,r,2})}{\partial Q_{o,r,2}} = 0
\]  \hspace{1cm} (3.3)

\[
\frac{\partial \pi_o}{\partial \rho} = -\frac{\partial c(z, \rho, Q_1)}{\partial \rho} - \frac{dG(\rho)}{d\rho} - \frac{\partial c(z, \rho, Q_{o,n,2})}{\partial \rho} - \frac{\partial c_{o,r,2}(z, \rho, Q_{o,r,2})}{\partial \rho} + \frac{A}{\frac{\partial P_{o,n,2}}{\partial Q_f} \frac{\partial Q_f}{\partial \rho} (Q_{o,n,2})} + \frac{B}{\frac{\partial P_{o,r,2}}{\partial Q_f} \frac{\partial Q_f}{\partial \rho} (Q_{o,r,2})} = 0
\]  \hspace{1cm} (3.4)

\(^5\) We note, however, that our model is different from the seminal Salop and Scheffman [48,49] models in three ways: (1) we present a remanufactured product as a differentiated product (an inferior substitute), (2) an OM product discarded by a consumer is used as an input by both independent (fringe) remanufacturers and the OM to produce a remanufactured product, and (3) for some period of time, the OM does not see competition from independent remanufacturers because it takes time for independent remanufacturers to collect and remanufacture the OM product that have been discarded by consumers.
Now, \( \frac{\partial P_{o,n,2}}{\partial Q_f}, \frac{\partial P_{o,r,2}}{\partial Q_f} < 0 \) and \( \frac{\partial Q_f}{\partial \rho} < 0 \). So the signs of the \( A \) and \( B \) terms are positive, corresponding to the terms of a non-price-discriminating firm’s marginal revenue (MR) function.

Simplifying Eq. (3.4), we have

\[
\frac{\partial \pi_o}{\partial \rho} = -\frac{\partial c(z, \rho, Q_1)}{\partial \rho} - \frac{dG(\rho)}{d\rho} - \frac{\partial c(z, \rho, Q_{o,n,2})}{\partial \rho} - \frac{\partial c_{o,r,2}(z, \rho, Q_{o,r,2})}{\partial \rho} + A + B = 0
\]

(3.5)

and the OM chooses \( \rho_p \) (where subscript \( p \) denotes privately optimal) such

\[
A + B = \frac{\partial c(z, \rho, Q_1)}{\partial \rho} + \frac{dG(\rho)}{d\rho} + \frac{\partial c(z, \rho, Q_{o,n,2})}{\partial \rho} + \frac{\partial c_{o,r,2}(z, \rho, Q_{o,r,2})}{\partial \rho}, \text{ or where}
\]

\( MR(\rho) = MC(\rho) \). Raising \( \rho \) raises the fringe’s costs, thereby reducing \( Q_f \).

An analogous first-order condition holds with respect to the firm’s choice of \( z \):

\[
\frac{\partial \pi_o}{\partial z} = -\frac{\partial c(z, \rho, Q_1)}{\partial z} - \frac{dF(z)}{dz} - \frac{\partial c(z, \rho, Q_{o,n,2})}{\partial z} - \frac{\partial c_{o,r,2}(z, \rho, Q_{o,r,2})}{\partial z} + A' + B' = 0
\]

(3.6)

where the \( A' + B' \) terms represent the OM’s marginal benefit (MB, or marginal revenue product, MRP) from exercising \( z \). As for Eq. (3.6), as with Eq. (3.5), the OM would choose \( z_p \) such that

\[
A' + B' = \frac{\partial c(z, \rho, Q_1)}{\partial z} + \frac{dF(z)}{dz} + \frac{\partial c(z, \rho, Q_{o,n,2})}{\partial z} + \frac{\partial c_{o,r,2}(z, \rho, Q_{o,r,2})}{\partial z}, \text{ or}
\]

where \( MR(z) = MC(z) \). It is helpful to examine the graphs of the OM’s privately optimal choices of \( \rho_p \) and \( z_p \) (Figures 3.1 and 3.2), as opposed to the socially optimal choices \( \rho_s \) and \( z_s \) (Figures 3.3 and 3.4):
Figure 3.1 OM optimal selection for $\rho$.

Figure 3.2 OM optimal selection for $z$.

A few observations are in order:

1. The OM’s privately optimal choices $\rho_p$ and $z_p$ are by definition not able to be improved upon by the OM’s substitution of $\rho$ for $z$, or vice versa. A proof by contradiction shows why. First, consider any $\rho$ less than $\rho_p$. In that case, $MB(\rho) > MC(\rho)$. But this gap (lost profit) cannot be balanced by or compensated for by taking $z > z_p$. Taking $z > z_p$ reduces the OM’s profit even further. The same argument applies to choosing $\rho > \rho_p$ or $z < z_p$. Alternatively, consider that the privately optimal pair ($\rho_p, z_p$) is at the center of circular iso-profit functions, as in, for instance, Holland et al. [53].

2. If it is the case, however, that (a) the environmental harm from $Q_{MSW}$ is not directly taken into account by the OM and (b) that the OM is not currently able to exercise $z$ all the way to $z_p$ (because of prevailing intellectual property right guidelines or rules), then
we will see in the social planner’s problem (introduced below) that we have an additional term that raises $MC_s(\rho)$ above $MC_p(\rho)$ as shown in Figure 3.3. At the same time, if it is possible that current intellectual property policy restrains the OM to $\hat{z} < z_p$ in Figure 3.4, then there is a Pareto-improving basis for exploring the tradeoff between $\rho$ and $z$. We are inclined to believe that in fact OMs are constrained in reaching their privately optimal choices of intellectual property right strengths, based on the fact that in the United States, fewer than half (approximately 46%) of patent applications have been approved over the last ten years, while patent applications increased 65%, from approximately 315,000 in 2000 to 520,000 in 2010 [54]. In addition, not all claims that OMs originally list in their patent applications are approved by patent officers. As OM profit is reduced in Figure 3.3 if the OM were to implement $\rho_s < \rho_p$, see that OM profit can be expanded (i.e., can be made whole) in Figure 3.4 if the OM is able to raise $z$ from $\hat{z}$ to $z_p$. Depending upon the slopes of the functions in Figures 3.3 and 3.4, a modest increase in $z$ could lead to a more than modest reduction in $\rho$; this in turn can reduce environmental harm and raise social welfare.

---

We turn now to the social planner’s problem, which is to maximize social welfare taking into account consumer surplus, all firm profit, and the environmental harm from products that enter the municipal solid waste stream. The social welfare function is:

$$W = CS_1 + CS_2 + \pi_1 + \pi_2 + \pi_f - D(Q_{\text{MSW}}(\rho, z))$$

(3.7)

Recall in period two, we have a differentiated product market and consumer surplus is represented by

$$CS_2 = \int_0^{Q_1^*} (P_{o,n,2}(Q) - P_{o,n,2}^*)dQ + \int_0^{Q_{o,r,2}} (P_{o,r,2}(Q) - P_{o,r,2}^*)dQ + \int_0^{Q_f} (P_f(Q) - P_f^*)dQ$$

whereas in period one we only have the OM producing a new product with consumer surplus represented by

$$CS_1 = \int_0^{Q_1^*} (P_1(Q) - P_1^*)dQ.$$  Environmental harm from products that enter the municipal solid waste stream may be represented by $D(Q_{\text{MSW}}(\rho, z))$ where $Q_{\text{MSW}} = Q_i + Q_{o,n,2} - Q_f(\rho, z) - Q_{o,r,2}$. 

---

**Figure 3.3** Private and social optimal selections for $\rho$.  **Figure 3.4** Private and social optimal selections for $z$.  

---

**Figure 3.3**

[Diagram showing private and social optimal selections for $\rho$.]  

**Figure 3.4**

[Diagram showing private and social optimal selections for $z$.]
In period one, the OM is a monopoly and can invest in some combination of \( z \) and \( \rho \) that will raise an independent remanufacturer’s cost to produce a remanufactured version of the OM’s product in period two. The asymmetry in this model results from the assumption that only the OM, not an independent remanufacturer, can invest in some level of \( z \) with associated fixed costs \( F(z) \) and some level of \( \rho \) with fixed costs \( G(\rho) \) in period one, such that (1) the level of \( z \) granted to the OM increases the marginal costs of an independent remanufacturer in period two, and (2) the level of \( \rho \) chosen will increase the OM’s marginal costs to produce new units in both periods, and increase both the OM’s and an independent remanufacturer’s cost to produce remanufactured units in period two. The social planner’s first-order conditions are:

\[
\frac{\partial W}{\partial \rho} = \frac{\partial CS_1}{\partial \rho} + \frac{\partial CS_2}{\partial \rho} + \frac{\partial \pi_1}{\partial \rho} + \frac{\partial \pi_2}{\partial \rho} + \frac{\partial \pi_f}{\partial \rho} - \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial \rho} = 0
\]  

(3.8)

\[
\frac{\partial W}{\partial z} = \frac{\partial CS_1}{\partial z} + \frac{\partial CS_2}{\partial z} + \frac{\partial \pi_1}{\partial z} + \frac{\partial \pi_2}{\partial z} + \frac{\partial \pi_f}{\partial z} - \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial z} = 0
\]  

(3.9)

Eqs. (2.8) and (2.9) together imply that the socially optimal rates of \( \rho \) and \( z \) are where:

\[
\frac{\partial CS_1}{\partial \rho} + \frac{\partial CS_2}{\partial \rho} + \frac{\partial \pi_1}{\partial \rho} + \frac{\partial \pi_2}{\partial \rho} + \frac{\partial \pi_f}{\partial \rho} = \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial \rho}  
\]  

(3.10)

\[
\frac{\partial CS_1}{\partial z} + \frac{\partial CS_2}{\partial z} + \frac{\partial \pi_1}{\partial z} + \frac{\partial \pi_2}{\partial z} + \frac{\partial \pi_f}{\partial z} = \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial z}
\]  

(3.11)

Dividing Eq. (3.10) by Eq. (3.11) and simplifying, we have:
\[
\frac{\partial CS_1}{\partial \rho} + \frac{\partial CS_2}{\partial \rho} = \frac{\partial D}{\partial Q_{MSW}} \frac{\partial Q_{MSW}}{\partial \rho} = \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial \rho}
\]
\[
\frac{\partial CS_1}{\partial z} + \frac{\partial CS_2}{\partial z} = \frac{\partial D}{\partial Q_{MSW}} \frac{\partial Q_{MSW}}{\partial z} = \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial z}
\]

(3.12)

Eq. (3.12) is seemingly complicated, but it has nice intuition: the social planner (policy maker) wants to adjust \(z\) and \(\rho\) such that the ratio of marginal damages avoided (on the RHS) just equals the necessary ratio of reductions in consumer surplus and profit from OM and fringe firms (on the LHS). Note that \(\frac{\partial \pi_f}{\partial \rho}\) and \(\frac{\partial \pi_f}{\partial z}\) are both negative, and that all \(\frac{\partial CS}{\partial \rho}\) and \(\frac{\partial CS}{\partial z}\) terms are either zero (if the OM raises output) or negative (if the OM does not raise output).\(^7\) Also \(\frac{\partial Q_{MSW}}{\partial \rho}, \frac{\partial Q_{MSW}}{\partial z} > 0\) (i.e., we’ll have less remanufacturing and therefore more product going to MSW), but \(\frac{\partial Q_{MSW}}{\partial \rho} < \frac{\partial Q_{MSW}}{\partial z}\) because greater \(\rho\) increases remanufacturing costs of both the OM and the fringe firms, reducing total output of remanufactured product.

Totally differentiating Eq. (3.7) we get:

\[
dW = d\rho \left( \frac{\partial CS_1}{\partial \rho} + \frac{\partial CS_2}{\partial \rho} + \frac{\partial \pi_1}{\partial \rho} + \frac{\partial \pi_2}{\partial \rho} + \frac{\partial \pi_f}{\partial \rho} - \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial \rho} \right) + \frac{\partial Q_{MSW}}{\partial \rho} \frac{\partial Q_{MSW}}{\partial \rho}
\]
\[
dz \left( \frac{\partial CS_1}{\partial z} + \frac{\partial CS_2}{\partial z} + \frac{\partial \pi_1}{\partial z} + \frac{\partial \pi_2}{\partial z} + \frac{\partial \pi_f}{\partial z} - \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial z} \right)
\]

(3.13)

Setting \(dW = 0\) and collecting terms we get:

\[
\frac{dz}{d\rho} = \frac{\left( \frac{\partial CS_1}{\partial \rho} + \frac{\partial CS_2}{\partial \rho} + \frac{\partial \pi_1}{\partial \rho} + \frac{\partial \pi_2}{\partial \rho} + \frac{\partial \pi_f}{\partial \rho} - \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial \rho} \right)}{\left( \frac{\partial CS_1}{\partial z} + \frac{\partial CS_2}{\partial z} + \frac{\partial \pi_1}{\partial z} + \frac{\partial \pi_2}{\partial z} + \frac{\partial \pi_f}{\partial z} - \frac{\partial D}{\partial Q_{MSW}} * \frac{\partial Q_{MSW}}{\partial z} \right)}
\]

(3.14)

\(^7\) As in Salop and Scheffman [49] page 26, whether the OM is inclined to raise or maintain output as its choices of \(\rho\) and \(z\) reduces the fringe output is ambiguous.
The RHS of Eq. (3.14) can be expressed as:
\[
\frac{dz}{d\rho} = \frac{MB_s(\rho) - MC_s(\rho)}{MB_s(z) - MC_s(z)}
\]

(3.15)

When \(MB_s(\rho) = MC_s(\rho)\) and \(MB_s(z) = MC_s(z)\), \(dW = 0\) and welfare may be represented by point \(G\) in Fig. 3.5. If we take a little more \(z\) and \(\rho\), then we will be northeast of point \(G\) in quadrant \(j\); as in our formula for \(\frac{dz}{d\rho}\) from Eq. (3.15) we will have \(MB_s(z) < MC_s(z)\) and \(MB_s(\rho) < MC_s(\rho)\). This is because while \(MB_s\) is positive at greater \(z\), it is less positive than the \(MC_s\) at \(z\) greater than \(\hat{z}\) and \(\rho\) greater than \(\hat{\rho}\). Since both the numerator and denominator of the RHS of Eq. (3.15) would be negative, and the RHS is preceded by a negative sign, the slope of any point on any iso-welfare function in quadrant \(j\) is negative.

The slope of an iso-welfare function in quadrant \(h\) is negative for the same reasons.

Finally, the slope of an iso-welfare function in quadrants \(i\) and \(k\) must be positive, since either the numerator or denominator of the RHS of Eq. (3.15) will be positive while the other (numerator or denominator) is negative, preceded by a negative sign.

---

\(\text{Note that we illustrate the iso-welfare functions in Figure 5 with ellipses, as in Holland et al. [53] Figures 2 and 3, however, the iso-welfare functions may be circles. The important point is that the level set is convex by the assumptions on the functions that comprise the welfare function. Qualitatively speaking, increases in } z \text{ reduce the quantity of products provided by the OM, which reduces consumer surplus but also reduces the amount of products routed to municipal solid waste. In contrast, increases in } \rho \text{ lead to an increase in the amount of product routed to municipal solid waste. Iso-welfare ellipses would be vertically (horizontally) oriented if the welfare reduction from an increase in } \rho \text{ (resp., } z \text{) exceeds the welfare reduction from the same increase in } z \text{ (resp., } \rho).
Figure 3.5. Private iso-profit curves (dashed circles) with social iso-welfare curves (ellipses) for selections of $z$ and $\rho$.

With the iso-welfare function in place, we conclude this section by adding the OM’s iso-profit function as dashed circles in Figure 3.5. Doing so enables us to conceptualize welfare improvement that also maintains firm profit (for incentive compatibility). Point $D$ in Figure 3.5 represents the OM’s unconstrained privately optimal profit level. Since the OM appears to in fact be constrained in the amount of $z$ it can embed in its product for which it would be granted intellectual property rights by the
regulator to \( \hat{z} < z_p \), the OM’s *constrained* privately optimal profit may be represented by \( E \) in Figure 5. The key result of our paper is that Pareto-improvement can arise from offering the OM stronger intellectual property rights in exchange for greater remanufacturability built into its products. In Figure 5, such an exchange would move the OM northwest from point \( E \). Two possibilities immediately present themselves. First, we might ask “How much remanufacturability could we obtain from the OM that leaves its profit unchanged?” The answer to this question is given by point \( F \). The improvement in remanufacturability is represented by the reduction of physical product attributes (to deter independent remanufacturers) from \( \rho_p \) to \( \rho_s \). Observe that point \( F \) is located on a higher iso-welfare function than point \( E \). This leads us to a second question, which is “How high could welfare be if the regulator is constrained to preserve the OM’s profit?” The answer to this question is given by the coordinates at point \( L \), where an iso-welfare function is tangent to the OM’s baseline iso-profit function. In this case, remanufacturability improves as physical product attributes are reduced from \( \rho_p \) to \( \rho^* \).

The degree of intellectual property strength necessary to achieve this Pareto-improvement may be relatively modest (i.e., \( z^* < z_p \)). The Pareto-improvement from point \( E \) to point \( L \) represents the second-best optimum.

### 3.3 Model simulation

In this section, we introduce additional assumptions so that we can (a) simulate how the market in Section 3.2 operates from both private and social perspectives and (b) illustrate how trading stronger intellectual property rights for greener design of products by OMs can be welfare-enhancing. Assume that in the first period, a monopolist OM produces a
new product for linear demand given in the (inverse) form \( P_1 = \beta - \chi Q_1 \), and let the OM’s cost of producing the new version of the product be represented by the additive form \( c(z, \rho, Q_1) = \gamma Q_1 + \theta Q_1^2 \) as often seen in the industrial organization literature[55].

Suppose that the above functional forms are specified as follows: \( P_1 = 100 - 0.02Q_1 \) and \( c(z, \rho, Q_1) = 10Q_1 + 0.0075Q_1^2 \). (Note that \( \rho \), \( z \) and private/external costs of dealing with discarded products at the end of the first period are set equal to zero for now, but will be introduced later in this section.) We can immediately solve for the monopoly quantity and price of new product in the first period; the quantity simultaneously defines the number of used products (“cores”) that are available for remanufacturing in the second period.

The OM’s first-period problem is:

\[
\text{Max } \pi_1(Q_1) = [100 - 0.02Q_1]Q_1 - [10Q_1 + 0.0075Q_1^2]
\]

Rearranging the first-order condition yields \( Q_1^* = 1636.36 \) and \( P_1^* = $67.27 \). Note that in contrast with this monopoly result, the socially efficient quantity and price (where \( P = MC \)) is given by \( Q_{s,1} = 2571.43 \) and \( P_{s,1} = $48.57 \). Note also that the marginal cost at the monopolist’s optimal quantity is $34.54, from \( MC(1636.36) = 10 + 0.015(1636.36) \).

Up to this point, we have assumed that consumer disposal of cores at the end of period 1 is costless, and that the cores do not have value to the OM or any other firm in terms of remanufacturing. Under these assumptions, the monopoly power exerted by the OM creates deadweight loss. However, we note that if core disposal happens to yield a marginal external cost that is equal to the monopoly price mark-up, then as Buchanan [56] showed, the monopoly power acts like a pollution tax to yield the socially efficient
rate of output. In our example, the monopoly price mark-up \((P - MC)\) is $67.27 - $34.54 = $32.73.

Let us hold on to that thought for a moment, however, and proceed to analysis of the two-period model. Assume that consumers have the same market demand for the product in period two as in period one and consumers differentiate between new and remanufactured products such that their reduced willingness to pay for a remanufactured product is represented by a multiplier \(\delta\). At \(\delta\) equal to one, consumers would be indifferent between purchasing a new unit or a remanufactured unit. We also assume for simplicity that consumers are indifferent between remanufactured products from the OM and from independent fringe remanufacturers given equivalent quality. Although consumers express different willingness-to-pay for remanufactured products based on the specific product, we assume a value of \(\delta = 0.70\) for our hypothetical product. With these assumptions, we follow Ferguson and Toktay [52] Appendix B in determining prices for new and remanufactured products to get

\[
P_{o,n,2} = 100 - 0.02Q_{o,n,2} - 0.02\delta(Q_{o,r,2} + Q_f(\rho, z)) \quad \text{and}
\]

\[
P_f = p_{o,r,2} = \delta(100 - 0.02Q_{o,n,2} - 0.02(Q_{o,r,2} + Q_f(\rho, z))).
\]

In the second period, the OM is able to produce new products by the previously given cost function, \(c(z, \rho, Q) = 10Q + 0.0075Q^2\) or it is able to remanufacture cores into remanufactured products according to \(c_{o,r,2}(z, \rho, Q_{o,r,2}) = 5Q_{o,r,2} + 0.015Q_{o,r,2}^2\). Note that the OM cost function to produce a remanufactured product has a marginal cost that is assumed to start at a lower initial value ($5 vs. $10), but to rise more steeply ($0.03 vs. $0.015) than the marginal cost function for new production. In addition, there is another firm \(f\) that competes in the remanufactured product market with cost function given
by \( c_f(z, \rho, Q_f(\rho, z)) = 2Q_f + 0.01Q_f^2 \). This fringe cost specification has a marginal cost that starts at a lower point (\$2 vs. \$5), and does not rise as quickly as the OM remanufacturing marginal cost (\$0.02 vs. \$0.03) but rises more steeply than the OM marginal cost for new product production. These assumed parameter values in the cost functions enable us to study the most interesting case in which the OM has an incentive to produce positive quantities of both new and remanufactured units and the fringe is likewise able to produce a positive quantity of remanufactured units. Consumers can dispose of cores at the end of the first period at zero cost, or they can return them to the OM or a remanufacturing competitor. We can then cast the OM and the remanufacturing competitor \( f \) as Cournot-competitors, with the OM having two production lines: one producing new products and one producing remanufactured products.\(^9\) The OM’s second-period problem is:

\[
\pi_2(Q_{o,n,2}, Q_{o,r,2}, Q_f) = (100 - 0.02Q_{o,n,2} - 0.02(Q_{o,r,2} + Q_f))Q_{o,n,2} + (\delta(100 - 0.02Q_{o,n,2} - 0.02(Q_{o,r,2} + Q_f)))Q_{o,r,2} - 10Q_{o,n,2} - 0.0075Q_{o,n,2}^2 - 5Q_{o,r,2} - 0.015Q_{o,r,2}^2
\]  

(3.17)

The competitor firm \( f \)'s problem is:

\[
\pi_f(Q_{o,n,2}, Q_{o,r,2}, Q_f) = (\delta(100 - 0.02Q_{o,n,2} - 0.02(Q_{o,r,2} + Q_f)))Q_f - 2Q_f - 0.01Q_f^2
\]  

(3.18)

Eq. (3.17) yields two first-order conditions, as follows:

\[
\frac{\partial \pi_2}{\partial Q_{o,n,2}} = 90 - 0.055Q_{o,n,2} - 0.04\delta Q_{o,r,2} - 0.02\delta Q_f = 0
\]  

(3.19)

\[
\frac{\partial \pi_2}{\partial Q_{o,r,2}} = 100\delta - 5 - 0.04\delta Q_{o,n,2} - 0.04\delta Q_{o,r,2} - 0.03\delta Q_{o,r,2} - 0.02\delta Q_f = 0
\]  

(3.20)

\(^9\) We note that the Cournot-Nash framework is fairly standard in the literature; see, e.g., Bernard [44].
And Eq. (3.18) yields a single first-order condition:

$$\frac{\partial \pi_f}{\partial Q_f} = 100 \delta - 2 - 0.02 \delta Q_{o,n,2} - 0.02 \delta Q_{o,r,2} - 0.04 \delta Q_{f} - 0.02 Q_{f} = 0$$  \hfill (3.21)

Solving Eqs. (3.19), (3.20) and (3.21) simultaneously yields the following results:

$$Q_{o,n,2}^* = 1207.8, \quad Q_{o,r,2}^* = 362.4 \quad \text{and} \quad Q_{f}^* = 958.7.$$  

Substituting these quantities into the price functions, we get  

$$P_{o,n,2}^* = $57.35 \quad \text{and} \quad P_{o,r,2}^* = P_f^* = $34.60.$$  

See that total remanufacturing in the industry in period two is given by $362.4 + 958.7 = 1321.1$. The first period yielded 1636.36 cores. Therefore, 315.26 cores were routed for disposal in period two, following their single-use in period one.

In the model thus far, however, disposal comes at a zero cost to the consumer and to society (i.e., the cores just disappear). As well, at this point in the model the OM’s use of intellectual property ($z$) and physical product attributes ($\rho$) are present, but silent (i.e., set equal to zero). While, the social cost of core disposal by consumers is not zero, difficulties associated with applying a Pigouvian tax on disposal in this context motivated our interest in upstream strategies for modulating $Q_{MSW}$ via $\rho$ and $z$. We now introduce $\rho$ and $z$ into the simulation. In a strict sense, the OM’s intellectual property may be entirely represented in fixed costs and are independent of the number of units produced and do not affect the OM’s marginal cost functions. Hence, the OM will absorb a fixed cost for a given level of $z$, and the level of $z$ may affect a fringe firm’s marginal cost function either by increasing the $y$-axis intercept or the slope. Although we have restricted $z, \rho \in [0,1]$ to be consistent with previous literature, there will be a specific cost function of $z$ seen by the fringe firm, which will be different if $z$ affects the $y$-axis intercept or the slope of the fringe firm’s marginal costs. Recall the level of $\rho$ signifies
the amount of physical attributes incorporated into the design to deter independent remanufacturing firms, and so it affects all marginal cost functions, but again may do so by either increasing the y-axis intercept or the slope. Similarly, there will be a specific cost function of \( \rho \) that will affect the OM’s costs, and a different cost function of \( \rho \) that will affect the fringe firm’s costs. For example, for \( \rho = 0.2 \), the cost function applied to the y-axis intercept for the OM’s new product may be $0.40, OM’s remanufactured product may be $0.20, and the fringe firm’s product may be $0.33. The possible combinations of how \( \rho \) and \( z \) may affect OM and fringe costs are summarized in Table 3.2.

<table>
<thead>
<tr>
<th>Case</th>
<th>( z ) affecting MC</th>
<th>( \rho ) affecting MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>y-axis intercept for fringe</td>
<td>y-axis intercept for all</td>
</tr>
<tr>
<td>2</td>
<td>slope for fringe</td>
<td>slope for all</td>
</tr>
<tr>
<td>3</td>
<td>y-axis intercept for fringe</td>
<td>slope for all</td>
</tr>
<tr>
<td>4</td>
<td>slope for fringe</td>
<td>y-axis intercept for all</td>
</tr>
</tbody>
</table>

It should be emphasized that we do not know the values of \( z \) and \( \rho \) (and how they affect OM and fringe costs) from market data; rather, we selected representative parameter values to illustrate the qualitative properties of the model and its results. Hence, our example is limited to \( z \) and \( \rho \) affecting cost functions as shown in Table 3.3. Similarly, the environmental damage associated with a product routed to disposal will vary for each product. For our empirical model, we assume each unit of product routed to disposal results in a cost to society of $0.10. Future work could estimate these parameters econometrically.
Table 3.3 Resulting cost equations for \( z \) and \( \rho \) for each case

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_{o,n,2}(z, \rho, Q_{o,n,2}) = (10 + \rho)Q_{o,n,2} + 0.0075Q^2_{o,n,2} )</td>
<td>( c_{o,n,2}(z, \rho, Q_{o,n,2}) = 10Q_{o,n,2} + (0.0075 + \rho)Q^2_{o,n,2} )</td>
</tr>
<tr>
<td>( c_{o,r,2}(z, \rho, Q_{o,r,2}) = (5 + \rho)Q_{o,r,2} + 0.015Q^2_{o,r,2} )</td>
<td>( c_{o,r,2}(z, \rho, Q_{o,r,2}) = 5Q_{o,r,2} + (0.015 + \rho)Q^2_{o,r,2} )</td>
</tr>
<tr>
<td>( c_f(z, \rho, Q_f(\rho, z)) = (2 + \rho)Q_f + 0.01Q_f^2 )</td>
<td>( c_f(z, \rho, Q_f(\rho, z)) = 2Q_f + (0.01 + \rho)Q^2_f )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_{o,n,2}(z, \rho, Q_{o,n,2}) = 10Q_{o,n,2} + (0.0075 + \rho)Q^2_{o,n,2} )</td>
<td>( c_{o,n,2}(z, \rho, Q_{o,n,2}) = (10 + \rho)Q_{o,n,2} + 0.0075Q^2_{o,n,2} )</td>
</tr>
<tr>
<td>( c_{o,r,2}(z, \rho, Q_{o,r,2}) = 5Q_{o,r,2} + (0.015 + \rho)Q^2_{o,r,2} )</td>
<td>( c_{o,r,2}(z, \rho, Q_{o,r,2}) = (5 + \rho)Q_{o,r,2} + 0.015Q^2_{o,r,2} )</td>
</tr>
<tr>
<td>( c_f(z, \rho, Q_f(\rho, z)) = (2 + \rho)Q_f + (0.01 + \rho)Q_f^2 )</td>
<td>( c_f(z, \rho, Q_f(\rho, z)) = (2 + \rho)Q_f + (0.01 + \rho)Q_f^2 )</td>
</tr>
</tbody>
</table>

The next step is to compare results when an OM is able to increase the level of \( z \) embedded in its product in exchange for a reduction in the level of \( \rho \) across the four cases identified in Table 3.2. We restrict our analysis to those instances where the fixed costs of \( z \) and \( \rho \) are constrained to allow the OM to earn positive profits in at least one of the four cases. That is, we do not consider cases when the fixed costs of \( z \) or \( \rho \) are so high that if the OM embedded them into its product the OM would have negative profits in all four cases. We assume that the OM has been granted intellectual property rights such that \( z=0.4 \) and the OM has embedded technical barriers for remanufacturers such that \( \rho=0.5 \). Under these assumptions we are interested in exploring how OM profit, fringe profit, consumer surplus, environmental damage, and net social welfare change as we modulate \( z \) from \( z=0.4 \) to \( z=0.5 \) and \( \rho \) from \( \rho=0.5 \) to \( \rho=0.4 \). We find there are three different sets of results that may occur when we vary the fixed cost functions for \( z \) and \( \rho \) as shown in Table 3.4. When \( G(\rho) \) is greater than or equal to \( F(z) \) as shown in columns 1 and 3 of Table 3.4, OM profit increases for all cases as the OM increases \( z \) for an equal reduction in \( \rho \); even though fringe profit is reduced in all cases except case 3, net welfare is improved in all but one instance. Whereas, when \( F(z) \) is much greater than \( G(\rho) \) as
shown in column 2 of Table 3.4, the OM would only choose to increase $z$ and reduce $\rho$ for cases 2 and 3, but it is interesting that net welfare also increases for these two cases.

Table 3.5 specifically explores functional forms for fixed costs that cross as we increase $z$ or $\rho$ from 0.4 to 0.5, but the results are nearly identical to the same three sets found in Table 3.4. For our simulation, Pareto-improvement occurs for case 3, with consumers worse off in only case 4. Most of the scenarios considered in Tables 3.4 and 3.5 result in a decrease in environmental damage and a net increase in welfare.

**Table 3.4** Impact comparison for varying fixed cost functions for $z$ and $\rho$

<table>
<thead>
<tr>
<th>$F(\rho) &gt; = F(z)$ 25 $\rho$ vs. 25$z/(1+z^2)^{1/2}$</th>
<th>$F(\rho) &lt; &lt; F(z)$ 10$\rho$ vs. 10$e^{10\rho}$</th>
<th>$F(\rho) &gt;&gt; F(z)$ 10$e^{10\rho}$ vs. 10$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>OM Profit</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Fringe Profit</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CS</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Damage</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Net Welfare</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

**Table 3.5** Impact comparison when fixed cost functions for $z$ and $\rho$ intersect

<table>
<thead>
<tr>
<th>$F(\rho) &gt; F(z)$ $z, \rho =0.4$</th>
<th>$F(\rho) &lt; F(z)$ $z, \rho =0.5$</th>
<th>$F(\rho) &lt; F(z)$ $z, \rho =0.4$</th>
<th>$F(\rho) &gt; F(z)$ $z, \rho =0.5$</th>
<th>$F(\rho) &gt; F(z)$ $z, \rho =0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>OM Profit</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Fringe Profit</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CS</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Damage</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Net Welfare</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

In determining the distribution of welfare changes for consumers, the original manufacturer, and the fringe firms for these four cases as we modulate $z$ from $z=0.4$ to
$z=0.5$ and $\rho$ from $\rho=0.5$ to $\rho=0.4$, it is worth noting that the OM’s profit is affected by its fixed costs associated with $z$ and $\rho$ (i.e., $F(z)$ and $G(\rho)$). For those cases where the OM profit increases and $F(z)$ and $G(\rho)$ are small, the OM sees between 47% to 80% of the total gain in welfare, consumers see 30% to 52% of the total gain, and fringe firms see between -16% to 20% of the total gains in welfare. But when $F(z)$ and $G(\rho)$ are large, the OM experiences more modest gains from 20% to 59%, consumer gains range from 44% to 47%, and fringe firms see between -0.02% to 32% of total gains in welfare.

An increase in $\delta$ from 0.6 to 0.7 indicates consumers are willing-to-pay more for a remanufactured product because consumers perceive the remanufactured product to be a closer substitute to a new product, where $\delta$ may reflect strong preferences for greener products or that functionally the products are considered close substitutes. As shown in Table 3.6, as $\delta$ increases consumers desire more remanufactured product, so remanufactured output increases in the second period by both the OM and the fringe firm, while the OM reduces the number of new units produced in the second period. Although the OM is worse off, the improvement to consumer surplus and fringe firm profit outperforms losses in OM profit to yield an increase to social welfare. Since the number of units routed to disposal decreases, environmental impact falls and net welfare is further improved. These results indicate that as consumers perceive remanufactured product (both OM and fringe versions) as closer substitutes for new OM product, competition in the remanufactured product market restricts prices and reduces the OM’s total profit.
Table 3.6 Results comparison as $\delta$ increases

<table>
<thead>
<tr>
<th>Second Period</th>
<th>As $\delta$ increases</th>
</tr>
</thead>
<tbody>
<tr>
<td>New OM units</td>
<td>Decrease</td>
</tr>
<tr>
<td>OM remanufactured units</td>
<td>Increase</td>
</tr>
<tr>
<td>Fringe units</td>
<td>Increase</td>
</tr>
<tr>
<td>Units routed to disposal</td>
<td>Decrease</td>
</tr>
<tr>
<td>Total units</td>
<td>Increase</td>
</tr>
<tr>
<td>Total OM profit</td>
<td>Decrease</td>
</tr>
<tr>
<td>CS</td>
<td>Increase</td>
</tr>
<tr>
<td>Fringe profit</td>
<td>Increase</td>
</tr>
<tr>
<td>Social Welfare</td>
<td>Increase</td>
</tr>
<tr>
<td>Environmental damage</td>
<td>Decrease</td>
</tr>
</tbody>
</table>

3.4 Conclusion and directions for future research

The purpose of our paper is to combine the economic concepts of green design, “raising rivals’ costs”, and intellectual property rights to suggest a new method for incentivizing product remanufacturability. Success along these lines would reduce the inefficient flow of virgin materials into production processes and reduce the inefficient flow of single-use products to landfills. The key take-away point from our study is that a regulator could raise social welfare by strengthening original manufacturer (OM) intellectual property rights in exchange for an increase in remanufacturability built into products by OMs.

Our results align with previous research exploring the remanufacturability level a firm will embed into its product. As in other studies, the OM in our model has an incentive to embed a level of remanufacturability in its product that maximizes the OM’s profit over a specified time period. The degree of remanufacturability selected by an OM is influenced by many factors, including market structure, consumer willingness-to-pay for a remanufactured product, OM management’s perception that remanufactured product
sales will cannibalize sales of new products, environmentally-motivated regulation and
the OM’s ability to cost effectively collect, process and sell remanufactured products
relative to that of independent remanufacturers. For a product market where
remanufactured products are desirable, an OM may increase the level of
remanufacturability embedded in its products if the OM is able to effectively recover its
products after a consumer use cycle, minimizing the effects of independent
remanufacturers free-riding on the OM’s investment in remanufacturability level. As
Bernard [44] suggested recently, one way forward is for the regulator to allow/encourage
OMs to agree upon a remanufacturability standard via collusion. We offer the
complementary proposal of strengthening intellectual property rights as an incentive to
encourage greener product design.

Indeed, we suggest that a modified intellectual property rights system may be
considered as part of an Integrated Product Policy (IPP) as emphasized by the European
Commission (EC). IPP, as defined by the EC, promotes environmental product
innovations to achieve a broad reduction of all environmental impacts along a product’s
life cycle [57]. Rehfeld et al. [47] find that technology push (i.e., research and
development activities), market pull and specific firm characteristics have a significant
influence on environmental product innovations undertaken by a firm. Our findings
suggest that policy makers should consider modifications to the intellectual property
rights’ system as an unconventional tactic to encourage OMs to increase the
remanufacturability of their products. OMs with increased intellectual property rights are
more likely to invest in increased remanufacturability of their product and take-back
systems to capitalize on future profits from remanufacturing operations once the threat of

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free-riding by independent remanufacturer’s is eliminated, provided that remanufacturing is practical (i.e., profitable for the OM and desired by consumers). Discarded products by consumers that were previously routed to municipal waste or independent remanufacturers would now be designed with a sufficient remanufacturability level such that the OM will more efficiently provide new and remanufactured product to the market.

Of course, institutions that administer intellectual property rights already exist, such that costly institutional change is not required in order to implement this policy lever. Leveraging this existing public policy mechanism may have lower transaction costs than other policy instruments (e.g. taxes and subsidies) or other mandated programs (e.g. product take-back systems) that have been considered in the literature as typical intervention options to deal with negative externalities associated with discarded products. One might ask why we are not recommending the policymaker mandate a level of $\rho$, and keep the intellectual property system as it is currently? While social welfare may be improved by such a mandate, such a mandate may change the dynamics in the market and alter the product system structure, creating opportunities for unintended consequences. Our suggested adjustment to an existing policy lever maintains the product system structure, minimizing unintended consequences. It is not our intent to prescribe operational changes that should be made to the intellectual property rights system to achieve more remanufacturing. But the intellectual property rights system may be modified so that the regulator awards intellectual property rights contingent upon the producer achieving a certain level of remanufacturing activity for products protected by the intellectual property rights. If the negotiated level of remanufacturing is not achieved by a defined time table, intellectual property rights could be withdrawn.
One possible extension of our model is to generalize beyond a two-period framework that only considers one remanufacturing cycle for the product. For products in sectors with fast evolving technology (e.g., information and communication technology) or products that undergo severe mechanical stress, multiple remanufacturing cycles may not be practical. But for those products where multiple remanufacturing cycles are likely, it would be interesting to investigate welfare impacts of increased intellectual property rights over multiple period and infinite time horizons. Since the OM will likely experience increasing marginal costs with remanufacturing cycles, we anticipate the OM will select a finite (optimal) number of remanufacturing cycles to undertake, and embed the corresponding remanufacturability level for the optimal remanufacturing cycles in the new product. History tells us that a dominant firm’s share of a product market generally falls over time until the point where no firm earns positive economic profits [58]. It would be interesting to investigate whether a dominant firm effectively remanufacturing its product could be able to maintain a dominant position in the product market for a longer period of time, since the OM would be able to suppress entry from competitors by offering a lower priced remanufactured version of its product.
IV. ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF TYING UNDER PRODUCT TAKE-BACK

4.1 Introduction

The basic premise supporting extended producer responsibility (EPR) is to hold producers responsible for the environmental impact of their products at end-of-life. EPR is a policy concept which can be implemented with several different instruments and each instrument will have a specific impact on various environmental goals, such as waste generation, product design, and the ultimate fate of products at end-of-life [59]. This paper investigates consequences that may result from an EPR product take-back requirement applicable for a durable product when a producer uses a requirements tie-in sales strategy by considering environmental and welfare impacts across both the durable and tied consumable markets. To achieve this goal, we propose combining literatures regarding EPR, policy analysis and industrial organization with environmental impact assessment findings for a long standing requirements tie-in case to illustrate trade-offs in environmental harm and welfare. Our specific contribution is to show within such a framework, that environmental and welfare performance is dependent upon whether product take-back legislation is implemented using an individual or collective scheme. We find environmental harm is reduced under the collective scheme, but also produced the lowest welfare of the alternatives. Environmental harm is reduced since durables are diverted from the municipal waste stream to recovery processing (e.g., recycling), and welfare is reduced because firms reduce durable production volumes in response to the costs of recovery processing they incur from complying with the take-back regulation. Whereas, under the individual take-back scheme, we find a reduction in environmental
harm compared to no take-back, but we also find that welfare can be increased if the firm implements reuse (e.g., remanufacturing) operations for the durable product. We also note that neither take-back scheme is a sufficient condition to deter the firm from using a requirements tie-in sales strategy. Furthermore, the individual durable product take-back scheme may reinforce the use of a requirements tie-in sales strategy, since the mandate allows the firm to reduce its costs by remanufacturing durables discarded by consumers that may not have been practical prior to the take-back requirement.

A requirements tie-in (or simply tie-in) is a pricing strategy where a firm sells one product (or service), the use of which requires the consumption of a complementary product (or complementary service) also sold by the firm. Some notable examples of exclusive supply relationships for product systems include printers and ink cartridges, copy machines and copy paper, razor and replacement blades, and branded cameras using branded film. Exclusive supply relationships are often seen in the communications sectors such as mobile phone services, internet service, and cable and satellite television services. A firm using tying may engage in several pricing strategies. Reitzes and Woroch [60] thoroughly investigate firm profits, consumer utility and welfare under one-part pricing, two-part pricing with commitment to usage related prices, and two-part pricing when the firm does not commit to usage related prices in advance of a consumer selecting their exclusive supplier. In one-part pricing, firms set the access fee (e.g., initial purchase price for a durable good or connection fee for internet services) equal to zero, and commit to a usage charge in advance of customers’ choosing their supplier. One-part pricing is just a specialized case of two-part pricing with commitment where the access fee is set equal to zero. In two-part pricing with commitment, firms set a high access fee,
but charge cost-based unit prices for usage. In two-part pricing without price commitment, firms set a low access fee, but charge a high unit price for usage, termed “bargain-then-rip-off” by Reitzes and Woroch [60]. In their model, Reitzes and Woroch [60] consider oligopoly competition of differentiated goods without requiring consumers to purchase the good. They find two-part pricing with unit-price commitment for usage is the dominant profit-maximizing policy, despite the prospect of aftermarket monopolization associated with two-part pricing without unit-price commitment for usage. In contrast, one-part pricing dominates in terms of both consumer and social welfare. From their analysis, it is clear that profit-maximizing firms should prefer two-part pricing with commitment for usage prices, and consumers should prefer one-part pricing. Neither firms nor consumers benefit from two-part pricing without commitment. However, two-part pricing without commitment can be found in many markets. It is this latter pricing strategy (two-part pricing without commitment) that we wish to explore further from firm profit, consumer and social welfare perspectives for the inkjet printer and cartridge markets by including environmental harm for markets where a product take-back mandate may result in the durable good being either recycled or remanufactured.

A consumer can choose a printer from a variety of manufacturers that offer several models (differentiated durable) with unique price schedules for consumables that result in a wide range of prices per printed page for a set output level [61, 62]. Consumers will typically use the current selling price for the consumable (ink/toner cartridge) to determine their price per page into the future by amortizing the cost of the printer over their expected usage. When firms offer these products on the market with
the same price schedule available to all consumers, consumers are free to select the
portion of the price schedule for each product offering. As described, requirements tie-in
sales would be considered to be a form of second degree price discrimination. The firm
is effectively able to price the tied package based on usage of the durable product,
extracting the maximum surplus from each consumer. Consumers with large usage
demands effectively pay more for the durable product than consumers with small usage
demands [2]. A firm price discriminates in order to increase its profits, but may only do
so if the firm has (1) some market power, (2) can infer consumers’ willingness to pay and
(3) can prevent or limit resales from consumers who pay a lower price to those who pay a
higher price [2].

There are many articles focused on identifying the welfare implications of tying. In a seminal paper, Whinston [63] showed that tying can be used as a strategy by a
monopolist in the tying product market to drive out competition in the tied product
market, and thus extract monopoly profits in the tied product market. Carlton and
Waldman [64] extended Whinston’s analysis to show a monopolist (or dominant firm)
can use tying to increase future profits by deterring entry of efficient firms into the tying
product market and newly emerging markets (tied product market). Heubrandner and
Skiera [65] build upon work by Kaserman [66] to show that tying can be welfare
enhancing if consumers exhibit higher discount rates than firms. Borenstein et al. [67]
show that a firm with market power over sales in its associated aftermarkets (i.e., tied
product) will exercise that power to some extent that results in pricing of tied products
above their competitive levels, regardless of the market structure in the durable (tying)
product market. This finding relies on the firm’s inability to commit to future prices for
the tied product. If commitment were possible, the firm’s ideal strategy would be to charge monopoly pricing for the tied product to all locked-in consumers, and charge marginal cost pricing for tied products to all future customers that have not purchased the firm’s durable product yet. As a matter of price discrimination theory, the welfare effects of tying are ambiguous.

While the welfare effects of product tying is an interesting and rich topic in itself, we are also interested in the environmental harm that may result from use of a tie-in strategy, and look to identify the effects an EPR product take-back law for a durable product will have across both the tying (durable) and tied (consumable) markets. The effectiveness of EPR policy instruments is a fairly young topic in the literature since EPR policy concepts were introduced in 1991 with the German Green Dot scheme. Fleckinger and Glachant [68] show that EPR product take-back is not sufficient to ensure an efficient producer response. When waste management is competitive, individual take-back acts like a Pigouvian tax and always yields a higher welfare than a perfectly collusive collective take-back scheme using a producer responsibility organization (PRO). But if waste management is not competitive, an individual take-back scheme will perform worse than the perfectly collusive collective scheme. Atasu et al. [4] focus on the effects of take-back legislation of existing policies such as the mass based Waste Electrical and Electronic Equipment (WEEE) Directive of the European Commission. They find that the WEEE directive is not efficient from an economical or ecological perspective and argue for a directive with focused targets for different product categories that consider: a) EOL treatment cost, b) environmental impact, c) consumer willingness-to-pay for a decrease in environmental impact, and d) competition intensity for a specific product
market. They also point out that the WEEE Directive favors recycling over reuse and the collective take-back scheme does not incentivize an individual firm to improve its product’s environmental quality as would be the case under an individual take-back scheme.

The requirements tie-in situation offers many challenges when determining environmental impact over both the tying (durable) and tied (consumable) product markets. In the “bargain-then-rip-off” scenario seen in the printer-cartridge markets, the durable product is sold at a low price leading to high levels of consumption, and high priced consumables make consumers meter their use of the durable. Tying leads to higher consumption of the durable product, and reduced consumption of the consumable product compared to consumption levels if both (durable and consumable) markets were independent. If the environmental impact attributed to the durable product dwarfs environmental impact from consumption of the complementary consumable product, then a requirements tie-in strategy will result in more environmental harm. And if environmental impact attributed to the durable product is dwarfed by environmental impact of consumption of the complementary consumable product, then a requirements tie-in strategy will result in less environmental harm than if the products were served by independent markets.

Up to this point we have not discussed what constitutes environmental impact. Typically Life Cycle Assessment (LCA) is used to characterize environmental impact of alternatives, such as competing product design choices, and product EOL treatment options. Although there are many categories that can be examined in the impact assessment stage of LCA, for our case study we utilize cumulative energy demand (CED)
as a proxy for environmental impact, since neither the durable or consumable product we consider consists of materials that pose a significant health risk to humans during their use phase and EOL routes.

While each EOL route has an associated environmental impact, an EPR product take-back requirement for a durable product should result in the durable undergoing some form of recovery or reuse, such as recycling or remanufacturer. If the firm selects a reuse option, the durable would be routed to recovery processing when reuse is no longer practical. We compare and contrast a scenario where no take-back requirement is in place with two possible implementations of a take-back law for the durable product. The two take-back schemes are distinguished by the degree of control that the original manufacturer (OM) has on the fate of its returned durable products at EOL. In the individual take-back scheme, the OM has responsibility for collecting returns and determines whether returns are immediately recycled, remanufactured one or more times before being recycled, or some other acceptable recovery fate. In the collective take-back scheme, the OM pays a fee for each returned durable product for collection and recycling operations. Under the collective scheme, collection and recycling costs are ultimately transferred to consumers in the form of increased prices. Where both implementations transfer the cost associated with discarded durable products from taxpayers to the OMs, only the individual take-back scheme offers the manufacturers an opportunity to offset the cost of compliance with the take-back law by engaging in activities to extract value from returned durable products. We argue that reuse (remanufacturing) is in alignment with EPR policy goals and is one such way a firm using a requirements tie-in sales strategy can extract value from returned durable products.
Although recycling is preferred to landfilling in that it recovers some material value and energy that has been invested through previous materials processing operations [69], remanufacturing involves recovering value from EOL products. Maslennikova and Foley [41] observe that Xerox continues to utilize a modular design strategy for most of its products that allows them to collect and profitably remanufacture products. Xerox was able to transform a potential disposal cost associated with 160,000 Xerox copy/print machines recovered from customers in Europe (in 1997) into a net savings of $80 million by reprocessing these machines [41].  

Since our focus is upon durable products associated with a requirements tie-in strategy, remanufacturing a durable product and releasing it to the market as an existing model, makes little sense if the durable product market experiences technological advances as found in electronic devices. However, if functions of the durable product are maintained over time, it may be advantageous for the firm to reclaim durable components/modules from returned product (as in the Xerox case) and use them in the production of “new” models. As stated earlier, a requirements tie-in strategy will result in an abundance of durable products brought to the market, with some portion often discarded with low levels of “wear and tear” since low and medium usage consumers use them sparingly due to the relatively high cost of tied consumables (as in the printer-cartridge tie). Prior to any type of product take-back mandate, unwanted durable products (with a tie-in strategy) would not be desired by consumers (as in a second-hand market) since “new” varieties are readily available at relatively low prices. But an individual take-back requirement would ensure discarded durable products are routed to the manufacturer, enabling remanufacturing that may not have been viable prior to the take-

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10 Maslennikova and Foley [41] page 228.
back requirement as shown by Webster and Mitra [6]. With assurance that durable products would be returned, the requirements tie-in manufacturer could initiate investments in product design and supply chain operations to lower future costs of remanufacturing returned durable products that would not have been practical prior to the take-back requirement. Recall that under a collective take-back scheme, collected products are destined for recycling and an individual producer is not incentivized to invest in the environmental quality of its products. We suggest readers interested in remanufacturing strategy under EPR to a recent article by Ozdemir et al [70] that investigates the firm’s optimal remanufacturing strategy under an individual EPR take-back requirement, and review articles by Esenduran[5] and Atasu and Van Wassenhove [71, 72].

Our paper proceeds as follows: In Section 4.2, we set forth the firm’s profit maximization problem and the social planner’s problem for our three take-back scenarios (i.e., no take-back, individual take-back scheme and collective take-back scheme). We demonstrate that an EPR product take-back law is not sufficient for the firm to abandon a requirements tie-in strategy and we introduce the social planner’s problem considering environmental harm. We introduce representative functional forms and parameters in Section 4.3 so that the model properties can be illustrated using environmental impact and market data for the printer-cartridge tie-in case study. Comparative statics follow, showing how different implementations of the product take-back mandate might affect the firm’s costs, firm’s profits, and social welfare differentially. We provide sensitivity analysis for our assumptions pertaining to environmental benefits associated with remanufacturing in Section 4.4, and put our results into perspective using data from the
European market for our case study in Section 4.3. Section 4.5 concludes with discussion of the results and directions for future research.

4.2 Theoretical model

The firm employing a requirements tie-in strategy is concerned with maximizing profit in two markets, the durable (tying) product market and the consumable (tied) product market. We assume there is a fixed number of consumable products (ink cartridges) demanded by the market for each durable (printer) produced. Although consumers will have varying usage rates, this assumption may be thought of as the average usage rate for all consumers. However, the demand curve for cartridges is influenced by the number of printers released to the market, expanding out as more printers are released and retracting inward as fewer printers are released.

![Diagram of Printer Market and Cartridge Market](image)

**Figure 4.1** Welfare distribution for independent printer and cartridge markets with Firm 1 a monopolist in printer market and Firm 2 a monopolist in the cartridge market.
First let’s consider the motivation for a firm to implement a requirements tie-in strategy. Figure 4.1 shows the typical monopoly set-up with independent printer and cartridge markets where Firm 1 is a monopolist serving the printer market, and Firm 2 is a monopolist serving the cartridge market. Firm 1 produces $Q_M$ printers at price $P_M$, and Firm 2 produces $Q_M$ cartridges at price $P_M$. Firm 1 decides to implement a requirements tie-in strategy as shown in Figure 4.2. Here we see that Firm 1 increases production of printers from $Q_M$ to $Q_T$ and the price per printer drops from $P_M$ to $P_T$, such that Firm 1 makes no profit in the printer market. But the requirements tie-in strategy results in forcing Firm 2 out of the cartridge market and pushes out the demand curve for cartridges due to the increased amount of printers Firm 1 released in the market. Firm 1 now produces $Q_T$ cartridges at price $P_T$, which is higher than the cartridge price ($P_M$) when the cartridge market was solely served by Firm 2. Firm 1’s profit in the cartridge market (as shown in Figure 4.2) is larger than when Firm 1 was not using a requirements tie-in strategy (as shown in Figure 1). The impacts to welfare under tying are ambiguous, and depend upon the distribution of low, medium and high volume printing consumers. Low and medium volume usage consumers are likely better off under tying, because they reap benefit from purchasing a printer that they would not have purchased prior to tying. But high volume consumers are likely worse off, since they pay higher than monopoly pricing for cartridges. However, society would prefer that the number of printers released to the market be reduced to where the social marginal cost ($SMC$) intersects the demand curve for printers, hence the motivation for a social planner to mandate a durable take-back requirement.
Figure 4.2 Welfare distribution when Firm 1 uses a requirements tie-in strategy. Using tying, Firm 1 is able to force Firm 2 out of the cartridge market, and Firm 1 is able to increase profits.

So now let’s look at Firm 1’s profit maximization problem when the firm uses a requirements tie-in strategy. Table 4.1 defines the variables and parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{IN}$</td>
<td>Price of a durable product in period $i$.</td>
</tr>
<tr>
<td>$q_{IN}$</td>
<td>Quantity of new durable products that last two periods produced in period $i$.</td>
</tr>
<tr>
<td>$c$</td>
<td>Cost to produce a new durable product.</td>
</tr>
<tr>
<td>$K$</td>
<td>The firm’s per printer profit from consumables used over the printer’s lifetime.</td>
</tr>
<tr>
<td>$Q_T$</td>
<td>The maximum amount of printers that can be sold per period.</td>
</tr>
<tr>
<td>$c_r$</td>
<td>Firm’s cost to recycle a durable product.</td>
</tr>
<tr>
<td>$q_{IR}$</td>
<td>Quantity of remanufactured durable products that last two periods produced in period $i$.</td>
</tr>
<tr>
<td>$s$</td>
<td>Cost savings per remanufactured durable product with $s \in [0,c)$.</td>
</tr>
</tbody>
</table>
Prior to any take-back mandate for the durable product, the firm’s profit maximization problem is:

\[
\max \pi = \sum_{i=1}^{M} \left( p_{iN} - c + K \right) q_{iN}
\]  

(4.1)

Subject to: \( q_{iN} \leq Q_T, \forall i \) and \( q_{iN} \) must be a non-negative integer \( \forall i \) periods.

As long as the profit \((K)\) from selling consumables over the printer’s lifetime is positive, and the profit from printers is non-negative, the firm will produce the maximum level of printers \((Q_T)\) in each period. From Figure 4.2, we can see that Firm 1 could take a loss in the printer market and provide printers to consumers for free. But we assume that any amount of printers beyond \(Q_T\) results in a shift of the cartridge demand curve that reduces Firm 1’s profit. We assume the firm has unlimited capacity to produce highly profitable consumables. The firm’s profit maximization under a durable product take-back requirement can take on two forms depending on whether the firm is able to remanufacture its returned durable product or required to fund the third-party firms for recycling the firm’s durable products discarded by consumers. Under collective take-back, the firm’s durable product is comingled with other durable products and is routed to recycling providers. Thus the firm’s profit maximization problem under collective take-back is:

\[
\max \pi = \sum_{i=1}^{M} \left( p_{iN} - c + K - c_r \right) q_{iN}
\]  

(4.2)

Subject to: \( q_{iN} \leq Q_T, \forall i \) and \( q_{iN} \) must be a non-negative integer \( \forall i \) periods.

If we assume that \(c_r\) is set equal to the difference between social marginal cost and private marginal cost \((SMC-PMC)\) for printers as shown in Figure 4.2, then \(c_r\) acts like a Pigouvian tax. Firm 1 would respond by reducing production of printers from \(Q_T\) to \(Q_{TC}\) as shown in Figure 4.3. This reduction in printers brought to the market per period,
results in the demand for cartridges to retract inwards from $D_T$ to $D_{TC}$ as shown in Figure 4.3.

![Diagram showing Printer Market and Cartridge Market with demand and supply curves]

**Figure 4.3** Welfare distribution when Firm 1 using a requirements tie-in strategy is made responsible for the cost of recycling its durable products (printers). Firm 1 reduces the quantity of printers brought to the market from $Q_T$ to $Q_{TC}$, and cartridge demand curve shifts inward resulting in a reduction in cartridges from $Q_T$ to $Q_{TC}$.

A product take-back requirement under the individual scheme provides each firm an opportunity to earn profit by harvesting residual value from returned durable product. In some cases, recycling may be profitable, leaving the firm with the decision to recycle or embark on remanufacturing operations that will likely require investment in product design and infrastructure [4]. For this analysis, we assume recycling is the preferred EOL treatment under the collective scheme, and remanufacturing is the preferred EOL treatment under the individual take-back scheme. With these assumptions, the firm’s profit problem under the individual scheme becomes:
\[
\max_{\{q_{IN}, q_{IR}\}} \pi = \sum_{i=1}^{M} ((p_{IN} - c)q_{IN} + (p_{IN} - c + s - c_r)q_{IR} + (q_{IN} + q_{IR})K - (q_{IN} - q_{IR})c_r) 
\] (4.3)

Subject to: 
\[ q_{IN} \leq Q_T, i = 1,2 \]
\[ q_{IN} + q_{IR} \leq Q_T, i = 3,4,\ldots,M \]
\[ q_{IR} \leq q_{(i-2)N}, i = 3,4,\ldots,M \]

and all decision variables must be non-negative integers.

Figure 4.4 Distribution of welfare when Firm 1 using a requirements tie-in strategy has an opportunity to extract value from returned EOL durable printers by remanufacturing. Cost savings from remanufacturing determine if Firm 1 can return to \( Q_T \) printer production. Environmental savings from remanufacturing determine how far \( SMC \) can be reduced in printer market.

Notice in this formulation the firm will always choose to remanufacture all returned products even when there is no cost savings from remanufacturing (i.e., \( s=0 \)). When the savings are positive (\( s>0 \)), remanufacturing is clearly more profitable than new
production. But when \( s=0 \) the firm still benefits by not having to pay to recycle returned durable product that could be remanufactured. So then the third constraint becomes

\[
q_{ir} = q_{(i-2)N}, i = 3, 4, ..., M.
\]

But \( K \) is maximized when \( Q_T \) printers are brought to the market in each period. Hence the firm is motivated to pursue remanufacturing to reduce its cost of complying with the take-back requirement in order to be able to produce \( Q_T \) printers in each period.

The social planner’s problem will take into account producer surplus described above, along with consumer surplus and environmental damage. Although determining environmental impact can be challenging, we estimate total environmental impact by considering energy usage over the durable product’s life cycle. Environmental damage is then estimated by multiplying environmental impact by an environmental cost per unit of energy. In calculating environmental impact in this way, it is necessary to know the cumulative energy demand (CED) for different life stages and the EOL treatment for the durable product as defined in Table 4.2.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e_N )</td>
<td>Energy required to manufacture a durable product</td>
</tr>
<tr>
<td>( e_u )</td>
<td>Durable product use phase energy</td>
</tr>
<tr>
<td>( e_d )</td>
<td>Energy required for durable product disposal</td>
</tr>
<tr>
<td>( e_r )</td>
<td>Energy required for durable product recycling</td>
</tr>
<tr>
<td>( e_R )</td>
<td>Energy required to remanufacture a durable product</td>
</tr>
<tr>
<td>( c_e )</td>
<td>Environmental cost per mega joule (MJ) of energy</td>
</tr>
</tbody>
</table>

The environmental damage associated with a durable product market (and tied market for use phase impact) is dependent upon the take-back mandate. Without a take-back requirement (and no durable product remanufacturing), durable products are simply
routed to disposal when consumers discard the product. Under the collective take-back scheme discarded durable products will be routed to recycling as opposed to disposal. For both schemes, we assume all discarded products are collected and ultimately recycled, but in reality take-back legislation may have collection and recycling targets less than 100%. For the individual take-back requirement, we investigate the case where discarded products can be remanufactured for another useful life and then ultimately recycled after seeing a second use cycle. Environmental damage for these three scenarios is shown in Table 4.3. If \( e_r < e_d \) then the collective scheme will result in less environmental damage; typically \( e_d \) will be positive and \( e_r \) will be negative.

<table>
<thead>
<tr>
<th>Take-back requirement</th>
<th>Environmental Damage (ED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>( c_r (e_N + e_u + e_d) \sum_{i=1}^{M} q_{IN} )</td>
</tr>
<tr>
<td>Collective</td>
<td>( c_r (e_N + e_u + e_r) \sum_{i=1}^{M} q_{IN} )</td>
</tr>
<tr>
<td>Individual</td>
<td>( c_r [(e_N + e_u) \sum_{i=1}^{M} q_{IN} + (e_R + e_u + e_r) \sum_{i=1}^{M} q_{IR} + e_r \sum_{i=1}^{M} (q_{IN} - q_{IR})] )</td>
</tr>
</tbody>
</table>

The social planner’s problem is to maximize the sum of producer surplus (\( PS \)) and consumer surplus (\( CS \)), less environmental damage (\( ED \)). If there are \( n \) firms producing durable products using a requirements tie-in strategy in a product market, then the social planner’s problem becomes:

\[
\max_{(q_{IN}, q_{IR})} \text{SW} = \sum_{i=1}^{n} PS_i + CS - ED
\]

Under the collective scheme, the social planner tries to balance reductions in \( PS \) and \( CS \) from fewer durables brought to the market with the decreased environmental
damage from fewer durables and with environmental gains from EOL handling (recycling instead of landfill). When $c_r$ and $(e_d - e_r)$ are very large, the collective scheme may be preferred to no take-back requirement. In the individual scheme, the social planner tries to balance increases in $PS$ and $CS$ from more durables brought to the market with the lower environmental damage per durable achieved by remanufacturing (assuming $e_R < e_N$) and recycling when durable reuse becomes impractical. In the individual scheme, the quantity of durable product released to the market depends on the cost savings each firm can obtain from remanufacturing operations. Whereas environmental damage per durable produced depends upon the realized environmental savings achieved from the specific remanufacturing operations of each firm.

In examining the firm’s problem under either collective take-back (Eq. (4.2)) or individual take-back (Eq. 4.3), as long as $c_r$ is not set at a level that prohibits the firm from making positive profit, the introduction of this term into Eqs. (4.2) and (4.3) is not sufficient to force the firm to abandon a tie-in sales strategy.

But if we focus on Firm 1 using requirements tie-in strategy, three questions come to mind:

1. What level of cost savings from remanufacturing enables Firm 1 to maximize profit by bringing the maximum amount of printers ($Q_T$) to the market in each period?

2. What level of environmental savings per printer from remanufacturing must be realized such that $SMC = PMC$ at $Q_T$ printer production?

3. How far could $SMC$ be lowered based on environmental savings achieved from remanufacturing?
These three questions will be examined in the next sections.

4.3 Model simulation

In this section, we introduce additional assumptions so that we can (a) simulate how the markets in Section 4.2 operate from both private and social perspectives and (b) illustrate how the product take-back requirement for the durable product (printer) may enable the firm to lower its cost of producing the durable tying product through remanufacturing and restore its profit while reducing environmental damage. Note that our version of a remanufactured product consist of both virgin and remanufactured components obtained from returned EOL printers used in the production of printers with newly introduced model numbers. This latter version would make the most sense for a firm employing tying.

Printers, like most information and communications technology (ICT), undergo rapid obsolescence. But components and modules within a printer (such as print media transport) rarely change. Typically, new features such as WI-FI capability are added to printer models just as new features are added to other ICT devices over time (e.g., cellular phones becoming smart phones). Under these market conditions, a firm forced to take-back unwanted durable printers, would best be served to reclaim the durable aspects of the printer components that can be reused in a new printer model that is paired with a new cartridge model.

In so doing, a firm is able to “lock-in” a new set of customers to a tied arrangement. Even though components from durable products may undergo several remanufacturing cycles, we assume that components retrieved from an EOL printer undergo just one remanufacturing cycle to maintain simplicity. Table 4.4 lists parameter
definitions and values used for the numerical example. We use total energy consumption to represent the environmental impact for activities used in Table 4.4 taken from Table 20 of a comprehensive study investigating imaging equipment in the European market [73]. The Stobbe report assumed an inkjet printer was used for 4 years with an annual output of 1,040 printed (A4) pages. Even though research suggests remanufacturing may theoretically achieve 85-90% energy savings compared to virgin production, many factors come into play in order to determine actual energy savings from remanufacturing that may be achieved by a firm [74]. Hence, we will look at a range of environmental savings from remanufacturing.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Damage Estimate (MJ)</th>
<th>Firm Cost Estimate ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printer Production (Virgin)</td>
<td>1437</td>
<td>10</td>
</tr>
<tr>
<td>Usage*</td>
<td>1614</td>
<td>2.50</td>
</tr>
<tr>
<td>Printer Recycling</td>
<td>-275</td>
<td>5</td>
</tr>
<tr>
<td>Printer Disposal</td>
<td>344</td>
<td>N/A</td>
</tr>
<tr>
<td>Printer Remanufacturing</td>
<td>various</td>
<td>various</td>
</tr>
</tbody>
</table>

*environmental damage includes electricity, paper and five cartridges, and firm cost reflects five cartridges with a cost of $0.50 each.

Following Figures 4.1 and 4.2, we assume the demand for printers is represented by \( P_P = 100 - Q_P \) and marginal revenue (MR) by \( P_P = 100 - 2Q_P \), where \( P_P \) is the price of a printer and \( Q_P \) is the quantity of printers. We also assume the following demand and marginal revenue functions for the cartridge market as shown in Table 4.5, where \( P_C \) is the price of a cartridge and \( Q_C \) is the quantity of cartridges.
If Firm 1 is a monopolist serving the printer market and Firm 2 is a monopolist serving the cartridge market, then each firm would set production such that marginal revenue was equal to marginal cost \((MR=MC)\). Firm 1 would produce 45 printers that sell for $55 each, providing Firm 1 a profit of $2,025. Firm 2 would produce 148 cartridges that sell for $25.33, providing Firm 2 a profit of approximately $3,675, assuming its cost to produce a cartridge is $0.50. If Firm 1 is able to use a requirements tie-in strategy and drive Firm 2 out of the cartridge market, Firm 1 would make no profit in the printer market and bring 90 printers to the market per period. Under tying, \(Q_C\) would be 450 cartridges \(((90 \text{ printers})*(5 \text{ cartridges per printer}))\). Substituting 450 cartridges into the demand function for cartridges under tying, we get \(P_C = \$70\). So then the total profit per period for Firm 1 under tying is \((450)*($70)-(0.50)* (450) = $31,275\).

Suppose the policymaker institutes a product take-back requirement in the printer market that is implemented as the collective scheme. A collective product take-back would divert discarded printers from the municipal waste stream and make the manufacturer responsible for the cost of recycling discarded printers. If the cost of recycling printers is equal to the social marginal cost less the private marginal cost \((SMC-\)

---

**Table 4.5 Cartridge demand and marginal revenue**

<table>
<thead>
<tr>
<th>Case</th>
<th>Cartridge Demand</th>
<th>Cartridge Marginal Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monopoly</td>
<td>(P_C = 50 - \frac{50}{300} Q_C)</td>
<td>(P_C = 50 - \frac{50}{150} Q_C)</td>
</tr>
<tr>
<td>Tying, No Take-back</td>
<td>(P_C = 140 - \frac{140}{900} Q_C)</td>
<td>(P_C = 140 - \frac{140}{500} Q_C)</td>
</tr>
<tr>
<td>Tying, Collective Take-back</td>
<td>(P_C = 100 - \frac{100}{650} Q_C)</td>
<td>(P_C = 100 - \frac{100}{350} Q_C)</td>
</tr>
</tbody>
</table>
Then the collective take-back requirement acts like a Pigouvian tax. In response to the collective take-back requirement, Firm 1’s private marginal cost would become the same as the social marginal cost, namely $15 in our example. Firm 1 would decrease its production of printers from 90 to 85 printers per period, and the reduced level of printers would shift the demand for cartridges inward per Table 4. Firm 1 would still earn zero profit in the printer market, but now its profit in the cartridge market becomes $(425)\times(34.62)-(0.50)\times(425) = 14,501$.

But now let’s consider if the product take-back requirement is implemented as an individual scheme, enabling Firm 1 to extract value from returned printers discarded by consumers. What cost savings from remanufacturing must be attained to enable Firm 1 to return to its previous profitability level prior to the durable product take-back requirement? In order to answer this question, we refer to Table 4.6 that shows 10 periods of Firm 1’s activity when it can remanufacture its durable printers which last two periods, one time as indicated in maximization problem Eq. (4.3). Setting revenue equal to costs and solving for $RC$ (per printer remanufacturing cost), we get $RC=2.5$. Hence, if Firm 1 is able to achieve a remanufacturing cost of $2.5$ per printer, Firm 1 can restore its profit level it had prior to the take-back requirement. Cost savings from remanufacturing discarded printers allow the firm to cover the cost of recycling printers that can no longer be remanufactured and ensure no printers are routed to the waste stream. Prior to the product take-back mandate, unwanted printers were just routed to the municipal waste stream since the product tying strategy of low durable pricing discourage the development of a secondhand market for the durable products.

Essentially, the take-back requirement may benefit a firm that can reuse EOL product to
lower production costs by more than product collection costs [6]. Table 4.7 summarizes the economic welfare performance for each take-back scenario.

### Table 4.6 Firm production under durable product take-back with remanufacturing

<table>
<thead>
<tr>
<th>Period</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin</td>
<td>90</td>
<td>90</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>90</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Returned</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>EOL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Remanufactured</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>90</td>
<td>-</td>
<td>90</td>
<td>90</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Revenue ($)</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>Virgin Production Costs ($)</td>
<td>900</td>
<td>900</td>
<td>-</td>
<td>-</td>
<td>900</td>
<td>900</td>
<td>-</td>
<td>-</td>
<td>900</td>
<td>900</td>
</tr>
<tr>
<td>Remanufacturing Costs ($)</td>
<td>-</td>
<td>-</td>
<td>90RC</td>
<td>90RC</td>
<td>-</td>
<td>-</td>
<td>90RC</td>
<td>90RC</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Recycling Costs ($)</td>
<td>-</td>
<td>-</td>
<td>450</td>
<td>450</td>
<td>900</td>
<td>900</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.7 Economic welfare for each product take-back scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Market</th>
<th>Profit</th>
<th>Consumer Surplus</th>
<th>Economic Welfare</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Take-back</td>
<td>Printer -</td>
<td>$4,050</td>
<td>$51,075</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cartridge $31,275</td>
<td>$15,750</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collective Take-back</td>
<td>Printer -</td>
<td>$3,612.5</td>
<td>$32,007</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cartridge $14,501</td>
<td>$13,893.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Individual Take-back with Remanufacturing*</td>
<td>Printer -</td>
<td>$4,050</td>
<td>$51,075</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cartridge $31,275</td>
<td>$15,750</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*when cost to remanufacture is $2.5 per printer

However, as stated previously, remanufacturing often yields environmental savings. In Chapter 2 we learned that remanufacturing of inkjet cartridges provided environmental savings of 20% to 60% based on variability in spent cartridge travel distance, spent cartridge quality and remanufacturer efficiency. Using the values listed in Table 4.4, we can calculate environmental damage as shown in Table 4.8. The collective
product take-back scheme has the desired effect of reducing environmental damage in two ways. First, discarded EOL printers are diverted from the waste stream and get recycled, providing an energy credit. Second, shifting landfill costs associated with EOL printers to the printer manufacturer and requiring the printer firm to incur recycling costs forces the printer firm to reduce the number of printers brought to the market, in turn reducing consumption of ink cartridges. The individual product take-back scheme that has the printer firm initiating environmentally desirable remanufacturing operations enabled by the product take-back law, leads to a further reduction in environmental damage than the collective scheme, when remanufacturing provides an environmental savings ($e_N - e_R$) of 50% compared to virgin printer production. Environmental harm per printer in the printer market is decreased due to the environmental benefits from remanufacturing.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Printer Production (MJ)</th>
<th>Cartridge Consumption (MJ)</th>
<th>Printer EOL (MJ)</th>
<th>Total Damage (MJ)</th>
<th>Damage per Printer (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Printer Take-back</td>
<td>90*1437</td>
<td>90*1614</td>
<td>90*344</td>
<td>305,550</td>
<td>3395</td>
</tr>
<tr>
<td>Collective Take-back</td>
<td>85*1437</td>
<td>85*1614</td>
<td>85*(-275)</td>
<td>235,960</td>
<td>2776</td>
</tr>
<tr>
<td>Individual Take-back*</td>
<td>(54<em>1437) + (36</em>719)</td>
<td>90*1614</td>
<td>54*(-275)</td>
<td>233,892</td>
<td>2598.8</td>
</tr>
</tbody>
</table>

*when remanufacturing provides a 50% environmental savings using data from Table 4.4

Stobbe estimated that the average installed base for inkjet printers in the EU-25 countries was 105,614,549 units [73] in 2010. If the environmental damage of each printer including usage is 3,395 MJ, then the calculated environmental damage is 8.57
Mtoe (Million Tonnes of Oil Equivalent). According to the International Energy Agency [75], the entire energy consumption for the EU-25 in 2009 was approximately 1200 Mtoe. Although energy consumption related to inkjet printers is only 0.7% of total energy consumption, considering an inkjet printer represents just one of many products consumed in EU-25 countries, this finding is far from trivial. If we extrapolate our findings from our numerical example and consider the impacts of a take-back law (individual versus collective) for the estimated 25,056,622 printer placements for 2010, we would have the results shown in Table 4.9.

**Table 4.9** Environmental damage calculations using printer placements in 2010 for EU-25 for each product take-back scenario when remanufacturing provides a 50% environmental savings compared to virgin printer production

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Printer Production (MJ)</th>
<th>Cartridge Consumption (MJ)</th>
<th>Printer EOL Treatment (MJ)</th>
<th>Total Damage (MJ)</th>
<th>Damage per Printer (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Printer Take-back</td>
<td>25,056,622*1437 =3.6x10^10</td>
<td>25,056,622*1614 =4.0x10^10</td>
<td>25,056,622*344 =8.62x10^9</td>
<td>8.56x10^10</td>
<td>3395</td>
</tr>
<tr>
<td>Collective Take-back</td>
<td>23,664,587*1437 =3.4x10^10</td>
<td>23,664,587*1614 =3.82x10^10</td>
<td>23,664,587*(-275) =-6.51x10^9</td>
<td>6.57x10^10</td>
<td>2776</td>
</tr>
<tr>
<td>Individual Take-back</td>
<td>30,819,645*[0.6<em>1437 + (0.4</em>719)] =3.54x10^10</td>
<td>30,819,645*1614 =4.97x10^10</td>
<td>18,491,787*(-275) =-5.08x10^9</td>
<td>8.01x10^10</td>
<td>2598.8</td>
</tr>
</tbody>
</table>

From Table 4.9, we can see the economic and environmental trade-offs are quite different depending on which take-back scheme is implemented. In the collective scheme, energy associated with printer production and use is reduced by 1.99 x10^10 MJ, but 1,392,035 printer placements that are desired by consumers do not occur because the
producers reduce printer output as a consequence of absorbing EOL collection and recycling costs. Whereas, in the individual take-back scheme with remanufacturing, energy associated with printer production and use is reduced by $0.55 \times 10^{10}$ MJ, while servicing the same number of consumers as when there is not a take-back requirement. The difference in the number of printer placements is easy to envision, but it may not be so apparent for energy differences without a frame of reference. To bring some perspective regarding energy, the United States Energy Information Administration [76] estimated that the average annual electricity consumption for a U.S. residential utility customer was 11,496 kWh (41,385.6 MJ) in 2010. Using this value, the collective take-back scheme would save the energy consumed by 480,843 U.S. homes, and the individual take-back scheme would save the energy consumed by 132,896 U.S. homes annually.

4.4 Sensitivity analysis

The previous section was based on the assumption that remanufacturing provided a 50% environmental savings compared to virgin production for the durable product (printer). Although this assumption is within reason [39, 74], broadening this assumption allows us to explore boundary conditions and determine if our general results still hold. Specifically, increasing environmental savings from remanufacturing allows us to explore how low $SMC$ can become in the printer market.

From Table 4.4 we see that the majority of the environmental damage in our case study comes from the durable production and disposal phases (1781 MJ) compared to the use phase (1614 MJ) prior to a take-back requirement. However, under either durable take-back scheme that ultimately requires discarded durable products be recycled, the use
phase now becomes the dominant contributor of environment damage (1614 MJ vs. 1162 MJ). Using the formulas for environmental damage for each take-back scenario from Table 4.3, and using a modest value for $c_e$ of $0.01, we can calculate social welfare for each take scenario as shown in Table 4.10.

**Table 4.10** Economic and environmental performance for each take-back scenario, showing social welfare range based upon environmental savings from remanufacturing under individual take-back

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Economic Welfare</th>
<th>Environmental Damage ($c_e=0.01$)</th>
<th>Social Welfare</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Take-back</td>
<td>$51,075$</td>
<td>$3,055$</td>
<td>$48,020$</td>
</tr>
<tr>
<td>Collective Take-back</td>
<td>$32,007$</td>
<td>$2,360$</td>
<td>$29,647$</td>
</tr>
<tr>
<td>Individual Take-back with Remanufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Providing No Environmental Savings</td>
<td>$51,075$</td>
<td>$2,597$</td>
<td>$48,478$</td>
</tr>
<tr>
<td>Individual Take-back with Remanufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Providing 50% Environmental Savings</td>
<td>$51,075$</td>
<td>$2,339$</td>
<td>$48,736$</td>
</tr>
<tr>
<td>Individual Take-back with Remanufacturing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Providing 90% Environmental Savings</td>
<td>$51,075$</td>
<td>$2,132$</td>
<td>$48,943$</td>
</tr>
</tbody>
</table>

Notice that there is an increase in social welfare under individual take-back versus the no take-back scenario even when remanufacturing provides no environmental savings. This occurs because the durable product take-back law requires discarded product be (eventually) routed to environmentally preferred EOL fates (e.g., recycling) with lower environmental damage compared to disposal (e.g., landfill) as is the case when no take-back law is in place.
4.5 Conclusion and directions for future research

This paper examined the social welfare effects of an extended producer responsibility (EPR) product take-back requirement for a durable product when a firm uses a requirement tie-in sales strategy. We found that the economic and environmental trade-offs were dependent upon whether the durable product take-back was implemented with a collective scheme (promoting recycling of durables) or an individual scheme (enabling each producer to determine how best to use returned EOL durables). For the latter implementation, we specifically considered what would happen if the durable producer implemented remanufacturing operations, often touted as being preferred over recycling from an environmental perspective. We found that the collective scheme reduced environmental damage, but also produced the lowest welfare of the alternatives. The individual scheme with remanufacturing (assuming remanufacturing offered an environmental benefit) resulted in reductions in environmental damage that varied based upon environmental savings achieved from remanufacturing, while increasing welfare. These findings are worth further exploration.

If policymakers intended for the product take-back law to reduce environmental damage in the durable product market, then the collective take-back scheme gives this result, but also reduces welfare from fewer durables (printers) brought to the market. Whereas, if policymakers intended for the product take-back law to reduce environmental damage on a per durable product (printer) basis, we see individual take-back can meet this objective when the firm implements remanufacturing while welfare increases. Since consumers realize benefit from using durables (printers), the consumer surplus gains are predominantly seen in the tied consumables market. Of course, these findings assume
that consumer demand remains unchanged and producers are not influenced by the product take-back law other than the producer implementing remanufacturing operations or incurring recycling costs. But, it seems unlikely that a firm forced to comply with a collective take-back law would not respond to try to maintain or exploit an opportunity to increase its profits. It is not possible to envision all these responses, and subsequent reactions of competing firms and consumers. However, one such producer response may be for the producer to raise the price of ink cartridges to try to recoup recycling costs incurred in the printer market from collective take-back. Although this may result in consumers printing less, let’s assume the printer producer is clever in disguising the price increase of ink cartridges by launching a lower yield (and lower priced) ink cartridge. A lower yield cartridge that effectively raises the price of ink, may lead to an increase in environmental harm even if consumers respond as expected and purchase fewer ink cartridges. How could this be? A reduction in ink per cartridge will result in an increase in environmental impact on a printed page basis [77]. The net change to environmental impact in the consumables market will increase if the per page impact contribution exceeds the reduction in environmental impact from printing less. If consumers purchase cartridges one at a time, lower yield ink cartridges may lead to more environmental harm from an increase in driving trips to the store by consumers to purchase cartridges holding printed output constant as demonstrated in Chapter 2.

It is clear that the introduction of a take-back law, regardless of whether it is collective or individual, will result in changes to the system dynamics of the durable and tied consumables markets when a requirements tie-in strategy is in place. What is unclear is whether the resulting system spanning these two product markets will lead to a
net gain or net loss to welfare and environmental impact metrics over the long run. This paper considered only the likely responses of reducing durable output by a producer in the collective take-back scheme, and reuse of returned durable product by a producer under the individual take-back scheme. Under these terms, we demonstrate that individual take-back with the tying monopolist remanufacturing can restore economic efficiency and provide environmental benefits, resulting in a net increase in social welfare. Future work could use real world data to examine markets prior to any take-back legislation with markets that use a collective scheme and markets with an individual scheme to see how producer and consumer responses to take-back beyond those analyzed here, have affected economic and environmental performance.

We presented a framework to include the cost of environmental damage in calculating social welfare, but we did not delve into what the cost to the environment per unit of energy should be. Further research could estimate this value for different products and different circumstances. When the cost to the environment is low and environmental savings from remanufacturing are low, then maybe the social planner would opt to recommend a collective scheme. But for products where the cost to the environment is relatively high and environmental savings from remanufacturing are high, the social planner may pursue an individual take-back scheme.
V. CONCLUSION

This dissertation emphasized the importance of using a product system structure to describe the interaction dynamics amongst actors with a product market in order to project the economic and environmental effects of an intervention anticipated to provide environmental improvement. Specifically, in Chapter 2 we demonstrated that there are opportunities to provide environmental improvement in how consumers go about purchasing products without affecting the quantity or type of product purchased. Information that results from scientific analysis is an intervention that maintains the product system structure, without inducing government or producers to respond in a manner that may undo environmental gains.

Chapter 3 explored the opportunity for government to fine tune the existing intellectual property rights (IPR) system to encourage firms to reduce physical attributes introduced in products to deter independent firms from remanufacturing the OM’s product in exchange for more intellectual property right protection. In particular, we show that it is possible for the firm to maintain profitability, while social welfare increases from more remanufacturing. Chapter 4 examines the case where a new policy, durable product take-back, can have a wide range of economic and environmental effects across both durable and tied consumable markets. In the case study we examined, the individual responsibility scheme enables the OMs to salvage value from durable printers that they were not able to recover prior to the take-back requirement. We show that cost savings and environmental savings that can be achieved from remanufacturing can enable a firm using product tying to maintain profitability levels prior to the take-back requirement, and improve social welfare. Social welfare gains occur from reductions in
environmental damage in two ways, (1) remanufacturing reduces virgin production and (2) the take-back law ensures EOL durable products are recycled versus landfilled when there is not a take-back law.

This dissertation stressed the importance of ensuring modelers have an awareness of the interaction dynamics amongst actors within a product system so that any intervention attempt aimed at providing a desired effect (such as environmental improvement) can be evaluated, while identifying possible unanticipated effects. A general framework is proposed and demonstrated to provide guidance in this regard, but there are many opportunities to improve the approach. The framework does not specify how to determine and classify interactions amongst actors, nor does it identify which interactions to include in the model and which to ignore. Similarly, the framework does not specify which product markets to consider in a product system structure in order to identify how an intervention in one product market may impact another product market. These judgments are left to the modeler, and each decision should be justified from real-world observations, market data and relevant literature. Future work could include criteria in the proposed modeling framework to help modelers make these decisions. Although the inclusion of both printer and cartridge markets proved to add complexity to the analysis, the tie-in sales strategy in use dictated that both markets needed to be included in our product system structure.
Appendix: Previous LCA Literature for Print Cartridges

A LCA study of a Hewlett-Packard inkjet cartridge conducted by Pollock and Coulon in 1996 provided an environmental impact baseline across five life cycle stages identified as Print head Manufacturing, Final Assembly, Distribution, Use and End-Of-Life (EOL)[12]. The functional unit chosen for the study was 100 monochrome single-sided printed pages, which represented approximately 15% of the cartridge expected page yield. The results of the study were used by Hewlett-Packard to prioritize and evaluate alternatives the company could take to reduce the environmental impact of an inkjet cartridge. Their baseline results indicated that 85% of the environmental impact of an inkjet cartridge was associated with the Production stage for Global Warming Potential (GWP) as seen in Table 2.1. The Production stage in the Pollock and Coulon study is the sum of two life cycle stages; Print head Manufacturing representing 41% GWP impact and the Final Assembly stage representing 44% GWP impact. The Distribution stage contributed 13% GWP impact, followed by the EOL stage with 2% GWP impact, which assumed the inkjet cartridge was routed to a landfill and incineration with some energy recovery. Interestingly, the Use phase represented a negligible impact (0% GWP) since Pollock and Coulon only considered the energy used by the printer in printing the functional unit and did not include the impact of paper. Under these assumptions, “usage impacts due to printing energy were found to be very small and are not shown in Fig. 3” [12]. Actual values were not given for GWP by life cycle stage in the Pollock and Coulon study, the percentages presented in Table 2.1 are extracted from Pollock and Coulon’s Figure 3 [12]. Pollock and Coulon considered the impact of paper and electricity consumed while the printer was idle over a one week period of time and
compared the impacts to the baseline inkjet life cycle impact. They found the impact of paper represented approximately 21.5 times the total inkjet baseline GWP impact and printer electricity consumed over one week represented approximately 2.25 times the total inkjet baseline GWP impact.

In a 2002 laser cartridge LCA, Berglind and Eriksson considered three new HP C4127X cartridges versus one new HP C4127X cartridge with two remanufacturing cycles[13]. Their study assumed the quality of a remanufactured cartridge was the same as a new one, in both page yield and printed output quality. Paper used during a use cycle was 10,000 A4 pages with 5% coverage for both a new cartridge use stage and a remanufactured cartridge use stage. Their study presented comparative results with and without paper, but did not break the results down by life cycle stages. Remanufacturing outperformed new cartridges by approximately 13% in Global Warming Potential (GWP) (93.1 kg CO2e for new vs. 82.1 kg CO2e remanufactured) considering paper impacts and 63% reduction (28.6 kg CO2e for new vs. 17.6 kg CO2e remanufactured) without considering the impacts of paper. The environmental impact of paper was responsible for 41.5% of the energy consumed for three new cartridges and 50% of the energy consumed for the remanufactured case. Table 2.1 reflects these impacts normalized to one life cycle to be consistent with other studies. This study considered idle and standby energy consumed by the printer over the estimated four month use stage within a cartridge life cycle in Europe. Interestingly, the electricity required to print 10,000 pages for one cartridge life cycle required less than 5% (4.9%) of the electricity consumed during the use stage, indicating that idle and standby electricity consumed by the printer over the expected cartridge use cycle duration is significant.
Table A.1 Cartridge performance factors considered in determining use phase impacts in First Environment Inc.[14] LCA study

<table>
<thead>
<tr>
<th></th>
<th>HP C4096A</th>
<th>Rem-Baseline</th>
<th>Rem - Drill &amp; Fill</th>
<th>Rem - Int'l Oper.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed Page Yield</td>
<td>2,960</td>
<td>2,741</td>
<td>2,283</td>
<td>2,428</td>
</tr>
<tr>
<td>Usable Pages</td>
<td>2,387</td>
<td>2,490</td>
<td>1,878</td>
<td>2,285</td>
</tr>
<tr>
<td>Unusable Pages</td>
<td>123</td>
<td>251</td>
<td>405</td>
<td>143</td>
</tr>
</tbody>
</table>

In 2004, First Environment issued a report of their findings of a comparative LCA study where one HP C4096A (“96A”) cartridge was compared with three scenarios of an HP 96A remanufactured cartridge [14]. The three scenarios considered were 1) a baseline remanufacturing cycle assumed to be representative of the remanufacturing industry in North America, 2) an international remanufactured cartridge with improved quality and reliability than the baseline version, and 3) a “drill and fill” operation where an empty OEM cartridge is just drilled in order to remove residual and waste toner in the cartridge and then filled with replacement toner. The functional unit for this study was 100 “usable” single-sided monochrome pages printed even though the cartridge has a rated yield of 5,000 pages. A usable page is defined as one which “may have a minor flaw such as a speck or uneven graphic rendering but the average user would still use it in a typical business document” or “has no apparent artefacts with the identifying rule of thumb being that a user would put this page in his or her resume” as defined in a 2003 study conducted by Quality Logic [14, 78].

The introduction of the adjective “usable” in the functional unit definition is an attempt to capture differences in performance across the cartridge scenarios considered. The authors argue that in order to accomplish a fair comparison across each cartridge scenario, the performance of a cartridge must be taken into account. In this study,
performance is represented by two dimensions, quantity of pages printed and quality of pages printed. Quantity of pages printed pertains to the number of pages printed (i.e. page yield) and quality is a subjective measurement (i.e. usability) of each page printed. However, the incorporation of these measures into the use stage affects paper usage, and since paper is the largest contributor to life cycle environmental impact; these factors strongly influence cartridge comparison results.

Page yield used in this study is based upon results reported in the 2003 Quality Logic study, where page yield is determined by averaging the observed page yield for each cartridge scenario [78]. Remanufactured cartridges will have different toner properties than new OEM cartridges and variations in the amount of toner supplied by each producer; both factors will affect the rated yield (i.e. the expected number of pages printed at 5% toner coverage) of the cartridge. The average observed page yield measure effectively captures higher yield opportunities from remanufactured cartridges as well as cartridge reliability. Premature cartridge failure will reduce the number of pages printed for the sample, and thus reduce the average observed pages printed. Table A.1 summarizes the average observed page yield, unusable pages and usable pages printed for each cartridge scenario considered in the 2004 LCA comparison study [14]. In the 2003 Quality Logic performance study, some remanufactured cartridges prematurely failed while none of the 50 new OEM cartridges prematurely failed.

The use stage GWP impact value by cartridge scenario from Table 1 correlates with the number of unusable pages printed in Table A.1. That is, as the number of unusable pages printed by cartridge type increases so does GWP impact associated with the use stage of the cartridge life cycle. In this study, the results were highly sensitive to
cartridge performance. Environmental impact savings attributed to remanufacturing would be undercut by increased impacts during a remanufactured cartridge’s use stage if the remanufactured cartridge prematurely failed, or had a large ratio of unusable to usable pages printed compare with a new OEM cartridge. This study also just considered the energy required by the printer to print 100 usable pages, whereas Berglind and Ericksson (2002) considered idle and standby power of the printer over the typical four month timeframe the cartridge was used which represented more than 95% of the electricity consumed during the use stage. Another interesting result from this study pertains to the environmental impact associated with EOL treatment. In the OEM case, the assumption that the metals within the cartridge are recycled and the balance of the materials go to waste-to-energy represent a 20% credit in environmental impact, whereas EOL treatments for the three remanufactured versions provide a modest credit ranging from 1% to 8% of the life cycle.

In 2008, Four Elements Consulting, LLC issued a refreshed version of the 2004 study performed by First Environment, Inc., but used updated assumptions consistent with the European cartridge market[14]. However, as opposed to considering three different remanufactured cartridge alternatives, this study considered one baseline remanufactured alternative, with sensitivity analysis on component replacement rate, transportation distance, percentage of cartridges collected that are unsuitable for remanufacturing, distribution distance, number of pages printed, and EOL treatment. Similar to the 2004 study results, the use stage dominated the environmental impact, and represented 90% of the environmental impact in GWP for an OEM cartridge and 96% of the environmental impact in GWP for the remanufactured cartridge as seen in Table 1.
The use phase for a remanufactured cartridge contributed 0.835 kg CO2 eq compared with 0.72 kg CO2 eq for a new OEM cartridge. The reason for this difference is attributed to the number of pages printed during the use cycle to achieve the functional unit of 100 usable pages. The new OEM cartridge required 101 pages printed, while the remanufactured cartridge required 117 pages printed to achieve 100 usable pages.

In 2011, Gutowski et al considered the energy savings that may be achieved from remanufacturing for a variety of products, including laser cartridges [8]. In this article, the authors used the 2008 Four Elements Consulting, LLC study as the primary basis for their analysis, but made two assumptions in favor of remanufacturing. The two assumptions were: 1) end-of-life (EOL) treatment for a remanufactured laser cartridge was the same as EOL treatment for a new cartridge returned to the OEM after end-of-first-life (EOFL), and 2) the remanufactured cartridge performed as a new OEM cartridge. Gutowski et al determined that under these assumptions, a remanufactured laser cartridge would provide a 6% energy savings compared to a new OEM cartridge.
References


