Springer Series in Supply Chain Management

Atalay Atasu *Editor*

Environmentally Responsible Supply Chains

Springer

Springer Series in Supply Chain Management

Volume 3

Series Editor
Christopher S. Tang
University of California
Los Angeles, CA, USA

More information about this series at http://www.springer.com/series/13081

Atalay Atasu
Editor

Environmentally Responsible Supply Chains

Springer

Editor
Atalay Atasu
Scheller College of Business
Georgia Institute of Technology
Atlanta, GA, USA

ISSN 2365-6395 ISSN 2365-6409 (electronic)
Springer Series in Supply Chain Management
ISBN 978-3-319-30092-4 ISBN 978-3-319-30094-8 (eBook)
DOI 10.1007/978-3-319-30094-8

Library of Congress Control Number: 2016937410

Printed on acid-free paper

This Springer imprint is published by Springer Nature
The registered company is Springer International Publishing AG Switzerland

Foreword

This book is very timely considering that sustainability concerns increasingly take centre stage in business and society and perhaps even government. It certainly fills a gap in literature from a scientific as well as an educational perspective, especially since it takes a broad view and offers many new angles on this broad subject. Clearly, the recent COP21 in Paris has renewed interest in climate change actions and their impact on business. Similarly, the European Union is big on pushing its circular economy agenda and ready to direct a lot of money that way. Business has no option but to carefully consider how this new paradigm poses challenges and offers opportunities. For this, it may need support from research as well as education, for there will be difficult problems to solve and this will require well-trained people.

At a global level, one could state that this is the time to shape the society we want to live in the future. This society will be situated in a complex world where resource scarcity, costly externalities, climate change, and many other aspects like poverty, exclusion, and resulting conflicts will create a dynamic context. Within this context, the society needs to reunite policy making (legislation, governance, enforcement) with the public (consumer behaviour, priorities, and aspirations) and business. These three entities mutually influence one another and need to be kept in balance. This is not a simple task given the gaps between business, government, and the public have grown in recent times. Technological progress (e.g. robots, social media, and the Internet of things) greatly impacts this delicate balance, to be re-established for a sustainable future where nine billion people will not consume several times the resources available to mother earth and where there will be a better equity between the haves and have-nots.

Obviously one book cannot solve these complex issues at once, but this one does tackle some of its important components and allows for a nice introduction and basis for further study or analysis. There are several things I particularly like about this book:

First, it is based on brand new research in several disciplines, a lot of which is still to appear in print in academic journals. Many contributions are written by young people who are the ones to shape our future world. So this book is “fresh” and refreshing in many ways.

Second, the book carefully considers different perspectives and business stances. It discusses pure for profit, seeing the business opportunities, perspective, as well as the compliance to legislation angle. Few publications acknowledge both sides of the coin. Business can be in the driver’s seat but so can policy makers. Mostly they strongly influence one another in what we would call a complex dynamic system with feedbacks and feed forwards, influenced by the public and its changing behaviours, as well as by technological breakthroughs.

Third, the book takes a very comprehensive supply chain view of environmental impact and responsibility. Given that supply chain management is my favourite topic, I certainly welcome this. The book contains recent and refreshing work on closed-loop supply chains (another pet subject of mine), remanufacturing (finally becoming mainstream in the circular economy movement), network design, inventory control, and product design and capacity management, among others. In short, it takes a broad system perspective instead of focusing unilaterally on a single issue. This is exemplified by the book’s treatment of problems in the context of broad impacts on tomorrow’s supply chains, or better supply networks, by including issues like climate change, consumer behaviour, environmental regulations, more careful recycling, and responsible sourcing, to mention just a few. Seeing the many sides of this complex coin is a great asset.

Fourth, this book is targeted at a broad audience. Sure, some chapters are rather technical in nature, but then again some adepts of the new trends like the circular economy would be well-advised to make themselves familiar with some technical knowledge to better support their righteous claims with scientific evidence from different disciplines. This book makes this possible since many chapters are organized such that they can be read by both academics and practitioners, and appeal to both. As such, this book can be a good introduction for novices to the field as well as a source for deepening knowledge for an expert in a subfield. We need all interested people, academics and practitioners, experts and laymen, technical and social/legal, to create a common understanding of the complex issues in sustainability.

While four is not a magic number in most cultures (better to have 3 or 7), I nevertheless hope that these four reasons why I like the book have convinced you to take a serious look at it. Above all things, the book is timely and fills an important gap.

Luk N. Van Wassenhove
Henry Ford Professor of Manufacturing
INSEAD
Fellow of POM, M&SOM, EurOMA, and EURO Gold Medallist
Past President of POMS

Preface

Environmental responsibility is increasingly perceived as a necessary component of a firm's business strategy. Be it driven by market pressure (e.g. via consumer or NGO demands) or from a resource economics perspective (e.g. in reference to a circular economy), identifying an environmentally responsible business strategy is crucial for any firm today.

This book aims to highlight what it takes to be successful in identifying and executing environmental responsibility from an operational perspective. Written by academic experts, using language that speaks to practice, this reference book provides cutting-edge research from globally recognized field experts. It is a useful resource for practitioners to explore why and how firms engage in environmentally responsible operations. It is also a valuable resource for academics as an introductory reference that provides direct exposure to key environmental operational problems faced by many firms today. In addition, it can be used as an introductory reading for students with varying educational backgrounds—from business school students interested in environmental issues to environmental scientists interested in obtaining a business perspective—as it provides a broad scope of key issues at the interface of operations management and environmental and social responsibility.

Structured in a modular fashion, each chapter in this book introduces and analyses a specific timely topic, allowing readers to identify the chapters that relate to their interests. More specifically, the book distinguishes between two key drivers of environmentally responsibility: profit and regulatory compliance.

The first three sections of the book explore profit-driven environmental responsibility—and provide examples as to where the motives for environmentally responsible business practices come from, where business opportunities are, and what operational perspectives are key to profitability.

In the first chapter of the book, James Abbey and Dan Guide focus on motives for environmentally responsible business in the context of remanufacturing, a product-life extension strategy. They explore consumer markets for remanufactured products and provide a number of new insights as to how and when consumers value remanufactured products. The insights from this chapter can help a consumer goods manufacturer that considers remanufacturing as to when and how it can position remanufacturing as an environmentally responsible business practice and, most importantly, where the profit opportunities are. In the second chapter, Necati Tereyagoglu builds on Abbey and Guide's research and focuses particularly on drivers of consumer valuation for remanufactured products in traditional and online markets. He investigates the effects of seller reputation, warranties, and money-back guarantees on consumer perceptions of remanufactured products and whether these perceptions affect consumers' valuations of new products. This chapter nicely illustrates that the bottom line profit potential of the assumed environmental benefits of remanufacturing may not be straightforward. Finally, Karen Zheng, Leon Valdes, and Tim Kraft extend the scope of how markets or consumers perceive environmental responsibility practices from the context of remanufacturing to a general social responsibility environment and show once again that the market reaction to responsible business practices is not straightforward. Overall, these three chapters nicely illustrate the need for exploring and identifying the profit-driven motives for social or environmental responsibility.

The second section focuses on examples of for-profit opportunities from environmentally responsible business. Deishin Lee starts the section with a chapter that introduces the concept of by-productsynergies, an opportunity to gain improved economic and environmental benefits through a joint production model that leverages economies of scope. She presents this concept as an opportunity to effectively use natural resources while simultaneously reducing waste and explores its economic and environmental implications. In the next chapter, Vishal Agrawal teams up with Deishin Lee to explore opportunities from (environmentally or socially) responsible-sourcing and provide an overview of possible responsible-sourcing challenges faced by firms and the mechanisms firms can use to overcome these challenges. In the third chapter, Paolo Letizia takes a deeper dive into the implications of supply chain structure on the feasibility of and opportunities from responsible sourcing and illustrates by examples if and how collaboration between different supply chain partners can be sustained. Finally, Vishal Agrawal and Ioannis Bellos highlight the potential of servicizing (e.g. selling services as opposed to products) as an environmentally responsible business strategy and identify conditions where it can create a win-win solution both from economic and environmental perspectives.

The third section of the book continues to consider environmental responsibility in a non-regulated system with particular focus on operational variables such as inventory, capacity, and network design choices. Ashish Kabra, Elena Belavina, and Karan Girotra analyse network design and inventory location choice problems in a bicycle-sharing system; the social and environmental benefits of which as a public transportation mechanism are clear. They identify the unique characteristics of a bicycle-sharing system as it differs from traditional public transportation models and illustrate the operational/infrastructural variables that can help maximize the environmental benefits of bicycle-sharing. Michael Lim and Yanfeng Ouyang, on the other hand, focus on how one can design a biofuel network/supply chain that can help improve the environmental benefits associated with replacing traditional fuels with biofuels. They explore and illustrate core trade-offs in this context and discuss key issues around logistics network optimization, transportation, inventory management, and land use. Finally, Mark Ferguson, Shanshan Hu, Gil Souza, and Wenbin Wang discuss a firm's capacity investment decision in renewable energy technologies. They focus on factors that complicate this decision, such as variability in energy demand and prices, and show that the trade-offs in this decisions can be resolved by solutions that are simple to compute and intuitive, which allows them to provide managers with a framework for evaluating the trade-offs of investing in renewable and conventional technologies. Overall, this chapter provides three excellent examples of why an operational outlook should be a key component in environmentally responsible business.

The last two sections of the book focus on regulation as a driver of environmental responsibility and identify motives, opportunities, or operational perspectives as to effective regulatory compliance.

The first chapter in the penultimate section (by Douglas Webber, Luk Van Wassenhove, and I) argues that environmental legislation will be in most firms' radars in today's economy and suggests ways to cope with potential upcoming legislation. In particular, the chapter suggests and exemplifies firm strategies that involve raising awareness and political competence development (e.g. having a strong lobbying presence) in order to shape the environmental legislation before it is written, as opposed to being reactive to it. In the next chapter, David Drake and Robin Just provide a complementary perspective and discuss a number of reactive strategies that firms can use to respond to environmental regulation. Essentially, these two chapters provide a roadmap for firms to take a competitive edge when facing environmental regulation as a threat or a reality. In the next chapter, Basak Kalkanci, Erjie Ang, and Erica Plambeck analyse how firms could respond to environmental or social impact disclosure mandates, considering their impact on investor valuation of the firm and consumer valuation of the firm's products or services. They suggest that mandated disclosure may discourage a firm from investigating or identifying the social and environmental impacts of its supply chain. Demonstrated by consumer experiments, they show that a voluntary disclosure (instead of a mandated one) can be beneficial for the firm as it can help improve a firm's valuation by its consumers or investors. In the final chapter of this section, Gokce Esenduran and I analyse the implications of an economic value added from environmental compliance in a regulated market. In particular, we use the example of electronics take-back regulation and show how environmental regulation targeted at potentially valuable electronic waste can lead to a distorted competitive landscape and how firms can leverage regulation in the presence of competition. Overall, this chapter exemplifies a number of ways environmental regulation affects supply chain efficiency or firm profitability and suggests ways to deal with such concerns from a supply chain, firm, or social planner perspective.

The final section in the book focuses on how firms should design their supply chains or products to cope with environmental regulation, particularly focusing on the impacts of climate change, substance control, and take-back policies. In the first chapter of the section, Nur Sunar provides a comprehensive perspective on how emissions regulation works around the globe and discusses a series of emissions control challenges for firms (be it driven by regulation or voluntary efforts). The chapter also leverages a number of existing research papers to demonstrate supply chain, firm, or social planner level strategies to maximize the efficiency of emissions regulation from economic or environmental perspectives. In the next chapter, Ozge Islegen, Erica Plambeck, and Terry Taylor take a deeper dive into the economics of emissions regulation. They analyse how a firm will design its supply chain under different forms of climate change policies and investigate their economic and environmental implications. In particular, they show that a cap-and-trade system may have unexpected welfare benefits (in comparison to a basic emissions tax) when there is variability in emissions cost: It can drive producers to design supply chains that primarily operate in a region with climate policy. Next, Tim Kraft, Kathryn Sharpe, and Ozgen Karaer explore the challenges that firms face in managing the chemicals and substances found in their products and supply chains. They examine and illustrate levers available to both for-profit firms and nonprofits for improving the environmental performance of a supply chain. Finally, Luyi Gui, Natalie Huang, Beril Toktay, and I take a stab at the product design implications of environmental regulation in the form of a take-back mandate and show that the assumed implications of environmental regulation on product design do not hold in general. In particular, we show that design incentives under environmental regulation may be weakened, muted, or even negated as a result of operational factors such as design trade-offs, market competition, and recycling resource sharing in the reverse supply chain. Overall, this chapter shows that an operational outlook should be a key component of how a firm or supply chain responds to environmental regulation or how a policy maker should craft the same.

It is my sincere hope and expectation that the reader (be it a practitioner, an academic professional, or a student) of this book will benefit from the broad exposure to different environmental and social responsibility-related topics in the supply chain context and realize the importance of an operational lens in successfully identifying and executing environmental responsibility.

Atalay Atasu
Atlanta, GA, USA
November 2015

Acknowledgements

This book is a product of many years of work and interactions with esteemed colleagues in the field of sustainable operations management and the support of many friends. I would especially like to thank my colleagues who have contributed to this book; those who attended the Georgia Tech Scheller College of Business Early-Career Faculty Network Workshop and to colleagues and co-authors at Georgia Tech and in different parts of the world for their support.

I would like to thank Professor Chris Tang, the editor of Springer's International Series in Operations Research and Management Science, who has encouraged me to work on this book. Special thanks to Luk Van Wassenhove for introducing me to the field and for his support and mentorship ever since; to Beril Toktay, for her support as a friend, mentor, and co-author; and the Ray C. Anderson Center for Sustainable Business at Georgia Tech. Last, but not least, I am grateful to Mirko Janc for typesetting each chapter extremely carefully and rigorously.

I dedicate this book to my family. The two witches (Irem and Peri), Ceren, Kubilay, and Perihan: This book could not have been here without your support. Thank you!

About the Editor

Atalay Atasu, PhD (INSEAD, 2007), is an associate professor of operations management at Georgia Tech Scheller College of Business. His research expertise is on sustainable operations management, with focus on product recovery economics and extended producer responsibility, on which he has published extensively. His research appeared in *Management Science, Manufacturing & Service Operations Management, Production and Operations Management, Journal of Industrial Ecology, and California Management Review.* He is recipient of a number of research awards, including the Wickham Skinner Best Paper Award (winner 2007, runner up 2014), Wickham Skinner Early Career Research Award (2012), and Paul Kleindorfer Award in Sustainability (2013). His research originating from extensive collaborations with a number of Electronics Manufacturers in Europe, particularly in the context of extended producer responsibility, has been particularly influential in the European WEEE Directive implementations.

Contributors

James D. Abbey Mays Business School, Texas A&M University, College Station, TX, USA

Vishal V. Agrawal McDonough School of Business, Georgetown University, Washington, DC, USA

Erjie Ang Graduate School of Business, Stanford University, Stanford, CA, USA

Atalay Atasu Scheller College of Business, Georgia Institute of Technology, Atlanta, GA, USA

Elena Belavina University of Chicago Booth School of Business, Chicago, IL, USA

Ioannis Bellos School of Business, George Mason University, Fairfax, VA, USA

David F. Drake Harvard Business School, Boston, MA, USA

Gökçe Esenduran Fisher College of Business, The Ohio State University, Columbus, OH, USA

Mark E. Ferguson Management Science Department, University of South Carolina, Columbia, SC, USA

Karan Girotra INSEAD, Fontainebleau, France

V. Daniel R. Guide, Jr. Smeal College of Business, Pennsylvania State University, University Park, PA, USA

Luyi Gui Paul Merage School of Business, University of California, Irvine, Irvine, CA, USA

Shanshan Hu Department of Operations and Decision Technologies, Kelley School of Business, Indiana University, Bloomington, IN, USA

Ximin (Natalie) Huang Scheller College of Business, Georgia Institute of Technology, Atlanta, GA, USA

Özge İşlegen Kellogg School of Management, Northwestern University, Evanston, IL, USA

Robin L. Just Harvard Business School, Boston, MA, USA

Ashish Kabra INSEAD, Fontainebleau, France

Basak Kalkanci Scheller College of Business, Georgia Institute of Technology, Atlanta, GA, USA

Özgen Karaer Industrial Engineering Department, Middle East Technical University, Ankara, Turkey

Tim Kraft Darden School of Business, University of Virginia, Charlottesville, VA, USA

Deishin Lee Carroll School of Management, Boston College, Chestnut Hill, MA, USA

Paolo Letizia Haslam College of Business University of Tennessee, Knoxville, TN, USA

Michael K. Lim Department of Business Administration, University of Illinois at Urbana-Champaign, Champaign, IL, USA

Yanfeng Ouyang Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA

Erica L. Plambeck Stanford Graduate School of Business, Stanford University, Stanford, CA, USA

Kathryn Sharpe Darden School of Business, University of Virginia, Charlottesville, VA, USA

Gilvan C. Souza Department of Operations and Decision Technologies, Kelley School of Business, Indiana University, Bloomington, IN, USA

Nur Sunar Kenan-Flagler Business School, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA

Terry A. Taylor Haas School of Business, University of California, Berkeley, Berkeley, CA, USA

Necati Tereyağoğlu Scheller College of Business, Georgia Institute of Technology, Atlanta, GA, USA

L. Beril Toktay Scheller College of Business, Georgia Institute of Technology, Atlanta, GA, USA

León Valdés Massachusetts Institute of Technology, Cambridge, MA, USA

Luk N. Van Wassenhove INSEAD, Fontainebleau, France

Wenbin Wang Department of Operations Management, School of International Business Administration, Shanghai University of Finance and Economics, Shanghai, China

Douglas Webber INSEAD, Fontainebleau, France

Yanchong Zheng Massachusetts Institute of Technology, Cambridge, MA, USA

Contents

Part I
Profit-Driven Environmental Responsibility in Supply Chains: Motives

Chapter 1
Consumer Markets in Closed-Loop Supply Chains

James D. Abbey and V. Daniel R. Guide Jr.

Abstract Though product reuse through closed-loop supply chains has many benefits for firms, as outlined throughout this book, consumers may not fully appreciate the benefits of buying previously used products. This conjecture led to a series of studies related to how consumers perceive reused products produced in a closed-loop supply chain. Specifically, this chapter summarizes the results from a series of studies that examined how consumers perceive remanufactured and refurbished products. The studies ranged from measuring simple reactions to remanufactured products through experimental manipulation of discount levels and brand equity as a means to determine the appeal of remanufactured products in the general U.S. consumer market. The findings breakdown into multiple levers that prompt consumer interest in remanufactured products including the usually assumed consumer greenness, quality perceptions, discounts, and brand equity. However, the studies also revealed the issue of aversion toward remanufactured products through both disgust and a segment of consumers who only desire new products.

J.D. Abbey (✉)
Mays Business School, Texas A&M University, 4217 TAMU,
College Station, TX 77843-4217, USA
e-mail: jabbey@mays.tamu.edu

V.D.R. Guide Jr.
Smeal College of Business, Pennsylvania State University,
480 Business Building, University Park, PA 16802, USA
e-mail: dguide@psu.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_1

1.1 Introduction to Closed-Loop Supply Chains for Consumer Products

Whether a closed-loop supply chain has a consumer or business-to-business focus, many of the supply chain processes remain the same. A firm employing reuse in a closed-loop supply chain must choose to reuse at the product, component, or materials level. Of course, each level of reuse generates different constraints that stem from the earliest design stages through the end-of-life disposition choices. Much research has gone into means to overcome the technical constraints of choosing among the various levels of reuse (Guide and Van Wassenhove 2009). Yet, for many firms using closed-loop supply chain strategies, understanding the market for the products has been a more elusive challenge. Multiple misconceptions persist as rules of thumb or common managerial wisdom (Atasu et al. 2009). This chapter will address these and many other issues. To lay some groundwork for tackling these various issues, Sect. 1.1.1 provides a simple look at closed-loop supply chain processes.

1.1.1 Closed-Loop Supply Chain Processes and Flows

Before a supply chain can become a closed-loop supply chain, the forward supply chain must put the product into the market for at least one lifecycle. After the product reaches end-of-use in a lifecycle, the product must be collected separately from the waste stream. In many cases, the product reacquisition process—commonly known as product acquisition management or PrAM—is relatively simple for larger, business-to-business products such as large printing equipment or heavy earth moving machinery (Guide et al. 2003). However, the issue becomes significantly more complex when dealing with widely dispersed, lower value consumer goods. Whatever the nature of the product, the core process flows remain similar. Figure 1.1 displays the core process flows involved in a closed-loop supply chain: the forward supply chain, the market, and the reuse supply chain (adapted from Abbey et al. 2013).

As Fig. 1.1 displays, product design comes first in the forward supply chain and further represents the first step in the closed-loop supply chain. Effective product design is often an iterative process with each new generation using recovery and design feedback from prior generations. Such feedback is particularly critical in a closed-loop environment, as consumers may use the products in unexpected ways that lead to particular types of wear or damage that were initially unexpected.

After the design and production of the forward supply chain, the market (i.e., consumers) hold the product through a lifecycle that leads to some form of disposal at end-of-use. Not all products reenter a closed-loop supply

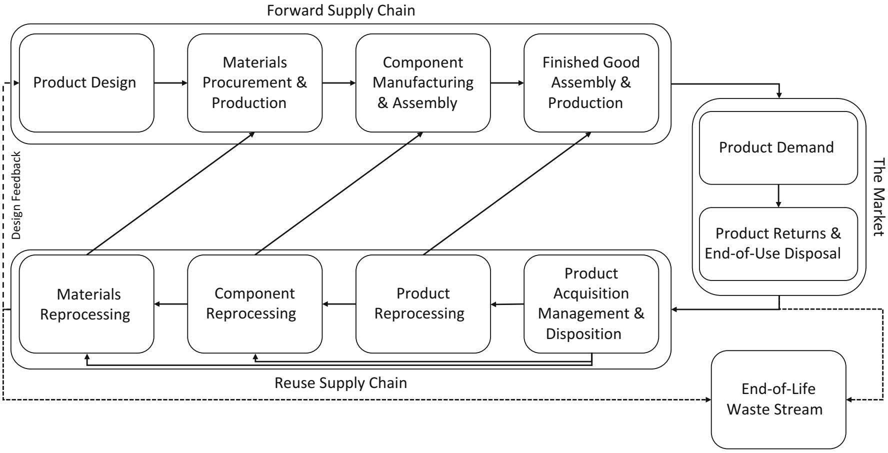

Fig. 1.1 Closed-loop supply chain processes (adapted from Abbey et al. 2013)

chain. Even of the products acquired through product acquisition management, some proportion will not be viable for reuse. As such, some degree of end-of-life waste stream will usually occur. For those returned products that are viable for reuse through remanufacturing, the degree of reuse can range from the product (e.g., an entire smartphone), to the component (e.g., a working screen from a smartphone), to the materials (e.g., extraction of rare earth metals from the defective or obsolete product). Each of these levels has differing market viability, requirements on the condition of the returned products, and intensity in the labor and energy to perform reuse. In general, product reuse is preferable to component reuse is preferable to materials reuse from an environmental and energy intensity perspective (Abbey et al. 2013).

1.1.2 Understanding Remanufactured Product Markets

As the previous section makes clear, reuse in a closed-loop supply chain often derives from remanufacturing or refurbishment at the product or component level. Though materials reclamation—commonly known as recycling—also occurs, the primary focus should be on product or component reuse for both environmental and profitability metrics. As such, understanding the nature of the remanufacturing industry is key to moving forward with a closed-loop supply chain.

As of 2012, the United States International Trade Commission (USITC) defines remanufacturing as the process of returning previously used products to their original working condition (U.S. International Trade Commission 2012). The USITC also reports that the industry grew at a remarkably fast 15 % pace over the years 2009–2011. Additionally, the remanufacturing industry employs at least 180,000 full time workers in the U.S. alone. Other studies indicated that the remanufactured product market sits at well over $100 billion per year with consumer markets comprising $10 billion in sales per year (Abbey et al. 2015d; Hauser and Lund 2003). In general, business-to-business markets still dominate consumer markets in overall revenue. Yet, the consumer market for remanufactured products appears to be enlarging due to the increased accessibility to remanufacturing products through auctions and online channels.

1.1.3 Putting the Process and Market Together

With the rapid growth of the remanufacturing sector in both business-to-business and business-to-consumer channels, the question facing both practitioners and scholars is how best to manage a closed-loop supply chain system. Of course, as Fig. 1.1 shows, a closed-loop supply chain requires coordination among multiple moving parts: the forward supply chain, the market, and the reuse supply chain. In effect, a closed-loop supply chain cannot exist without all the pieces working together. Hence, the absence of market-oriented research in closed-loop supply chains represents a major growth area for practitioners and scholars alike.

To address the closed-loop supply chain market issues, the remainder of this chapter goes through a building process from multiple studies. Section 1.2 covers the general state of the ever-evolving literature. Section 1.3 delves into the authors' various studies and experiments from recently published research, summarizes other recent publications, and discusses the status of ongoing works. Sections 1.4 and 1.5 present continuing opportunities and concluding remarks.

1.2 State of Research in Closed-Loop Supply Chains

With the fundamentals of a closed-loop supply chain in place, this section moves into the state of closed-loop supply chains and related literature. In particular, this section focuses on issues related to the consumer side of closed-loop supply chains and markets. Loosely following the principles of Fig. 1.1, each of the following subsections delves into issues that directly relate to how a firm can match its ability to supply remanufactured products to meet consumer demand.

1.2.1 Product Reacquisition and the Marginal Value of Time

As consumer products tend to be widely dispersed geographically, one of the biggest challenges for a consumer products remanufacturer is the product acquisition management process. Product acquisition management (PrAM) is the process of obtaining used products from the current owner or user. Guide and Van Wassenhove (2001) describe three major elements to the PrAM process: establishing value through reuse, systematic management of profitability through reuse, and related operational issues in managing the returns. Overall, the primary theme of PrAM is that managers must proactively monitor and control the market for returned products.

Blackburn et al. (2004) expand on this theme in the context of commercial returns, such as returns of consumer electronics to a retailer. One of the major hurdles many consumer product firms face is rapidly decaying market value of the returned products—a concept known as the marginal value of time (MVT). In fast moving industries, such as computers and consumer electronics, the pace of moving the product back to market can have a highly significant impact on the overall recoverable value. After all, a smartphone can be out of date within mere months after release. If the product sits in a warehouse waiting to be inspected and tested for reuse, the major recoverable value may have already vanished. Conversely, other consumer products have much slower rates of MVT decay. For instance, power tools may have some technological upgrades over time but largely serve a functional purpose (e.g., cutting pipe or drilling a hole).

Overall, firms need to match their reuse processes—through both PrAM and understanding their products' MVT—with the market demand for remanufactured products. Such a matching of supply and demand requires a deeper understanding of the consumer markets for remanufactured products.

1.2.2 Returns Management

There can be no PrAM unless a return occurs. Returns are a major issue for consumer product firms as consumer returns in the U.S. are well over \$250 billion per year (National Retail Federation 2012). Of course, when dollar figures reach into the billions, firms take the problem seriously. As such, returns management for consumer products is another major area of continuing research. Interestingly, most literature targeted toward the closed-loop supply chain audience takes returns as a given flow of product cores. In a rare exception, Blackburn et al. (2004) discusses issues related to returns and false failures (i.e., products returned that have no material defect).

Whether the consumer returns the product due to a genuine failure or false failure, the focus of most returns management literature centers on return processes and policies. As Ketzenberg et al. (2015) establish, returns management processes and return rates vary widely by the nature of the industry. Griffis et al. (2012) describe how returns management can serve as a competitive edge to increase sales over time, particularly in online channels. Similarly, Bower and Maxham (2012) show that return policies can actually benefit long-term profitability by inducing greater customer loyalty after a perceived failure.

Return policies have also been an active topic in the marketing and psychology fields. For instance, Davis et al. (1998) describe how to establish an appropriate amount of hassle in the returns process. In contrast, Wood (2001) establishes that lenient returns policies may actually reduce return rates, as the salience of time to make a return may be lower. In a more recent work, Janakiraman and Ordonez (2012) establish that both time and effort have a major impact on a consumer's propensity to return. Kim and Wansink (2012) show that recommendation systems and return policies impact consumers' purchase intentions and quality perceptions. Another empirically motived work by Bechwati and Siegal (2005) examines mechanisms consumers use to decide when to make a product return.

One thing is certain: returns continue to represent a major, growing issue for retailers (National Retail Federation 2012). Clearly, firms cannot afford to let over $250 billion in returns go into the waste stream. As a result, managers need to have a clear understanding of how to match their closed-loop supply chain processes with the market for the returned and subsequently remanufactured products.

1.2.3 Design for Reuse and Remanufacturing

Using PrAM to reacquire a returned product—consumer or otherwise—that was not designed for reuse is generally viable only if the product is in nearly new or like new condition. Though upwards of 80 % of returned consumer products are false failures, appropriate product design can significantly streamline the remanufacturing process (Ferguson et al. 2006). Conversely, products that are damaged or defective can be extraordinarily difficult to repair if the initial design did not consider reuse or at least reparability (Akturk et al. 2016). Bras (2010) provides various insights into how product design can play an integral role in the functioning of a closed-loop supply chain. Additionally, Souza (2013) makes the case that product design in a closed-loop supply chain comprises a major gap in the current literature and requires great expansion. At the time of writing this chapter, such design issues represent an understudied area in the closed-loop supply chain literature.

Of course, consumers may not directly appreciate that a product design allows easier repairability and reuse. However, most consumers do require that the remanufactured product perform comparably to a new product. Thus, design for remanufacturing plays a crucial role in providing firms with an easy way to maintain perceived quality of the remanufactured product.

1.2.4 The Market for Remanufactured Consumer Products

The literature surrounding the consumer markets in closed-loop supply chains is still in its infancy relative to many other closed-loop supply chain domains. Though many papers have made assumptions about how consumers should behave, empirical evidence regarding consumer markets for remanufactured products have remained scarce. Guide and Van Wassenhove (2009) and Souza (2013) declare that much research will be needed to understand consumer behavior and define how those behaviors differ from new product markets.

Among the developing areas of research is the discovery that discounting, while effective to a degree, has limits due to price-quality concerns Ovchinnikov (2011) and is often not the dominant driver of preference toward remanufactured products (Abbey et al. 2015d). Curiously, branding and brand equity also show mixed results in terms of enhancing product attractiveness (Abbey et al. 2015d; Agrawal et al. 2015). Seller reputation also plays a critical role in how consumers perceive remanufactured products as discussed by Subramanian and Subramanyam (2012). Moreover, consumers are not consistent in their perceived quality and associated risks regarding the purchase of a remanufactured product (Abbey et al. 2015c).

Additionally, there is strong evidence that distinct consumer segments exist (Guide and Li 2010). One segment is roughly indifferent between new and remanufactured product options given an appropriate discount. Another segment will not consider a remanufactured product under any circumstances. This result is not limited to a small section of the population as shown in Abbey et al. (2015b). Additionally, the distinct segments offer new avenues of research into pricing and related revenue management. Further, some consumers find the remanufactured products not only unattractive but repulsive (Abbey et al. 2015a).

As the literature on consumer markets for remanufactured products continues to grow, Sect. 1.3 can only provide a snapshot view of the current state of knowledge. Of course, Sect. 1.3 focuses heavily on the authors' recent publications and studies in progress. As the field matures, additional insights and perhaps even anomalies may emerge. As such, the reader should take Sect. 1.3 not as the solution to issues in consumer markets but as the first steps toward isolating and understanding how consumers view remanufactured products.

Additionally, managers should use Sect. 1.3 as a means to address differences between new and remanufactured consumer product markets. For an expanded discussion, see Abbey et al. (2015d).

1.2.5 Matching Supply and Consumer Demand in Closed-Loop Supply Chains

Figure 1.2 provides a high-level overview of each of the topical areas of the literature related to consumer markets, returns, and related closed-loop supply chain processes. The four areas of literature all tie into the idea of matching supply and demand. Supply derives from product returns that firms manage through PrAM. Consumer demand is a complex topic deriving from many aspects, including the relevance of the product (i.e., has the marginal value of time caused excessive decay in the product's value), perceived quality, environmental aspects, and aversion due to perceived contamination of the product from the prior owner—a concept embodied in the "disgust" construct. Each of these various levers appears in studies described in Sect. 1.3.

1.3 Delving Deeper: Understanding the Fundamental Drivers of Remanufactured Products Preferences

Recent experiments by the authors and other researchers reveal many distinct drivers of preferences toward remanufactured and refurbished products. This section focuses on the work of the authors and draws in links from related research by Agrawal, Atasu, Ovchinnikov, and other researchers working in the field of consumer markets for remanufactured products.

1.3.1 Fundamental Studies into Remanufactured Product Perceptions

Free Associates Various fundamental studies sought to understand, in general terms, how consumers perceive remanufactured products. One study, covered in Abbey et al. (2015d), asked respondents to provide free associates (i.e., descriptive adjectives that come to mind) when considering the idea of a remanufactured product. The results could not have been more varied. Of the classifiable adjectival responses, approximately 52 % were negative and 48 % were positive. Curiously, the respondents did not show any significant association of environmental or green benefits related to remanufactured products.

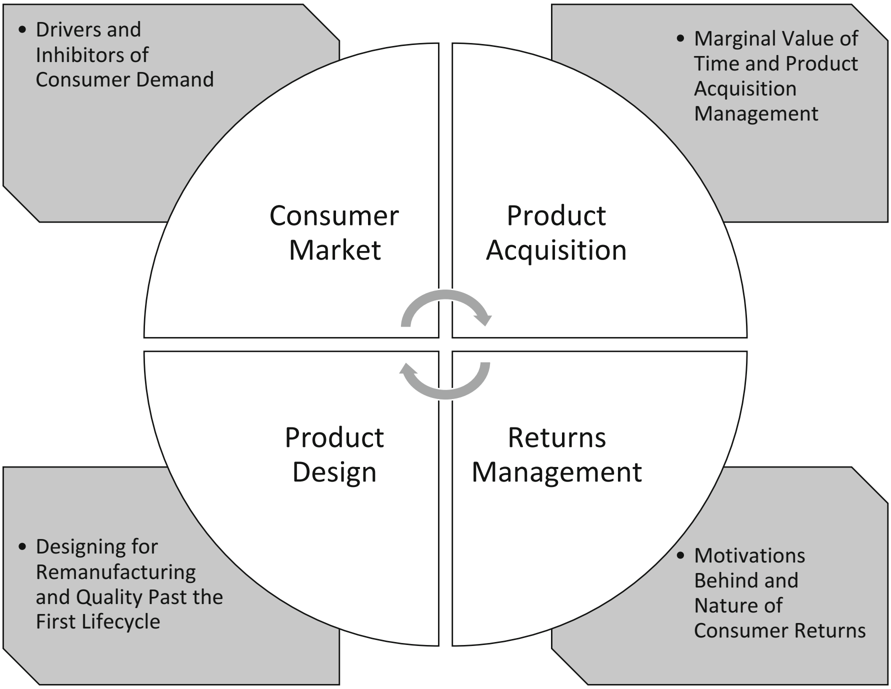

Fig. 1.2 Core topics of closed-loop supply chain and consumer markets literature

Figure 1.3, adapted from Abbey et al. (2015e), summarizes some of the most commonly associated adjectives found in the study.

Adjectival Factors and Mean Differences In a follow-up study, the authors streamlined the list of adjectives from the free associate through further testing. The streamlined adjectives served as the basis for a Likert-style 1–9 semantically differentiated scale. The results of the adjective testing were telling in the mean differences all showing that negative adjectives strongly associated to remanufactured products, positive adjectives associated to new products, and green adjectives associated slightly toward new products (Table 1.1).

The free associate and adjectival ratings studies both provided interesting insights into the general perceptions among respondents. The overall findings demonstrated quite a bit of confusion among consumers, as shown in the nearly equal split among positive and negative free associates, and a general preference for new products when evaluating the adjectival measures.

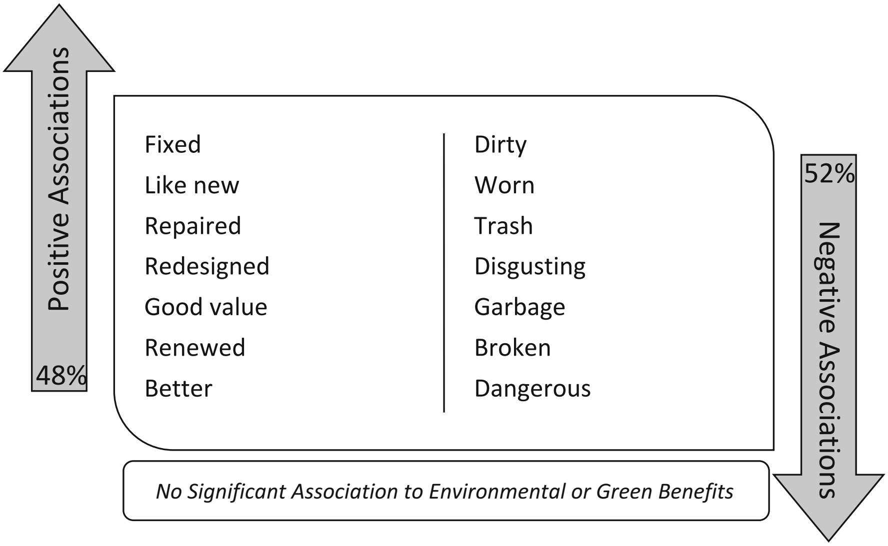

Fig. 1.3 Free association responses to remanufactured products

1.3.2 Combining Theory and Fundamental Studies

The results of the fundamental studies led to creation of much larger, experimental studies to isolate and rank the importance of the various factors. This led to an expanded nationwide study of U.S. consumers (Abbey et al. 2015d). The study measured the attractiveness of various products in three categories: technology (e.g., laptops and printers), household (e.g., toasters and mixers), and personal (e.g., electric toothbrushes and electric razors). The study experimentally manipulated the discount level versus a reference price for a new product at 20, 40, 60, 80, and 95 % off the reference price. This discount manipulation was then crossed with a brand equity manipulation of either all high brand equity products or all low brand equity products. The result was a $5 \cdot 2$ or 10 cell experimental design. Though the full results are too detailed to cover fully in this chapter, a quick summary of the overall regression results appears in Table 1.2.

The overall results for the manipulated effects showed that discounting consistently mattered in the positive direction, but brand equity was poorly behaved. In fact, brand equity actually showed negative direct effects and remediation of the negative effect through the interaction of discounting with brand equity only at high discount levels. This finding may seem odd at first. After all, in new product markets, higher brand equity should encourage greater interest by definition (Aaker 1991). The study did confirm that when considering new products, the respondents did find the higher brand equity products higher in quality and trustworthiness as would be expected. Perhaps the respondents saw the remanufactured products, and thereby the brands,

Table 1.1 Adjectival ratings and mean differences

Adjective	Latent factors[a]			Mean difference: new – remanufactured		
	Negative attributes	Quality attributes	Green attributes	New mean mean [s.e.]	Remanufactured mean [s.e.]	Mean difference[b]
Dirty	0.92	0.16	−0.10	1.92 [0.08]	3.06 [0.09]	−1.14***
Disgusting	0.83	0.12	−0.09	2.03 [0.08]	2.63 (0.08)	−0.60***
Worn	0.58	−0.20	0.16	2.02 [0.10]	4.13 [0.11]	−2.11***
Unattractive	0.56	−0.14	0.09	2.70 [0.10]	3.66 [0.09]	−0.96***
Risky	0.51	−0.11	0.05	3.83 [0.10]	4.39 [0.10]	−0.56***
High quality	−0.10	0.85	−0.07	5.10 [0.08]	3.70 [0.09]	1.40***
Safe	0.12	0.84	0.02	4.88 [0.08]	3.84 [0.08]	1.04***
Reliable	−0.07	0.82	0.01	4.68 [0.09]	3.84 [0.09]	0.84***
Good value	0.01	0.55	0.14	4.46 [0.09]	4.53 [0.09]	−0.07
Green	0.00	0.01	0.78	4.64 [0.09]	4.57 [0.10]	0.07
Environmentally friendly	−0.03	0.26	0.59	4.92 [0.08]	4.45 [0.09]	0.47***
Environmentally conscious	0.05	−0.04	0.58	4.06 [0.09]	4.15 [0.10]	−0.09

***$p < \alpha = 0.004$

[a]EFA using MLE with oblique (Promax) rotation: RMSEA = 0.067

[b]Significant at Bonferroni repeated measure error corrected

as somehow failing (Aaker et al. 2004). Whatever the reason, other studies, such as Agrawal et al. (2015), have found similar oddities with regard to brand effects.

Table 1.2 also shows the relative importance of each manipulation and measure from the study in the form of standardized betas inside the brackets. For every product category, the perceived quality of the remanufactured product proved paramount to encouraging interest in the products. Discounting was consistently the next most important variable for all types of products. However, the results were muddied when comparing product categories for the other measures and effects. For the perceived "green attributes" of the remanufactured products, the importance was only significant in technology and household products. For the "consumer greenness"—a combination of belief in self as green and manifest recycling behaviors—the results were always at least weakly statistically significant but relatively unimportant as a standardized beta effect. Additionally, brand equity, as already noted, was ill-behaved showing no effects in the household and personal product categories and a reversal in the technology product category.

Of particular note from the results was the introduction of the "negative attributes"—belief that the remanufactured product was somehow dirty, disgusting, and contaminated by the prior owner—showed increasingly significant effects as the product became more personal in nature. This idea that a product is permanently contaminated comes from the "law of contagion" that

Table 1.2 Nationwide study of U.S. consumer responses to remanufactured products (adapted from Abbey et al. 2015d)

Term	Technology	Household	Personal
Intercept	−0.05	−0.11	0.656
Age	−0.01 [−0.07]***	−0.01 [−0.05]**	−0.01 [−0.07]***
Gender	−0.22 [−0.04]*	0.02 [0.00]	−0.27 [−0.05]**
Education	−0.13 [−0.03]	−0.32 [−0.06]**	−0.31 [−0.06]***
Income	0.10 [0.02]	0.34 [0.06]**	0.13 [0.02]
Number of children	0.05 [0.04]*	0.12 [0.08]***	0.06 [0.04]*
Quality attributes	0.79 [0.44]***	0.70 [0.36]***	0.77 [0.42]***
Negative attributes	−0.12 [−0.06]**	−0.18 [−0.09]***	−0.18 [−0.09]***
Green attributes	0.21 [0.12]***	0.15 [0.08]***	0.08 [0.04]
Consumer greenness	0.32 [0.04]*	0.50 [0.06]**	0.34 [0.05]**
Discount	0.02 [0.22]***	0.02 [0.20]***	0.01 [0.11]***
Brand equity	−0.64 [−0.13]***	−0.15 [−0.03]	−0.41 [−0.08]
Discount × Brand Equity	0.01 [0.15]***	0.00 [0.05]	0.00 [0.00]
Adjusted R^2	0.35	0.22	0.20

***$p < 0.01$, **$p < 0.05$, *$p < 0.1$ [all tests p-values are two-tailed]
Coefficients appear as unstandardized betas [standardized betas inside brackets]

states, "once in contact, always in contact" as shown by Rozin et al. (1986). In other words, there is a permanent or at least semi-permanent transfer or contamination of the product by the prior user (Rozin and Fallon 1987). The effect was surprisingly robust for every product category. This disgust reaction represents a major challenge that seems to be quite difficult to remediate (Abbey et al. 2015a).

1.3.3 Advancing the Experimental Design: Combining Effects to Isolate Consumer Segments

In light of the fundamental drivers and findings from the experimental work, recent research moved into an even deeper analysis of consumer market segments. The results of a large mixed between and within-subjects model combining both new and remanufactured product preferences revealed distinct consumer segments (Abbey et al. 2015b). Roughly in line with Guide and Li (2010), one segment showed significant aversion toward remanufactured products and a relatively low sensitivity to discounts for new products. Another segment was the opposite: little concern for the new or remanufactured status of the product but very high sensitivity to the discount level. These results led to multiple outcomes.

The foremost result of this and other ongoing studies is that pricing strategies, when introducing a remanufactured product to market, may actually require a higher price for the new product (Abbey et al. 2015b,e).

The higher pricing for new products captures the premium new product only consumers who are willing to pay more than their discount sensitive counterparts. Conjointly, the study reveals that a relatively smaller discount than some firms currently employ for remanufactured products is sufficiently enticing for many consumers (Ovchinnikov 2011). Though such a result may seem counterintuitive as a remanufactured product competes for sales with a new product, the existence of a sizeable segment of consumers (upwards of 35 %) who will not consider a remanufactured product under any discount changes the perspective of market behavior. In effect, the remanufactured product is not even an imperfect substitute for a sizeable portion of consumers. Rather, for such consumers, the remanufactured product is effectively a non-substitute. As a result, firms need to use this knowledge of market segments as a means both to price and decide whether offering a remanufactured product makes sense in light of the shrinking market pool.

1.4 Continuing Needs for Research and the Environment

Even with all the recent findings, many questions remain. Abbey et al. (2015d) contend that education may serve as a tool to encourage consumer interest in reused products. Yet, continued studies show mixed results for educational effects. Additionally, significant proportions of consumers continue to show strong aversions toward remanufactured products. Resolving these aversions has been nothing short of impossible for some consumer segments as found in recent studies (Abbey et al. 2015a). The lack of brand equity effects, or even reversals of brand effects, begs the question of how to market remanufactured products if brand is not a sufficient signal of quality (Abbey et al. 2015d; Agrawal et al. 2015).

The environmental benefits of remanufacturing have long been discussed and known (Atasu et al. 2008; Kleindorfer et al. 2005). However, as shown in various studies, consumers do not seem to grasp these environmental benefits and do not prioritize the environmental benefits as highly as discounting and quality concerns (Abbey et al. 2015b,d). Thus, academics and practitioners both face a daunting challenge of educating consumers about the virtues of reuse through remanufacturing. Fortunately, the reduce, reuse, recycle (3R) campaign has gained significant traction in recent years, though there is still much room for improvement (Laseter et al. 2010).

1.5 Concluding Remarks

The closed-loop supply chain community and sustainable operations areas continue to gain traction among both academics and practitioners. Whether the reasons for growth stem from increasing legislative pressures, strategic shifts toward the triple bottom line, or the simple desire for increased profitability, the result is the same: improved environmental performance. Yet, even as legislators and businesses move to improve sustainability practices, many consumers seem to be confused about such environmental improvements—particularly improvements related to product reuse. Though the reduce, reuse, recycle hierarchy holds reuse as the second major lever, consumers do not always associate remanufacturing as a prime form of reuse. This confusion and lack of understanding, along with the negative associations toward remanufactured products, will continue to pose a vexing issue for academics and practitioners alike. Over time, perhaps the best course of action will be increased involvement through academic-industry alliances to forge both new understanding through research and improved closed-loop supply chain performance in practice.

References

Aaker DA (1991) Managing brand equity: capitalizing on the value of a brand name. The Free Press, New York

Aaker J, Fournier S, Brasel SA (2004) When good brands do bad. J Consum Res 31:1–16

Abbey JD, Guide VDR Jr (2013) Closed-loop supply chains. In: Bansal T, Hoffman A (eds) Oxford handbook on business and the natural environment. Oxford University Press, New York, pp 290–309

Abbey JD, Atalay AS, Meloy MG (2015a) Remanufactured products: is that which is more familiar also less disgusting. Working Paper

Abbey JD, Blackburn JD, Guide VDR Jr (2015b) Optimal pricing for new and remanufactured products. J Oper Manag 36:130–146

Abbey JD, Kleber R, Souza GC, Voigt G (2015c) The role of perceived quality risk in pricing remanufactured products. Working paper

Abbey JD, Meloy MG, Guide VDR Jr et al. (2015d) Remanufactured products in closed-loop supply chains for consumer goods. Prod Oper Manag 24(3):488–503

Abbey JD, Meloy MG, Blackburn J, Guide VDR (2015e) Consumer markets for remanufactured and refurbished products. Calif Manag Rev 57(4):26–42

Agrawal V, Atasu A, Van Ittersum K (2015) Remanufacturing, third party competition and consumers' perceived value of new products. Manag Sci 61(1):60–72

Akturk S, Abbey JD, Geismar N, Guide VDR Jr (2016) Strategic design for remanufacturing: analyzing the complicating factors for multiple lifecycle products. Working Paper

Atasu A, Sarvary M, Van Wassenhove LN (2008) Remanufacturing as a marketing strategy. Manag Sci 54:1731–1747

Atasu A, Guide VDR Jr, Van Wassenhove LN (2009) So what if remanufacturing cannibalizes new product sales? Calif Manag Rev 52:56–76

Bechwati NN, Siegal WS (2005) The impact of prechoice process on product returns. J Mark Res 42:358–367

Blackburn JD, Guide VDR Jr, Souza GC, Van Wassenhove LN (2004) Reverse supply chains for commercial returns. Calif Manag Rev 46:6–22
Bower AB, Maxham JG (2012) Return shipping policies of online retailers: Normative assumptions and the long-term consequences of free and free returns. J Mark 76:110–124
Bras B (2010) Product design issues. In: Ferguson ME, Souza GC (eds) Closed-loop supply chains new developments to improve the sustainability of business practices. CRC Press, Boca Raton, pp 39–66
Davis S, Hagerty M, Gerstner E (1998) Return policies and the optimal level of "hassle." J Econ Bus 50:445–460
Ferguson M, Guide VDR Jr, Souza GC (2006) Supply chain coordination for false failure returns. Manufact Service Oper Manag 8:376–393
Griffis SE, Rao S, Goldsby TJ, Niranjan TT (2012) The customer consequences of returns in online retailing: an empirical analysis. J Oper Manag 30:282–294
Guide VDR Jr, Li J (2010) The potential for cannibalization of new products sales by remanufactured products. Decision Sci 41:547–572
Guide VDR Jr, Van Wassenhove LN (2001) Managing product returns for remanufacturing. Prod Oper Manag 10:142–155
Guide VDR Jr, Van Wassenhove LN (2009) The evolution of closed-loop supply chain research. Oper Res 57:10–18
Guide VDR Jr, Teunter RH, Van Wassenhove LN (2003) Matching demand and supply to maximize profits from remanufacturing. Manufact Service Oper Manag 5:303–316
Hauser W, Lund RT (2003) The remanufacturing industry: anatomy of a giant. Boston University, Boston
Janakiraman N, Ordonez L (2012) Effect of effort and deadlines on consumer product returns. J Consum Psychol 22:260–271
Ketzenberg M, Heim G, Abbey JD, Kumar S (2015) Consumer returns: a typology and critical literature review. Working Paper
Kim J, Wansink B (2012) How retailer's recommendation and return policies alter product evaluations. J Retail 88:528–541
Kleindorfer P, Singhal K, Van Wassenhove LN (2005) Sustainable operations management. Prod Oper Manag 14:482–492
Laseter T, Ovchinnikov A, Raz G (2010) Reduce, reuse, recycle … or rethink. Strategy Bus 61:28–32
National Retail Federation (2012) Return fraud survey 2012. Available at NRF. http://www.\penalty0theretailequation.com/retailers/IndustryReports. Accessed 5 Mar 2014
Ovchinnikov A (2011) Revenue and cost management for remanufactured products. Prod Oper Manag 20:824–840
Rozin P, Millman L, Nemeroff C (1986) Operation of the laws of sympathetic magic in disgust and other domains. J Pers Soc Psychol 50:703–712
Rozin P, Fallon A (1987) A perspective on disgust. Psychol Rev 94:23–41
Souza GC (2013) Closed-loop supply chains: a critical review, and future research. Decis Sci 44(1):7–38
Subramanian R, Subramanyam R (2012) Key factors in the market for remanufactured products. Manufact Service Oper Manag 14:315–326
U.S. International Trade Commission (2012) Remanufactured goods: an overview of the U.S. and global industries, markets, and trade. Available via USITC. http://www.usitc.gov/\penalty0publications/\penalty0332/pub4356.pdf. Accessed 10 Aug 2014
Wood SL (2001) Remote purchase environments: the influence of return policy leniency on two-stage decision processes. J Mark Res 38:157–169

Chapter 2
Market Behavior Towards Remanufactured Products

Necati Tereyağoğlu

Abstract This chapter provides an overview of recent empirical research on market behavior towards remanufactured products. We focus on three key themes: factors influencing the differences in consumer valuation of new and remanufactured products, differences in perceived valuation of seller signals for new and remanufactured products, and impact of the presence of remanufactured products on consumer valuation of new products. The results point to the unique properties of remanufactured products and how they differ from new products. We posit that considering these findings could lead to an increase in the profit-generating capability of remanufactured products.

2.1 Introduction

The core principle in closed-loop supply chains is to recover the remaining value in end-of-use products after receiving them back from the market. The remanufactured products are attractive because manufacturers incur significantly lower costs from remanufactured products relative to the cost of producing their brand new counterparts. However, the traditional concern for many manufacturers is the potential cannibalization of their new product sales by remanufactured products. In fact, many organizations do not introduce remanufactured versions of their products. To test the validity of this concern and realize the profitability of remanufactured products, it is critical for manufacturers to realize how remanufactured products are perceived by consumers.

N. Tereyağoğlu (✉)
Scheller College of Business, Georgia Institute of Technology, Atlanta, GA 30308, USA
e-mail: necati.tereyagoglu@scheller.gatech.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_2

Recent empirical studies show that the perceived value of new products can be significantly different from the perception of remanufactured products. In this chapter, we focus on three key themes: (1) factors influencing the differences in consumer valuation of new and remanufactured products, (2) differences in perceived valuation of seller signals for new and remanufactured products, and (3) impact of the presence of remanufactured products on consumer valuation of new products. We utilize the findings from three empirical studies by Subramanian and Subramanyam (2012), Subramanian et al. (2015), and Agrawal et al. (2015) in discussion of these themes, respectively.

We first focus on how the factors influencing consumers' valuation of new and remanufactured products may differ. Subramanian and Subramanyam (2012) show that both seller reputation and seller identity (original equipment manufacturer (OEM) vs. third-party remanufacturer) play a significant role in explaining the differences in valuation of new and remanufactured products. Surprisingly, they find that specifying a warranty does not have a significant role in explaining the differences in valuation. This finding suggests that offering a warranty for a remanufactured product may not be an effective signaling tool like it can be for new products.

If a warranty for a remanufactured product is not useful, which signals can effectively influence the valuation of remanufactured products? There are multiple safeguards available to sellers, particularly in online marketplaces, which are designed to alleviate the consumers' concerns about product's condition. Traditionally, seller-related safeguards (e.g., seller reputation) are designed to alleviate consumer concerns related to seller trustworthiness or integrity, along with product-related safeguards (e.g., returns acceptance) that are designed to reduce the concerns related to product condition. Subramanian et al. (2015) show that both seller feedback score and returns acceptance influence the valuation of remanufactured products in online marketplaces. They also find that the impact of specifying returns acceptance amplifies when this signal is specified by sellers with a high reputation for remanufactured products. We focus on this unique finding for remanufactured products in the discussion of the second theme.

In the discussion of the third theme, we focus on another unique property of remanufactured products: the influence of the presence of remanufactured products on consumer valuation of their new counterparts. Agrawal et al. (2015) find that the valuations of new and remanufactured products indeed interact when they are present in the marketplace at the same time. In particular, they show that the presence of an OEM remanufactured product decreases the valuation of its new counterpart, while the presence of a third-party remanufactured product increases the valuation of its new counterpart.

The rest of this chapter is organized as follows. In Sect. 2.2, we explore why remanufactured products are perceived differently from their new counterparts. In Sect. 2.3, we focus on the first theme to highlight the key factors influencing the differences in consumers' valuation of remanufactured and new products. In Sect. 2.4, we discuss the second theme to look at the influences of sellers signals on consumer valuation of new and remanufactured products. In Sect. 2.5, we elaborate more on the third theme to discuss the impact of the presence of remanufactured products on the perceived value of new products. We conclude in Sect. 2.6.

2.2 Unobservable Remanufacturing Processes

The United Nations Environment Programme (UNEP) defines remanufacturing as the process of returning "used products and individual product components to a 'like-new' functional state" (2013). Typically, recovery of a used product to its original condition requires the implementation of a set of tasks including: product disassembly, component servicing, component testing, and reassembly. These processes are unobservable to consumers, so the term *remanufactured* can incite more questions than confidence on the current state of the product. For example, consumers do not observe whether the remanufacturer carries out full or partial disassembly, inspects all components, uses the original parts as replacements, and tests each part in accordance with the OEM specifications.

With the 15 % growth in the remanufacturing industry in the United States over 2009–2011 (USITC 2012), both practitioners and scholars are examining how best to reduce the consumer concerns related to the purchase of remanufactured products to increase the sales further. Some OEMs disclose full information about the entire remanufacturing process on their web sites in an attempt to reduce the uncertainty. For instance, HP has a section on its web site titled "Why buy refurbished?" (HP 2015). Apple states that their refurbished Macs go through an extremely thorough refurbishment process to make sure it is up to the quality standards of a brand new Apple product (Jacobs 2011). Such strategies are common in the marketplace.

Another strategy to deal with consumer uncertainty is to provide a warranty to signal the quality of the remanufactured product. Consumers will be looking for signals to indicate the quality of the remanufactured product relative to its new version. In that case, providing the same warranty for both the remanufactured and new versions will imply that the producer has equal confidence about the quality of both versions of the product. Apple provides a standard 1-year limited warranty; a customer can purchase an AppleCare Protection Plan for the remanufactured product until the end of the first year just like buying the plan for a new version of the product.

Although these strategies are practically feasible for OEMs in the industry, their impact on the perception of remanufactured products is likely to vary in online marketplaces. Online marketplaces increase the accessibility to products that are remanufactured by third-party manufacturers. Yet, consumers do not have physical interactions with a product offered online prior to purchase. Hence, their concerns are likely higher and influence their purchasing and bidding behavior.

With the remarkable increase in market size for remanufactured products due to online marketplaces, both the original equipment and third-party manufacturers face the challenge of setting up a careful strategy to ease consumer uncertainties, and increase the valuation, and purchase for remanufactured products in online marketplaces. Although the expectation is that remanufactured products should be "like-new," we still see significant price differences between new and remanufactured products in online marketplaces. In a study of 250 remanufactured and 1979 new electronics products sold during the first 2 weeks of August 2009 on eBay, a comparison of the average prices for new and remanufactured products at the time of each remanufactured product transaction shows that 90 % of the observations have average new product prices greater than the average remanufactured product prices (Subramanian and Subramanyam 2012). Similarly, in an experimental study of bids from ascending-price auctions for new and remanufactured versions of two different types of products (Skil Jigsaw and Cisco security system), Guide and Li (2010) show that the average prices associated with the remanufactured versions are significantly lower than that of their new counterparts.

Such price differentials between remanufactured products and their new counterparts suggest that carrying out a rigorous process to make sure a remanufactured product is up to the quality standards of its new counterpart, and promoting such practice as part of a selling strategy, may not be sufficient for increasing the valuation, and purchase in online marketplaces. Seller- or market-related characteristics in marketplaces may have a significant influence on consumer behavior towards remanufactured products. Hence, a seller should understand which of these characteristics influence the differences in purchase behavior towards new and remanufactured products.

2.3 Factors Influencing the Valuation of Remanufactured Products

Online marketplaces provide diverse mechanisms for sellers to show their confidence in their products, such as product descriptions, product pictures, warranties, and specifications of money-back guarantees. Given the inherent information asymmetry between buyers and sellers, these mechanisms play a key role in decreasing consumer uncertainty by acting as safeguards, keeping more reputable sellers in the market, and hence drawing more potential buyers. In this section, we focus on the impact of these safeguards on the price differences observed between remanufactured products and their new counterparts.

Given the lack of a physical interaction with a product offered online, consumers often have to rely on signals of seller trustworthiness, such as online reputation score for the seller, signals of remanufacturer identity such as OEM versus third-party remanufacturer, and some transaction safeguards, such as warranties. These mechanisms are designed to decrease consumer concerns and influence their purchasing behavior.

Seller reputation has been posited to play a key role in addressing buyer uncertainty in online marketplaces (Dewan and Hsu 2004). In many online marketplaces, consumers can see a summary of the seller's reputation. For instance, eBay provides a seller feedback score, as an indicator of reputation, in terms of counts and percentages of transaction feedback ratings over a certain time period and recent transaction history. Research on used products has shown that sellers with a higher reputation can alleviate consumers' concerns, and thereby command higher prices (Dellarocas 2003; Pavlou and Dimoka 2006; Ghose 2009). On top of the general problem of lack of experience with the product prior to an online purchase, unobservability of the remanufacturing process makes it harder for the consumer to determine the actual quality of a remanufactured product in online marketplaces. Hence, seller reputation is likely to have a significant impact on the prices achieved for remanufactured products in online marketplaces.

Subramanian and Subramanyam (2012) show that seller reputation has a significant relationship with the price differentials between new and remanufactured products. They find that greater negative reputation is associated with higher price differences between remanufactured products and their new counterparts, while higher positive reputation is associated with lower price differences between remanufactured products and their new counterparts. These results imply that an excellent reputation can help the seller to reduce consumer uncertainty, thereby facilitating the ability to command higher prices for their remanufactured products.

Researchers also explore why consumers treat third-party remanufactured products differently than products remanufactured by OEMs. From a practical standpoint, some remanufacturing processes may require excessive capital investments, which can only be sustained by OEMs. This suggests that consumers may prefer a OEM remanufactured product relative to a third-party remanufactured counterpart. The assumptions on such behavior in theoretical studies are also mixed: Ferrer and Swaminathan (2006) assume that consumers favor OEM remanufactured products over third-party remanufactured products, while Ferguson and Toktay (2006) assume consumers do not pay attention to whether the product is remanufactured by an OEM or a third-party manufacturer. Subramanian and Subramanyam (2012) empirically show that a seller can command higher prices for products remanufactured by OEMs than products remanufactured by third-parties.

Although there is an extensive literature on the impact of warranties on prices for used products, empirical evidence is scarce regarding consumer behavior towards warranties for remanufactured products. Warranties have been shown to ease the burden of information asymmetry, i.e., the "lemon" problem (Akerlof 1970), in the economics and marketing literature (Boulding and Kirmani 1993; Soberman 2003; Chu and Chintagunta 2011). This result implies that sellers can enjoy higher prices by providing warranties for their products in online marketplaces (Pavlou and Dimoka 2006). However, Subramanian and Subramanyam (2012) find no statistical evidence of a positive relationship between offering warranties and the prices for remanufactured products. They state that other safeguards such as seller reputation and type of remanufacturer (OEM vs. third-party) may sufficiently mitigate consumer uncertainty, thereby reducing the need for warranties.

These findings point to a unique property of remanufactured products. In line with new products, seller reputation and seller identity also influence consumer valuation of remanufactured products. However, offering warranties for remanufactured products does not appear to have a significant influence on consumers' valuations.

2.4 Buyer Safeguards Influencing Market Behavior Toward Remanufactured Products

Seller use of diverse signaling mechanisms to mitigate consumer uncertainty for remanufactured products in online marketplaces may not be always effective for several reasons. First, few of these mechanisms can fully reduce consumer uncertainty, thereby eliminating the need for any other mechanism. Subramanian and Subramanyam (2012) use this reasoning to explain why warranties do not appear to have an influence on the prices for remanufactured products in the presence of other marketing mechanisms, such as seller reputation. Second, one mechanism can act to provide assurance for another mechanism. In this section, we focus on the impact of such interactions on consumer behavior toward remanufactured products.

Subramanian et al. (2015) explore the impact of the interaction between returns acceptance and seller feedback scores on prices for remanufactured products. Returns acceptance is another auction feature that serves as a safeguard for consumers. The signal does not require upfront costs from the seller, but it could prove to be a relatively expensive signal in the long run as a result of unexpected excessive returns. This suggests that a specification of returns acceptance can serve as a signal about the condition of a remanufactured item.

From a consumer's standpoint, it is hard to evaluate the condition of a remanufactured product prior to purchase knowing that a seller might not conduct all the required elements of a remanufacturing process. An offer of a returns acceptance demonstrates the seller's confidence in the remanufacatured product to a defined original specifications.

One online selling tool shows a seller's capability for selling items as described. A seller's feedback score provides information on the buyers' responses to the products they received as compared to a comparable new product. Because their responses help mitigate consumer uncertainty, returns acceptance can be seen as a credible signal only if the seller's feedback score is high.

Subramanian et al. (2015) use data that include all auction listings for one particular category of remanufactured iPod Touches offered on eBay. They test whether seller feedback score influences the impact of returns acceptance on consumers' bids. Specifically, they test whether the specification of returns acceptance impacts the final prices for the iPod Touches. To understand the changes in the impact of returns acceptance, the tests for the items listed by sellers with low and high feedback scores are carried out separately. The authors find a statistically significant increase in the final prices of sellers with high feedback scores who specify returns acceptance, but no increase is identified for those sellers with low feedback scores. Thus, specifying returns acceptance does not influence consumers' purchase and bidding behavior for remanufactured iPod Touches when offered by sellers with low feedback scores.

Subramanian et al. (2015) also conduct the same tests for new iPod Touches on eBay. Since a new item does not require additional manufacturing processes such as disassembling or testing, it is not possible for its condition to be changed by the seller's efforts. This implies that specification of returns acceptance would not be valued differently based on the seller's feedback score. The authors find no statistical evidence for an increase in the final prices of new items for specification of returns acceptance when the seller has a high feedback score.

To the best of our knowledge, the research in this domain of closed-loop supply chains is fairly new. Researchers in this domain could provide some guidelines on how to design the features in online marketplaces differently for remanufactured products relative to their new counterparts.

2.5 Impact of Remanufactured Products on New Product Valuations

In this section, we discuss how consumers value new products in the presence of their remanufactured counterparts. Researchers examining the closed-loop supply chains (see Atasu et al. 2008; Guide and van Wassenhove 2009; Souza 2013 for recent overviews) have implicitly assumed that the presence of remanufactured products does not influence consumer behavior towards the new versions of the same product. This assumption implies that remanufactured products should not cannibalize the demand for their new counterparts, so any OEM may consider selling the remanufactured version of its products without the fear of cannibalization. Many OEMs nonetheless avoid selling remanufactured products. Moreover, their new products also face competition from third-party remanufactured counterparts.

Preliminary studies indicate significant differences in the perceived values of new, OEM, and third-party remanufactured products of the same type. Subramanian and Subramanyam (2012) observe that 90 % of the remanufactured transactions have prices lower than the average price of new products at the time of the transactions. Similarly, in an experimental study, Agrawal et al. (2015) find that the willingness-to-pays (WTPs) for remanufactured products are smaller than those for new products. Agrawal et al. (2015) also observe that the WTPs for OEM remanufactured products are higher than those for third-party remanufactured products.

Agrawal et al. (2015) expand on these findings and show that the presence of OEM remanufactured products has a negative effect on the WTPs for new products. They explain this finding based on the assimilation effects from the contextual reference points literature (McKenna 1984; Mussweiler 2003). An assimilation effect describes a shift in the valuation for a product towards one that acts as the contextual reference point for the consumer. Because the OEM remanufactured product is perceived to be very similar to its new counterpart, a consumer accepts the OEM remanufactured product as the contextual reference point, shifting the valuation for the new product downward (Agrawal et al. 2015). The presence of an OEM remanufactured product may also signal lower quality for the new counterpart because the remanufactured products would not exist without returns due to defects from the market. Consequently, the consumers' WTPs may go down as a result of perceiving it as such a signal.

In contrast, Agrawal et al. (2015) find that the presence of third-party remanufactured products has a positive effect on the WTPs for the new products. They explain this result with the contrast effects (McKenna 1984; Mussweiler 2003). Unlike the perceived similarities between an OEM remanufactured product and its new counterpart, a product being remanufactured by third-parties may trigger more questions than confidence because of uncertainties involved in conforming with the remanufacturing specifications. This will shift the valuation for the new product away from that of the third-party remanufactured product.

These findings point to another unique property of remanufactured products. While the presence of an OEM remanufactured product can decrease the valuation of its new counterpart, thereby lowering margins for the new product seller, the presence of a third-party remanufactured product can be beneficial for the seller by increasing the valuation of its new counterpart.

Research in this domain is still in its early stages relative to many other closed-loop supply chain domains. A promising direction for this domain is to test the similar claims using transaction-level data from secondary markets. Another promising direction is to test whether the same claims will hold in the presence of competition from other OEMs, as suggested by Agrawal et al. (2015).

2.6 Conclusions

Changes in today's marketplaces for remanufactured products (e.g., increasing availability in online marketplaces) involve multiple marketing mechanisms for sellers to influence consumer valuation for remanufactured products in addition to the traditional methods: promoting their remanufactured products being up to the quality standards of their new counterparts. A closer look at the consumers' concerns for a typical remanufacturing process shows that there are several seller- and market-related factors that can have differing effects on consumers' valuation of remanufactured products relative to new products.

Three themes are used in this chapter to differentiate remanufactured products from new products. Seller reputation and identity are found to be influential factors in consumers' valuation of remanufactured products, while offering warranties does not influence consumer valuation of remanufactured products. An analysis of the influence of multiple buyer safeguards as signals of the valuation of remanufactured products show that the positive influence of returns acceptance on consumer valuation amplifies when the seller has high reputation for remanufactured products, but not for their new counterparts. Finally, consumers' new product valuations are lower if its remanufactured counterpart in the market is OEM manufactured, and higher if it is remanufactured by a third-party.

These findings provide leads on how valuation of environmental goods can be different particularly in the remanufacturing context. We believe that these unique findings provide a broad picture of this landscape to the OEMs, which will help them devise strategies to deal with potential cannibalization from remanufactured products, and increase their sales and profit-generation capability. Higher remanufactured product sales will also aid in maximizing the environmental objectives stated by Eurostat (2009), such as control, restore, treat, and minimize environmental problems related to waste, biodiversity, and landscapes.

Even with all of these findings on seller- and market-related factors, additional questions remain on whether remanufactured products uniquely differ from their new counterparts when it comes to testing the influence of brand equity and working conditions. We refer the reader to the other chapters in this book: by Abbey and Guide for an overview of studies that examines how consumers perceive the brand equity for remanufactured products, and by Zheng, Kraft, and Valdes for an overview of how consumers' valuations may differ based on transparency of a firm's social responsibility practices.

References

Agrawal V, Atasu A, van Ittersum K (2015) Remanufacturing, third-party competition and consumers' perceived value of new products. Manag Sci 61(1):60–72

Akerlof GA (1970) The market for "lemons": quality uncertainty and the market mechanism. Q J Econ 84(3):488–500

Atasu A, Guido V, van Wassenhove L (2008) Product reuse economics in closed-loop supply chain research. Prod Oper Manag 17(5):483–496

Boulding W, Kirmani A (1993) A consumer-side experimental examination of signalling theory. J Consum Res 20(1):111–123

Chu J, Chintagunta PK (2011) An empirical test of warranty theories in the U.S. computer server and automobile markets. J Mark 75(2):75–92

Dellarocas C (2003) The digitization of word-of-mouth: promise and challenges of online reputation mechanisms. Manag Sci 49(10):209–230

Dewan S, Hsu V (2004) Adverse selection in electronic markets: evidence from online stamp auctions. J Ind Econ 52(4):497–516

Eurostat EC (2009) The environmental goods and services sector: a data collection handbook. Technical report. http://ec.europa.eu/eurostat/documents/3859598/5910217/KS-RA-09-012-EN.PDF/01d1733e-46b6-4da8-92e6-766a65d7fd60?version=1.0

Ferguson M, Toktay LB (2006) The effect of competition on recovery strategies. Prod Oper Manag 15(3):351–368

Ferrer G, Swaminathan J (2006) Managing new and remanufactured products. Manag Sci 52(1):15–26

Ghose A (2009) Internet exchanges for used goods: an empirical analysis of trade patterns and adverse selection. MIS Q 33(2):263–291

Guide VDRJ, Li J (2010) The potential for cannibalization of new product sales by remanufactured products. Decis Sci 41(3):547–572

Guide D, van Wassenhove L (2009) The evolution of closed-loop supply chain research. Oper Res 57(1):10–18

HP (2015) Discover the benefits of refurbished products. http://www.hp.com/sbso/buspurchase_refurbished_whybuy.html.

Jacobs DL (2011) Ten secrets apple doesn't want you to know. Forbes (October 5):63. http://onforb.es/qbi8z4

McKenna F (1984) Assimilation and contrast in perceptual judgments. Q J Exp Psychol 36(3):531–548

Mussweiler T (2003) Comparison processes in social judgement: mechanisms and consequences. Psychol Rev 110(3):472–489

Pavlou PA, Dimoka A (2006) The nature and role of feedback text comments in online marketplaces: implications for trust building, price premiums, and seller differentiation. Inf Syst Res 17(4):391–412

Soberman D (2003) Simultaneous signaling and screening with warranties. J Market Res 40(2):176–195

Souza G (2013) Closed-loop supply chains: a critical review, and future research. Decis Sci 44(1):7–38

Subramanian R, Subramanyam R (2012) Key factors in the market for remanufactured products. Manufact Service Oper Manag 14(2):315–326

Subramanian R, Subramanyam R, Tereyağoğlu N (2015) The differential effects of buyer safeguards on new and refurbished products in an online marketplace. Working paper. Scheller College of Business, Georgia Institute of Technology

UNEP (2013) Green economy and trade—trends, challenges and opportunities. Technical report. http://www.unep.org/greeneconomy/Portals/88/GETReport/pdf/Chapitre%205%20Manufacturing.pdf

USITC (2012) Remanufactured goods: an overview of the U.S. and global industries, markets, and trade. Technical report. http://www.usitc.gov/publications/332/pub4356.pdf

Chapter 3
Assessing Consumers' Valuations of Socially Responsible Products with Controlled Experiments

Yanchong Zheng, Tim Kraft, and León Valdés

Abstract This chapter discusses the use of controlled experiments to study consumers' valuations of socially responsible products. We review three common experimental methodologies: conjoint analysis, controlled laboratory experiments, and controlled field experiments. We contrast these methods with examples and highlight the strengths of each method. Despite the large literature on consumers' valuations of social responsibility, few studies link consumers' valuations with a company's supply chain strategy. We present a recent study that fills this gap by utilizing a controlled laboratory experiment to investigate how the level of supply chain transparency may influence consumers' valuations of a company's social responsibility practices. We conclude by discussing a few interesting topics for future studies.

3.1 Introduction

In the field of Operations Management (OM), understanding the perspective of consumers is gaining increasing interests amongst both practitioners and researchers. In order to further improve OM decisions in practice, the modeling of consumer behavior is now being integrated into the design and analysis of operations processes and supply chains. An important method to study the behavior of consumers, or more generally, that of human

Y. Zheng (✉) • L. Valdés
Massachusetts Institute of Technology, Cambridge, MA 02139, USA
e-mail: yanchong@mit.edu; lvaldes@mit.edu

T. Kraft
University of Virginia, Charlottesville, VA 22903, USA
e-mail: KraftT@darden.virginia.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_3

decision makers, is through incentivized controlled experiments. The OM field has seen a dramatic increase in the number of studies that utilize controlled experiments to study human behavior in various operations contexts. Some examples include inventory decisions when facing demand uncertainty (e.g., Schweitzer and Cachon 2000; Bolton and Katok 2008), information sharing in a decentralized supply chain (e.g., Özer et al. 2011, 2014), and consumer behavior in queuing systems (e.g., Kremer and Debo 2015). These studies yield important insights regarding how a company should adjust its operational strategies to account for latent behavioral factors that have not been incorporated in prior models.

Sustainable supply chains is an emerging area in which behavioral studies are being used to examine how consumers can influence companies' sustainability strategies. In this chapter, we discuss how researchers and practitioners can utilize controlled experiments to examine whether and when supply chain transparency impacts consumers' valuations of a company's social responsibility[1] practices. Consumer-facing companies are experiencing increasing demand from their customers to be more transparent about where and how their products are manufactured. Hence, there is a need to understand the value of increasing transparency for consumers, companies, and society. This understanding can help companies make better decisions regarding investment in supply chain transparency and the type of information they should communicate to consumers.

The chapter is organized as follows. In Sect. 3.2, we first review the broader marketing and economics literature in which researchers attempt to understand and measure consumers' valuations of sustainable products. In Sect. 3.3, we present the findings and managerial implications from a recent controlled laboratory experiment. In Sect. 3.4, we discuss several interesting topics for future research and present a product choice study that can be the basis for testing our lab findings with actual products. In Sect. 3.5, we conclude the chapter.

3.2 Marketing and Economic Studies on Consumers' Valuations of Sustainability

There is a wealth of marketing and economic studies that investigate how much consumers value companies' environmental and social responsibility practices and how such valuations affect consumers' purchase decisions.

[1] We follow the European Commission's definition of social responsibility as "[companies integrating] social and environmental concerns in their business operations and in their interaction with stakeholders on a voluntary basis" (Dahlsrud 2008). The definition of social responsibility and how it differs from sustainability is subject to debate (Montiel 2008). For our purposes, we position social responsibility as a subset of a company's broader sustainability agenda.

Three methodologies are commonly used in these studies: conjoint analysis, controlled laboratory experiments, and controlled field experiments. In this section, we present several representative examples and discuss the strengths of each method. Note that a number of well-known attitudinal surveys in this domain also exist, including Straughan and Roberts (1999), Mohr et al. (2001), Mohr and Webb (2005), and Vermeir and Verbeke (2006). Our focus here is on studies where participants need to make purchase-related decisions as opposed to providing opinions.

Conjoint analysis is a widely-used method among marketing researchers for studying consumer choice (Orme 2005; Feinberg et al. 2012). In a typical conjoint design, participants are presented with multiple products that vary across different characteristics (e.g., price, quality, color, taste, etc.). Participants are then asked to indicate their preferences among the products or to state indifference. Most conjoint studies are non-incentivized. That is, the participants do not engage in an actual purchase or gain a monetary benefit due to their decisions. Nevertheless, the benefit of a conjoint design is to establish a hypothetical but realistic choice scenario, while at the same time limiting the participant's attention to a few salient attributes of interest. De Pelsmacker et al. (2005) conducted a conjoint study concerning the consumption of fair-trade coffee in Belgium. In their study, participants are shown eight different types of coffee that vary in the attributes of brand, blending, packaging, flavor, and whether or not its package has a fair-trade label. The participants state the highest price at which they are willing to buy each type of coffee; i.e., their willingness-to-pay (WTP). The results show that the attributes of brand, flavor, and existence/non-existence of a fair-trade label are the three most important attributes affecting the participants' WTP. About half of the sample are willing to pay a price premium for coffee with a fair-trade label, and the average premium in the entire sample is a 10 % increase in price (equivalent to \$0.22 U.S. dollars). The authors point out that there exist substantial variations of WTP for fair-trade coffee in their sample, and only 10 % are willing to pay the actual premium (27 %, equivalent to \$0.57 U.S. dollars) in the marketplace. This is one of the earliest studies demonstrating that prior surveys that do not explicitly account for prices in the design may well overestimate the market potential for socially responsible products. We refer the reader to Arora and Henderson (2007), Irwin and Naylor (2009), Elfenbein and McManus (2010), and Olson (2013) for additional examples of conjoint studies on consumer preferences related to sustainable products.

Increasingly, researchers are turning to incentivized experiments to investigate consumers' purchase behavior regarding sustainable products. This is because evidence exists that consumers often tend to overstate their preferences for sustainable products in non-incentivized surveys to "look good" from the eyes of the researchers (e.g., Devinney et al. 2010, p. 112). The two most popular methods for incentivized studies are controlled lab experiments and controlled field experiments. Controlled lab experiments offer the cleanest possible environment to test a behavioral hypothesis of interest. In the lab, a researcher can design the task environment to be free of external "noise" that may impact decisions but that are not of interest to the researcher. This allows the researcher to gain a deeper understanding of the behavioral factors and psychological processes that influence decision-making. For example, Koschate-Fischer et al. (2012) conducted a series of interesting experiments to study the impact of donation amounts on consumers' WTP in "cause-related marketing"—a scenario in which a company promises that a certain amount of money associated with the sales of its products will be donated to a social cause or a non-profit organization. Building on prior studies that show a positive effect of donation amount on consumers' WTP, the authors ask the question of how the fit between the company and the social cause it donates to impacts the relationship between donation amount and consumers' WTP. An example of a high company—cause fit is a bottled mineral water company donating to a project for revitalizing local rivers. An example of a low company—cause fit is the mineral water company donating to a nonprofit that prevents cruelty to animals. The authors show that for a variety of products, donation amount has a stronger effect on consumers' WTP when the fit is low. The authors show that this stronger effect is attributed to consumers' inference of the company's motive behind the donation. Since donating to a low-fit cause is unexpected, it induces consumers to believe that the donation is associated with an explicit motive beyond the necessary responsibility of the company. Hence, consumers react more strongly to changes in the donation amount. Additional examples of controlled lab experiments regarding consumer choice and sustainable products include Krishna and Rajan (2009), Munro and Valente (2009), Engelmann et al. (2011), and Agrawal et al. (2015).

Controlled field experiments are another popular method for conducting incentivized studies. A controlled field experiment is conducted in an actual marketplace where the researcher exerts some control on the market environment (e.g., product types, brands, consumer demographics). This permits the researcher to perform a more systematic analysis of specific market characteristics, as compared to an analysis based on archival data. Controlled field experiments are useful for examining how behavioral findings from the lab generalize to practical settings; however, the research focus is typically on investigating the effectiveness of various strategies in the market. For example, Gneezy et al. (2010) design a field experiment in the sale of souvenir photos to study how different pricing strategies affect charitable giving by consumers. In this experiment, consumers either encounter a fixed list price of the photo, or they are allowed to name their own prices (i.e., a "pay what you want" strategy). Under either strategy, half of the consumers are in the treatment where 50 % of the price they pay will go to a charity. Their findings reveal a strikingly positive effect of pay-what-you-want pricing on charitable giving. That is, when consumers name their own prices and they know that half of what they pay goes to a charity, photo sales yield the highest profit for the company and consumers make the largest donation to the charity. The authors postulate that this positive effect is due to consumers' perception of shared social responsibility under pay-what-you-want pricing; i.e., this pricing regime allows them to explicitly express their social consciousness through purchasing of the product, thereby increasing their willingness to contribute. Other field experiments in the sustainability domain include Prasad et al. (2004), Hainmueller and Hiscox (2012), and Hainmueller et al. (2015).

Despite the emerging literature examining consumers' valuations of sustainable products, few studies have linked a company's supply chain strategy regarding sustainability with consumers' purchase behavior (Carter and Easton 2011). We discuss in the next section a behavioral study that fills this gap. We design an incentivized controlled laboratory experiment to study an emerging question in social responsibility: How does supply chain transparency affect consumers' valuations of a company's social responsibility practices?

3.3 Supply Chain Transparency and Social Responsibility: A Controlled Laboratory Experiment

In the early 1990s, Nike was publicly accused of using child labor in Pakistan to sew soccer balls and running shoes (Doorey 2011). The crisis posed a serious threat to the company's brand image. In 1998, Nike President, Phil Knight, had to publicly apologize for the abusive working conditions in the company's global supplier factories. Knight introduced a series of new initiatives that the company would undertake to better monitor labor practices in its global supply chain. In April 2005, Nike disclosed the list of nearly 750 factories producing Nike products around the world. Nike's disclosure, albeit forced by pressure from social activists and public media, represented one of the earliest examples of a large corporation committing to supply chain transparency.

Today, as technology improves and the role of social responsibility in business continues to evolve, consumer demands are forcing companies to adapt their operations to meet the needs of a changing marketplace. Companies must address not only how to establish socially responsible practices throughout their supply chains but also how to demonstrate these practices to the public. In this regard, many companies are increasing the transparency of their supply chains. For example, in 2007 Patagonia launched "The Footprint Chronicles," a website dedicated to giving consumers visibility into Patagonia's supply chain (Patagonia 2014). The Footprint Chronicles includes detailed information regarding the social and environmental challenges that Patagonia's suppliers face, as well as how Patagonia works with its suppliers to address these challenges. Similarly, in 2013 Nestlé introduced a QR code on the packaging for Kit-Kats in the United Kingdom. Consumers can scan the code to obtain detailed information about the social and environmental impacts of the product (Nestlé 2013). Websites and smart labels such as these provide consumers with unique insights into the social and environmental impacts of a company's supply chain. However, providing such extensive visibility is a costly and time consuming investment for a company (Doorey 2011). In addition, there is a lack of research that quantifies consumers' valuations of supply chain transparency and hence, the potential revenue benefit it can provide to companies. Accordingly, many companies are still unsure of the extent to which they should invest to increase transparency in their supply chains. One key objective of our study is to determine, using a controlled laboratory experiment, when a company can benefit from increased transparency.

In today's marketplace, consumers are often overwhelmed and confused by the array of information available on product packages and online (e.g., Thøgersen et al. 2010; Delmas et al. 2013). Relatedly, many companies are still trying to understand what kind of information is important to their customers. Studies in consumer psychology have shown that different information cues can stimulate and influence the salience of distinct preferences in consumer perception and judgment (e.g., Reed II 2004; Kim and John 2008). Hence, we expect that what information resonates best with a consumer depends on the underlying behavioral motives driving consumers' care of social responsibility issues. Two distinct categories of social preferences are likely to play a role. The first category contains "outcome-based" social preferences, such as altruism (e.g., Levine 1998; Andreoni and Miller 2002) and inequality aversion (e.g., Fehr and Schmidt 1999; Bolton and Ockenfels 2000). A consumer driven by outcome-based preferences focuses on the results of a company's social responsibility initiative; e.g., who benefits from the initiative and how much. The second category regards "process-based" social preferences, such as reciprocity (e.g., Fehr et al. 1998; Nowak and Sigmund 1998). If a consumer is motivated by process-based preferences, then demonstrating the effort (e.g., capital and time investment) that a company exerts to maintain a socially responsible supply chain can benefit the company. In our study, we design the experiment to disentangle outcome-based versus process-based preferences in consumers' decisions. This distinction allows us to provide insights into how a company can better communicate its social responsibility practices to its consumers.

A third design element in our study concerns consumer heterogeneity in their tendency to care about social responsibility. This is important because not all consumers are equally concerned about a company's social responsibility practices (e.g., García-Gallego and Georgantzís 2011). In particular, we focus on consumers' heterogeneous "prosocial orientations," defined as the extent to which an individual is willing to sacrifice his/her own benefit to help others. Care about social responsibility represents a consumer's intention to indirectly help a third party by motivating responsible practices from companies. Hence, there is a natural connection between a person's prosocial orientation and his/her attention to social responsibility. We investigate whether the value of supply chain transparency differs for consumers with different prosocial orientations.

To operationalize social responsibility in our experiment, we study a social context in which a worker has helped a company to make a product that the company would like to sell to a consumer. Hence, the experiment focuses on the dimension of social responsibility regarding the company's treatment of the worker. We discuss next the design of our experiment in more detail.

3.3.1 Experimental Design

We design a three-player game called the Consumer Purchase Game. It consists of a Firm (she), a Consumer (he), and a Worker. At the beginning of the game, the three players are told to consider a hypothetical scenario in which the Worker has helped the Firm to make a product, and the Firm wants to sell the product to the Consumer. The Firm, the Consumer, and the Worker are initially given 160, 120, and 20 points, respectively. The Firm *provisionally* receives an additional 120 points. The Firm earns these provisional points only if she manages to sell the hypothetical product to the Consumer.

The dynamics of the Consumer Purchase Game are described in Fig. 3.1a. First, the Firm decides how much from the provisional 120 points she is willing to use to pay the Worker. We refer to the Firm's decision as her *effort* e. The potential values of e range from 0 to 120 in increments of 20; i.e., e can be any value of 0, 20, 40, 60, 80, 100, or 120. Second, the Consumer states the maximum price that he is willing to pay for the product, given the Firm's effort. The Consumer's willingness-to-pay (WTP) measures his valuation of social responsibility. The Worker does not make any decisions. If the product is sold, then the Worker receives a payment w that depends on e. After the Firm and the Consumer make their decisions, the computer randomly picks the product price, p, between 1 and 120 points with equal chance. If p is lower than or equal to the Consumer's WTP, then the product is sold. In this case, the final payoffs to all players (including initial endowments) are as follows: (1) the Consumer pays the price of the product to the Firm and earns a payoff of $(120 - p)$ points; (2) the Firm receives the provisional 120 points plus the price of the product minus her effort, earning a total payoff of $(160+120+p-e)$ points; and (3) the Worker receives the payment and earns a payoff of $(20 + w)$ points. Otherwise, if the price p is strictly higher than the Consumer's WTP, then the product is not sold and all players receive their initial endowments: 120 points for the Consumer, 160 points for the Firm, and 20 points for the Worker.[2] Making players' payoffs dependent on their

[2] The described approach for determining the players' payoffs is known as the Becker-DeGroot-Marschak mechanism (Becker et al. 1964). It is a common technique in the experimental economics literature to elicit a truthful WTP (e.g., Klos et al. 2005; Halevy 2007).

decisions is a common way to motivate participants to make careful decisions in lab experiments.

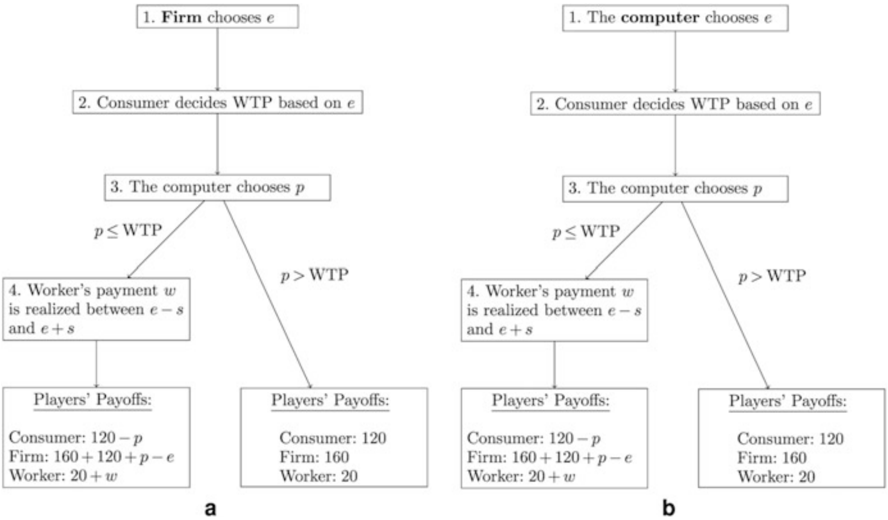

Fig. 3.1 Summary of experimental design. (**a**) Decision condition, (**b**) random condition

We manipulate the Consumer Purchase Game in two dimensions. First, we manipulate the relationship between the Firm's effort e and the payment to the Worker w to model different levels of transparency. Specifically, w depends on e in the following manner:

$$w = \begin{cases} 0, & \text{if } e = 0, \\ \text{a random number between } e - s \text{ and } e + s \text{ with equal chance}, & \text{if } e > 0. \end{cases}$$

We examine three different values of s for three different levels of transparency: $s = 0$ for *High* Transparency, $s = 10$ for *Medium* Transparency, and $s = 20$ for *Low* Transparency. The condition of $s = 0$ represents high transparency because the payment to the Worker if the product is sold is exactly equal to the Firm's effort e. Conversely, $s = 20$ represents low transparency because given e, there is still large uncertainty regarding the actual payment to the Worker. In our design, the Consumer always observes the Firm's effort. Hence, we study transparency regarding the extent to which the *outcome* of the Firm's social responsibility effort is precisely known to the Firm and the Consumer. In a fully transparent supply chain, both the Firm and the Consumer know exactly the Firm's effort and the resulting payment to the Worker (i.e., the outcome). In a non-fully transparent supply chain, however, there is uncertainty in the payment to the Worker for all players, even though the Firm's effort is still observable to both the Firm and the Consumer.

The second manipulation is designed to disentangle outcome-based and process-based social preferences. In particular, we seek to isolate the effect of reciprocity in affecting the Consumers' valuations.[3] To do so, we manipulate the process by which the effort e is selected and compare two Selection conditions: the *Decision* condition versus the *Random* condition. Under the Decision condition, the Firm chooses the effort e as discussed above (see Fig. 3.1a). In contrast, under the Random condition, the computer randomly chooses e from the seven possible values $\{0, 20, 40, 60, 80, 100, 120\}$ with equal chance, and the Firm automatically accepts the chosen value (see Fig. 3.1b). For ease of exposition, we still refer to e as the Firm's effort in the Random condition, although it is not actively chosen by the Firm. Since the Firm is not responsible for the selection of e in the Random condition, high or low values of e in this condition cannot be interpreted by the Consumer as a sign of the Firm treating the Worker responsibly or irresponsibly. Therefore, reciprocity cannot play a role in affecting the Consumer's WTP in the Random condition. Conversely, the Consumer's WTP in the Decision condition is driven by both outcome-based preferences *and* reciprocity. Hence, differences observed in WTP between these two conditions capture reciprocity. To measure reciprocity, we compare the marginal increase in WTP given a unit increase in effort between the Decision and Random conditions. Reciprocity exists if this marginal increase is larger when the Firm actively chooses e (the Decision condition) than when the computer chooses e (the Random condition). Pictorially, if we draw a line to describe how WTP changes with effort, then reciprocity exists when the line is steeper in the Decision condition than in the Random condition; i.e., we use the difference in the slopes of these lines to measure reciprocity. This approach is well established in prior works (e.g., Charness 2004).

Finally, to elicit the Consumer's prosocial orientation, we ask each Consumer to play a dictator game (Forsythe et al. 1994) that consists of two players: a dictator and a recipient. The dictator and the recipient are initially endowed with 120 and 20 points, respectively. The Consumer acts as the dictator and is asked to choose the number of points, a, from the set $\{0, 20, 40, 60, 80, 100, 120\}$ that he is willing to use to generate a payment to the recipient. Given the Consumer's decision, the recipient receives a payment t that is a random number between $a - s$ and $a + s$ with equal chance if $a > 0$, and a payment of zero if $a = 0$. The value of s used in this game is set equal to the value of s the Consumer has faced in the Consumer Purchase Game. The Consumer's decision a as the dictator measures his prosocial orientation, because a higher value of a implies that the Consumer is more willing to improve the recipient's payoff at his own cost.

[3] More precisely, we study the preference of indirect reciprocity, defined as "the return from a social investment in another ... from someone other than the recipient of the beneficence" (Alexander 1987, p. 5). In our design, a Consumer motivated by indirect reciprocity would be willing to reward the Firm for its responsible treatment of the Worker (e.g., ensuring a reasonable payoff).

Given the above design, we seek to understand how transparency, reciprocity, and individual prosocial orientation jointly affect consumers' valuations of a company's social responsibility practices.

3.3.2 Experimental Results

We conducted a total of six experimental treatments (three Transparency conditions combined with two Selection conditions) in the MIT Behavioral Research Lab and the VeconLab at the University of Virginia. Table 3.1 summarizes the number of Consumer participants in each treatment and the corresponding treatment conditions. A total of 198 participants played the role of the Consumer. All of the participants in the study were students; 82.4 % of them were undergraduates and the remaining 17.6 % were graduate students. In addition, 61.2 % of them were female, and the average age was 21.6 years old. Participants earned an average of \$29.56, with a minimum of \$20 and a maximum of \$40. Each session lasted on average 90 minutes.

Table 3.1 Summary of experimental treatments

Selection condition	Transparency condition	Number of Consumer participants
Decision	High	26
Decision	Medium	29
Decision	Low	31
Random	High	38
Random	Medium	34
Random	Low	40

Figure 3.2 summarizes the histograms of Consumers' average WTP decisions in the Decision condition for the three levels of transparency. The average WTP is computed by averaging a Consumer's decisions over all seven possible effort levels.[4] The red, green, and blue bars correspond to the high, medium, and low transparency conditions. Each bin includes the lower bound of the range but not the upper bound. For example, the first bin includes WTP decisions that are greater than or equal to 0 and strictly smaller than 20. Two observations are immediately evident. First, regardless of the transparency conditions, we observe a substantial portion of the Consumers state an average WTP of zero. These Consumers only care about their own

[4] We use the strategy method to obtain the Consumers' WTP decisions for all effort levels (see, e.g., Fehr and Fischbacher 2004; Falk et al. 2008). That is, we ask each Consumer to state his/her WTP for each possible effort level while the Firm is choosing the actual effort. Note that the final payoffs are determined by the actual effort chosen by the Firm and the Consumer's stated WTP corresponding to that effort.

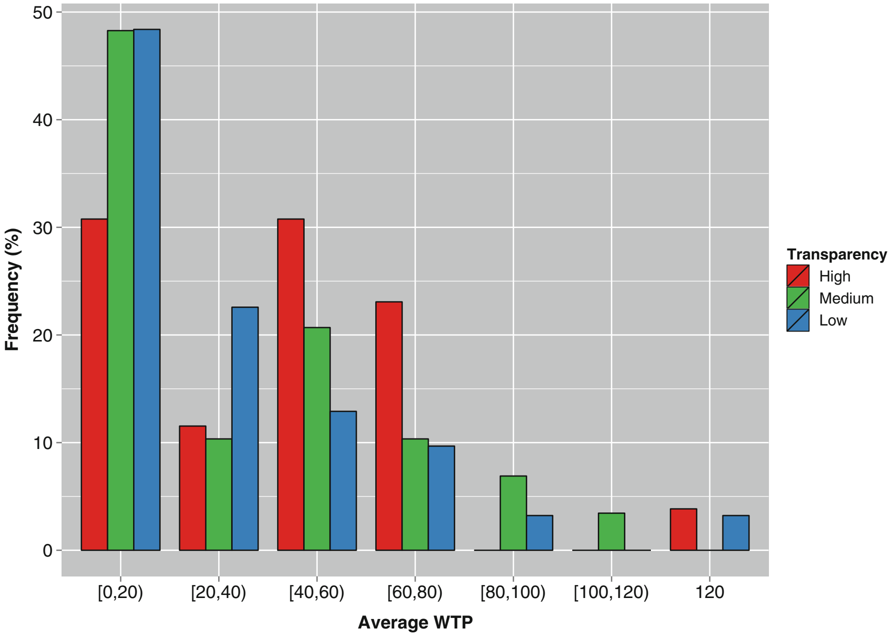

Fig. 3.2 Histogram of Consumers' willingness-to-pay in the Decision condition

welfare and are not willing to sacrifice their own payoffs to benefit the Worker. Nonetheless, over half of the Consumers state positive WTP. This result highlights the importance of considering individual heterogeneity when analyzing the Consumers' valuations of social responsibility. Second, there are notable differences in the distributions of the Consumers' WTP across different transparency conditions. In particular, substantially more Consumers state a zero WTP under medium or low transparency than under high transparency. In addition, when comparing the distributions of the positive WTP decisions, we observe that the peak WTP shifts from 40–60 under medium or high transparency to 20–40 under low transparency. This result suggests that transparency can affect consumers' valuations of a firm's social responsibility practices.

Before studying the role of transparency and reciprocity in the Consumers' valuations, we first define what constitutes a low versus a high prosocial Consumer based on the Consumer's decision in the dictator game. Figure 3.3 presents a histogram of dictator decisions by our Consumer participants. The median contribution is 20, and about 37 % of Consumers contribute zero to their recipients in the dictator game. Therefore, we define two types of Consumers in our sample. High prosocial Consumers are those who contribute 40 or more to their recipients, and low prosocial Consumers are those who contribute 0 or 20 to their recipients. In our sample, 36 % (71 participants) are of the high prosocial type and 64 % (127 participants) are of the low prosocial type. In what follows, we discuss in detail how transparency and reciprocity affect the behavior of high and low prosocial Consumers.

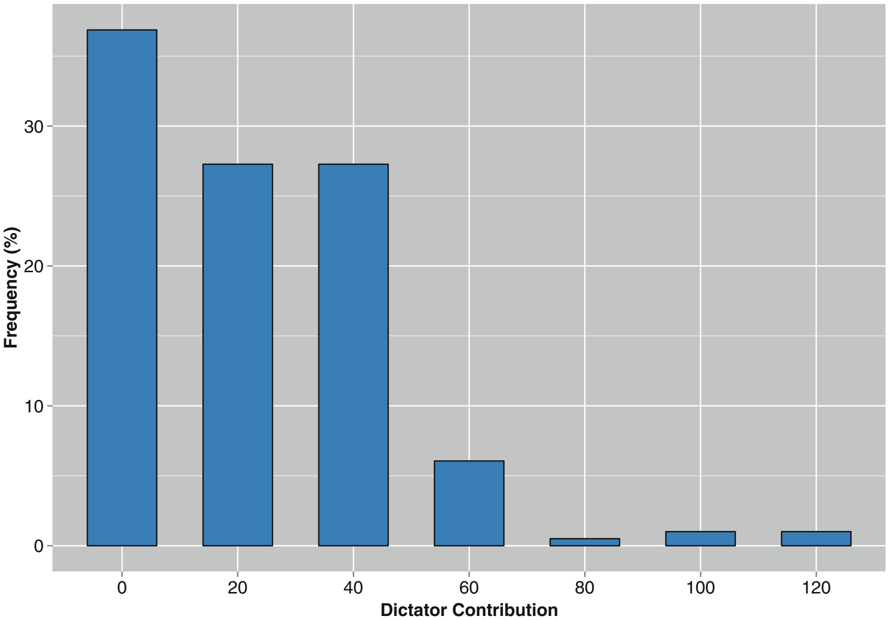

Fig. 3.3 Histogram of Consumers' decisions in the dictator game

3.3.2.1 Do Consumers Value Increased Transparency?

We begin by analyzing the effect of transparency on the Consumer's WTP in the Decision condition. Figure 3.4 shows the high and low prosocial Consumers' average WTP in each Transparency condition. We observe a positive effect of transparency on WTP.[5] For both types of Consumers, their WTP is higher under either medium or high transparency than under low transparency. Comparing between medium and high transparency, both types of Consumers state similar WTP across these two conditions. These observations suggest that the Consumers in our sample do value increased transparency. They are willing to pay a higher price when the supply chain is more transparent; however, increases in transparency generate diminished returns.

[5] All experimental results reported here are statistically significant. Please refer to Kraft et al. (2016) for more details of our statistical analysis.

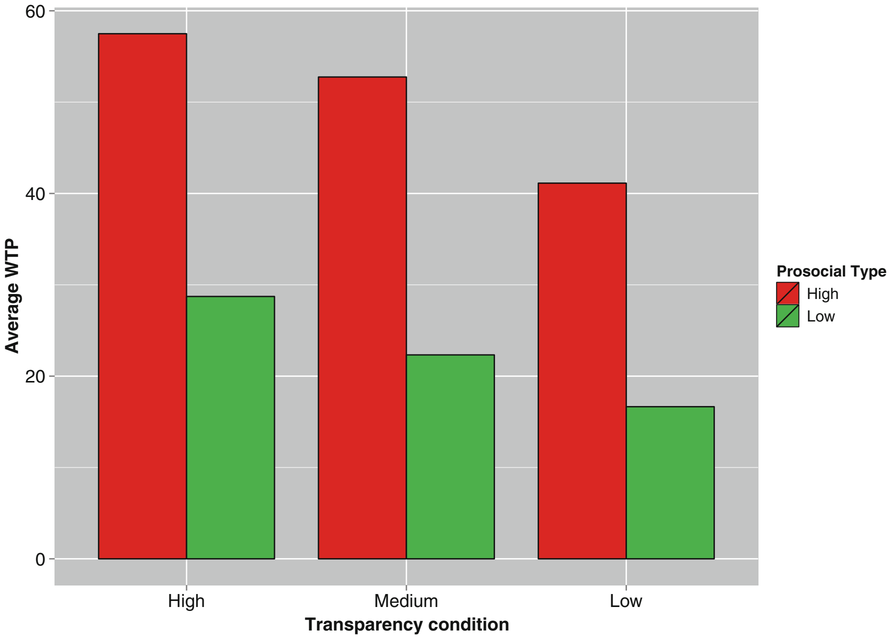

Fig. 3.4 Effect of transparency on Consumers' willingness-to-pay

3.3.2.2 Are Consumers Motivated by Reciprocity?

Next, we address whether the Consumers exhibit reciprocity in their WTP decisions for socially responsible products at each level of transparency. We begin with high prosocial Consumers.

Figure 3.5 presents the average WTP for high prosocial Consumers under each Transparency and Selection condition. The solid lines describe how the Consumers' WTP changes with effort levels when the Firms actively choose their effort levels (i.e., the Decision condition, see Fig. 3.1a). The dotted lines describe the same relationship but when the effort levels are randomly picked by the computer (i.e., the Random condition, see Fig. 3.1b). Recall from Sect. 3.3.1 that reciprocity exists if the solid lines are steeper than the dotted lines. We observe from Fig. 3.5 that in none of the Transparency conditions is the slope of the solid line steeper than that of the dotted line. Hence, *high prosocial Consumers do not exhibit reciprocity in any of the Transparency conditions*. Our findings suggest that high prosocial Consumers' WTP decisions are driven by the expected payment to the Worker (i.e., the value of e) and the level of transparency, but not by reciprocity.

In sharp contrast, Fig. 3.6 demonstrates that *low prosocial Consumers' behavior is significantly affected by reciprocity*. First, under high transparency (Fig. 3.6a), the solid line is steeper than the dotted line, showing the existence of reciprocity. In addition, reciprocity has a *positive* effect on WTP at a high

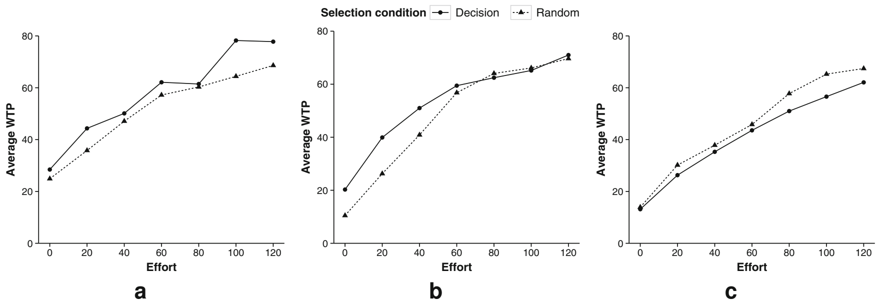

Fig. 3.5 Effect of reciprocity for high prosocial Consumers. (**a**) High transparency, (**b**) medium transparency, (**c**) low transparency

effort level since the average WTP is higher in the Decision condition than in the Random condition (e.g., when $e = 120$). Second, as shown in Fig. 3.6b, we continue to observe the presence of reciprocity for low prosocial Consumers under medium transparency. However, in this case, reciprocity has a *negative* effect on WTP as it drives the average WTP at low effort levels to be lower in the Decision condition than in the Random condition (e.g., when $e = 20$ or 40). Finally, Fig. 3.6c shows that reciprocity does not exist under low transparency as the slope of the solid line is not higher than that of the dotted line.

Notice that in the Low Transparency condition we observe a behavior unique to the low prosocial Consumers. The average WTP in the Decision condition is *lower* than the average WTP in the Random condition at all positive effort levels. Hence, when the level of transparency is low, the low prosocial Consumer seemingly penalizes the Firm regardless of the chosen effort when the Firm is an active decision maker. We postulate that this behavior is due to the low prosocial Consumer's perception of "responsibility alleviation" as described below.

When the Firm makes an active decision in the Decision condition, both the Firm's and the Consumer's decisions determine the final payoffs to all three players. Conversely, in the Random condition, the Consumer is the *only* player who makes an active decision to influence the final payoffs of all three players. Therefore, the Consumer is likely to feel more responsible for the Worker's well-being in the Random condition and less so in the Decision condition. With a decreased sense of responsibility for the final outcomes, the Consumer's low intrinsic prosocial orientation motivates him to state a lower WTP in the Decision condition than in the Random condition when transparency is low. We indeed find evidence in the post-experiment survey that our participants are potentially influenced by responsibility alleviation. For example, a participant who played the Consumer role in the Low Transparency, Random condition stated that "being [the Consumer] made me feel pressured as the decision maker … that affects other people." Our obser-

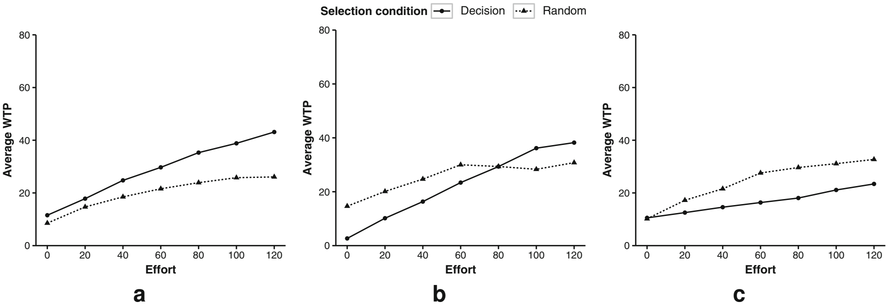

Fig. 3.6 Effect of reciprocity for low prosocial Consumers. (**a**) High transparency, (**b**) medium transparency, (**c**) low transparency

vation on low prosocial Consumers' perception of responsibility alleviation also echoes the "shared social responsibility" idea of Gneezy et al. (2010, see Sect. 3.2). That is, the Workers are better off and the achieved level of social responsibility is higher when the Consumers assume more responsibility for the welfare of the Workers.

3.3.3 Managerial Implications

Our results have important practical implications on (1) when a company can benefit from increased transparency in its supply chain, and (2) how a company should communicate social responsibility information to consumers. Our findings suggest that consumers are willing to pay more for products when a company adopts supply chain transparency with respect to its social responsibility practices. This is particularly true when the company improves the transparency of a non-transparent supply chain. As transparency further improves, however, the increase in consumers' willingness-to-pay diminishes. Going forward, as companies debate whether to increase the transparency of their supply chains, our results underscore a potential revenue benefit from this often costly investment.

Our study also takes an important first step to examine the type of information and the level of detail that consumers desire when a company communicates its social responsibility practices. We show that the particular communication strategy that a company should employ depends on the intrinsic prosocial orientation of the consumers. If the targeted population naturally cares about others' well-being (i.e., high prosocial consumers), then attention should be placed more on communicating social responsibility outcomes through transparent information and less on communicating the amount of effort exerted by the company. This is because high prosocial consumers are primarily driven by the outcomes of the social responsibility practices and do not exhibit reciprocal motives towards a company's effort. Conversely, if a company seeks to target consumers that are more driven by self-interest (i.e., low prosocial consumers), then it should focus on first improving the transparency of the information. Only when highly transparent information is available should the company then communicate its exerted effort. Otherwise, emphasizing exerted effort when the level of transparency is not high can inadvertently hurt the company. Without transparent information, the low prosocial consumers are more inclined to punishing low efforts with lower willingness-to-pay, or they find it easier to justify their low willingness-to-pay by shifting responsibility for the third parties' well-being onto the company.

3.4 Future Directions

Our findings from the above lab experiment lend themselves to a number of interesting future research directions. For example, how does supply chain transparency help a company establish credibility among consumers regarding its sustainability practices? To examine this question, one could consider an experiment in which consumers only observe the "claimed" sustainability practice, and improving the transparency of the supply chain would make it easier for consumers to verify the company's actual practice. Other relevant questions to study include, how does an industry standard (i.e., the average level of sustainability in the industry) affect consumers' valuations of a company's sustainability efforts? How do competitive forces in the market impact consumers' valuations and companies' decisions regarding sustainability? Are consumers' valuations of social responsibility affected by whether production occurs domestically or internationally? Investigating these questions with carefully-designed, incentivized lab experiments can be an important first step towards a comprehensive account of consumers' role in shaping companies' sustainability agenda.

Another important direction is to examine how findings from controlled lab experiments apply to actual purchase settings. Along this direction, we recently conducted a product choice study based on a simplified conjoint design. The goal of this study is to investigate how providing more or less transparent information about social responsibility practices may influence consumers' choices among similar products for different product categories and social responsibility topics.

In our product choice study, each participant is presented 24 pairs of products and states which one in each pair he/she prefers to buy. Similar to a conjoint design, we show the participants information about the characteristics of the products in each pair. Across different pairs, we vary two key pieces of information: the prices of the products and messages regarding the company's social responsibility practices. We examine six different price points for each product category. Each product is associated with either a vague or a precise message with social responsibility information. Compared to the vague message, the precise message represents increased transparency regarding the company's social responsibility practices. The two products in each pair differ in their social responsibility messages and may have the same or different prices. In our design, a product with a precise social responsibility message is priced equally as or higher than a product with a vague message. Table 3.2 shows an example question in this product choice study.

Table 3.2 An example question in the product choice study

Which one of the following products do you prefer to buy?	
Ground coffee (1 lb.) Unit price: \$11.00 Medium-roasted Unflavored Origin: Guatemala	**Ground coffee (1 lb.)** Unit price: \$10.00 Medium-roasted Unflavored Origin: Guatemala
The following additional information can be found on the product's packaging:	*The following additional information can be found on the product's packaging:*
"We have ensured that, in all countries where our suppliers operate, the wages paid to our suppliers' employees are at least twice as high as the minimum standard required by law. Our suppliers' employees work for no more than 48 h per week."	"We have ensured fair wages and reasonable working hours for all of our suppliers' employees."

We examine three different product categories: coffee, T-shirts, and laptop computers. Five different social responsibility topics are considered: treatment of the company's employees, treatment of the company's suppliers' employees, community development in regions where the company operates, community development in regions where the company's suppliers operate, and charitable donations. Table 3.3 summarizes the vague and precise messages for each of these topics in our design. As seen in the table, a precise message (versus a vague one) communicates more transparent information regarding the company's social responsibility practices.

Our findings in the product choice study are consistent with and complement our experimental findings that consumers are willing to pay higher prices with increased transparency (see Sect. 3.3.2.1). Figure 3.7 shows the fraction of participants who choose the product with precise social responsibility information when both products have the same price. Our data demonstrates that despite heterogeneity across products and topics, the majority of consumers prefer more transparent information when it does not come with a price premium.

When more transparent information is offered at a premium, Fig. 3.8 summarizes the average maximum premiums (as percentages) that the participants are willing to pay for different product categories and social

Table 3.3 Social responsibility messages used in the product choice study

Social responsibility topics	Vague message	Precise message
Treatment of employees	We have ensured fair wages and good working conditions for all of our employees.	We have ensured that, in all countries where we operate, the wages paid to our employees are at least twice as high as the minimum standard required by law. Our employees work for no more than 48 h per week.
	We have ensured fair wages and good working conditions for all of our suppliers' employees.	We have ensured that, in all countries where our suppliers operate, the wages paid to our suppliers' employees are at least twice as high as the minimum standard required by law. Our suppliers' employees work for no more than 48 h per week.
Community development	We have been working with local communities in which our company operates, in order to improve children's access to education and health services.	We have spent $1 million in the last 4 years in improving access to education and health services for over 2000 children in 45 communities in which our company operates.
	We have been working with local communities in which our suppliers operate, in order to improve children's access to education and health services.	We have spent $1 million in the last 4 years in improving access to education and health services for over 2000 children in 45 communities in which our suppliers operate.
Charitable donations	Between 10 % and 30 % of the profits from the sale of this product will be donated to a charitable organization.	20 % of the profits from the sale of this product will be donated to a charitable organization.

responsibility topics. The maximum premium for a participant is the highest premium at which the participant still prefers the higher-priced product with precise information. The average numbers shown in the figure are obtained by averaging the maximum premiums across all participants in Fig. 3.7. We first highlight that, for all product categories and all social responsibility topics we study, the participants are willing to pay some premium if more transparent information is provided. However, we do observe substantial differences across product categories and social responsibility topics. For example, within the three product categories, the participants are willing to pay larger premiums for having more transparent information in the coffee category. This result can be due to the salience of the fair trade movement in this industry. Similarly, in response to recent tragic events in garment factories in the upstream supply chain of apparel companies (Economist 2012), the participants also

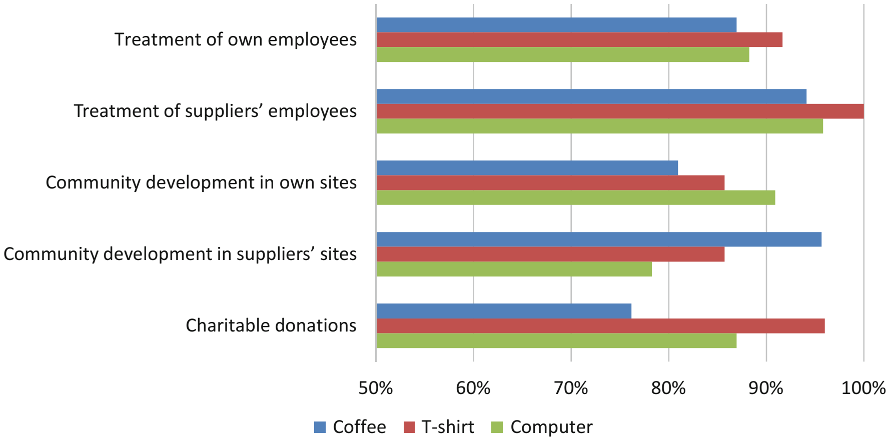

Fig. 3.7 Fraction of consumers preferring precise social responsibility information when prices are the same

prefer more transparent information even at a higher price when concerning the responsible treatment of the employees of a T-shirt company's suppliers. Our next step is to build upon this product choice study to design a controlled field experiment to study the impact of communicating more transparent sustainability information to consumers in an actual marketplace.

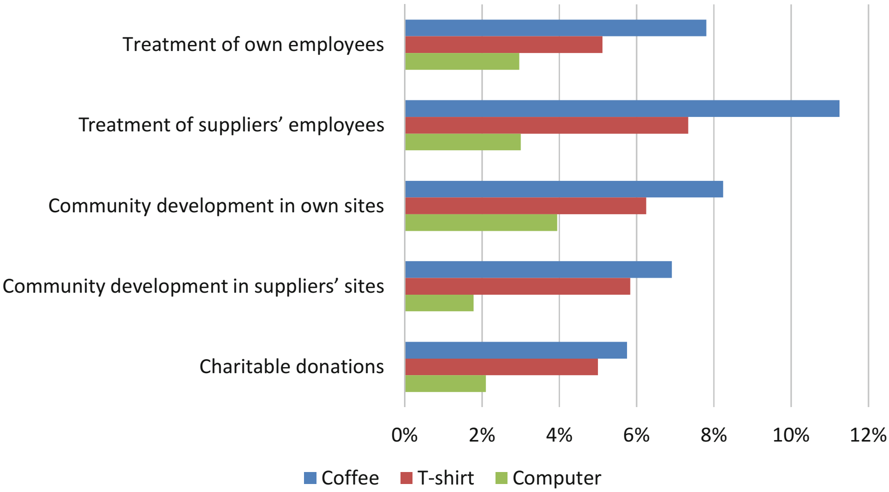

Fig. 3.8 Average maximum premiums (%) for precise social responsibility information

3.5 Conclusion

As sustainability continues to develop into a key element of corporate business agendas, it is critical for companies to integrate the perspectives of external stakeholders such as consumers, investors, and NGOs into the design of the companies' sustainability initiatives. In this chapter, we focus on the perspective of the consumers, and demonstrate how controlled experiments can be used to examine consumers' valuations of a company's social responsibility practices. Our study in Sect. 3.3 investigates the role of supply chain transparency, reciprocal motives, and consumers' heterogeneous prosocial orientations in jointly affecting consumers' valuations. The experimental results yield concrete managerial recommendations on how companies should communicate their social responsibility initiatives with their consumers.

Moving forward, lab experiments can be combined with controlled field experiments and analytical models to further strengthen the analysis and prescription of companies' sustainability strategies. Field experiments are valuable because they help to test the effectiveness of management strategies in the market. Conducting such field experiments for different demographic groups (e.g., female versus male) and different regional markets (e.g., the United States, Europe, and Asia) can be very valuable. Analytical models, in turn, can help to highlight fundamental tradeoffs in a complex decision environment so that one can better understand how strategies should be adapted when the decision environment has changed. We believe that behavioral experiments both in the lab and in the field, combined with analytical models, offer a systematic framework and a set of powerful tools to help companies better address the increasing demands and challenges for sustainability.

Acknowledgements The authors are thankful to Atalay Atasu, Buket Avci, Beril Toktay, and the participants at the 2015 Sustainable Operations Workshop at Georgia Institute of Technology, Scheller College of Business, for their constructive feedback.

References

Agrawal V, Atasu A, van Ittersum K (2015) Remanufacturing, third-party competition, and consumers' perceived value of new products. Manag Sci 61(1):60–72

Alexander RD (1987) The biology of moral systems. Transaction Publishers, New Brunswick, NJ

Andreoni J, Miller J (2002) Giving according to GARP: an experimental test of the consistency of preferences for altruism. Econometrica 70(2):737–753

Arora N, Henderson T (2007) Embedded premium promotion: why it works and how to make it more effective. Mark Sci 26(4):514–531

Becker GM, DeGroot MH, Marschak J (1964) Measuring utility by a single-response sequential method. Behav Sci 9(3):226–232

Bolton G, Katok E (2008) Learning-by-doing in the newsvendor problem: a laboratory investigation of the role of experience and feedback. Manuf Serv Oper Manag 10(3):519–538

Bolton GE, Ockenfels A (2000) ERC: a theory of equity, reciprocity, and competition. Am Econ Rev 90(1):166–193

Carter CR, Easton PL (2011) Sustainable supply chain management: evolution and future directions. Int J Phys Distrib Logist Manag 41(1):46–62

Charness G (2004) Attribution and reciprocity in an experimental labor market. J Labor Econ 22(3):665–688

Dahlsrud A (2008) How corporate social responsibility is defined: an analysis of 37 definitions. Corp Soc Responsib Environ Manag 15(1):1–13

De Pelsmacker P, Driesen L, Rayp G (2005) Do consumers care about ethics? Willingness to pay for fair-trade coffee. J Consum. Aff. 39(2):363–385

Delmas MA, Nairn-Birch N, Balzarova M (2013) Choosing the right eco-label for your product. MIT Sloan Manag Rev 54(4):10–12

Devinney TM, Auger P, Eckhardt GM (2010) The myth of the ethical consumer. Cambridge University Press, Cambridge

Doorey DJ (2011) The transparent supply chain: from resistance to implementation at Nike and Levi-Strauss. J Bus Ethics 103(4):587–603

Economist T (2012) A "distinctly South Asian" tragedy. http://www.economist.com/blogs/banyan/2012/12/garment-factory-fires. Accessed 28 Mar 2015

Elfenbein DW, McManus B (2010) A greater price for a greater good? Evidence that consumers pay more for charity-linked products. Am Econ J: Econ Policy 2(2):28–60

Engelmann D, Munro A, Valente M (2011) On the behavioural relevance of optional and mandatory impure public goods: results from a laboratory experiment. Working paper, Universidade do Minho – NIMA, Braga, Portugal

Falk A, Fehr E, Fischbacher U (2008) Testing theories of fairness – intentions matter. Games Econom Behav 62(1):287–303

Fehr E, Fischbacher U (2004) Third-party punishment and social norms. Evol Hum Behav 25(2):63–87

Fehr E, Schmidt KM (1999) A theory of fairness, competition, and cooperation. Quart J Econom 114(3):817–868

Fehr E, Kirchsteiger G, Riedl A (1998) Gift exchange and reciprocity in competitive experimental markets. Eur Econ Rev 42(1):1–34

Feinberg F, Kinnear T, Taylor J (2012) modern marketing research: concepts, methods, and cases, 2nd edn. Cengage Learning, Boston, MA

Forsythe R, Horowitz JL, Savin NE, Sefton M (1994) Fairness in simple bargaining experiments. Games Econ Behav 6(3):347–369

García-Gallego A, Georgantzís N (2011) Good and bad increases in ecological awareness: Environmental differentiation revisited. Strateg Behav Environ 1(1):71–88

Gneezy A, Gneezy U, Nelson LD, Brown A (2010) Shared social responsibility: a field experiment in pay-what-you-want pricing and charitable giving. Science 329(5989):325–327

Hainmueller J, Hiscox MJ (2012) The socially conscious consumer? Field experimental tests of consumer support for fair labor standards. Working paper no. 2012-15, MIT Political Science Department, Cambridge, MA

Hainmueller J, Hiscox MJ, Sequeira S (2015) Consumer demand for Fair Trade: evidence from a multistore field experiment. Rev Econ Stat 97(2):242–256

Halevy Y (2007) Ellsberg revisited: an experimental study. Econometrica 75(2):503–536

Irwin JR, Naylor RW (2009) Ethical decisions and response mode compatibility: weighting of ethical attributes in consideration sets formed by excluding versus including product alternatives. J Mark Res 46(2):234–246

Kim H, John DR (2008) Consumer response to brand extensions: construal level as a moderator of the importance of perceived fit. J Consum Psychol 18(2):116–126

Klos A, Weber E, Weber M (2005) Investment decisions and time horizon: risk perception and risk behaviour in repeated gambles. Manag Sci 51(12):1777–1790

Koschate-Fischer N, Stefan IV, Hoyer WD (2012) Willingness to pay for cause-related marketing: the impact of donation amount and moderating effects. J Mark Res 49(6):910–927

Kraft T, Valdes L, Zheng Y (2016) Transparency in social responsibility: Investigating consumers' behaviors and motives. Working paper, University of Virginia, Charlottesville, VA

Kremer M, Debo L (2015) Inferring quality from wait time. Manag Sci (forthcoming)

Krishna A, Rajan U (2009) Cause marketing: spillover effects of cause-related products in a product portfolio. Manag Sci 55(9):1469–1485

Levine DK (1998) Modeling altruism and spitefulness in experiments. Rev Econ Dynam 1(3):593–622

Mohr LA, Webb DJ (2005) The effects of corporate social responsibility and price on consumer responses. J Consum Aff 39(1):121–147

Mohr LA, Webb DJ, Harris KE (2001) Do consumers expect companies to be socially responsible? The impact of corporate social responsibility on buying behavior. J Consum Aff 35(1):45–72

Montiel I (2008) Corporate social responsibility and corporate sustainability: separate pasts, common futures. Organ Environ 21(3):245–269

Munro A, Valente M (2009) Green goods: are they good or bad news for the environment? Evidence from a laboratory experiment on impure public goods, working paper, Universidade do Minho – NIMA, Braga, Portugal

Nestlé (2013) Nestlé empowers consumers with new digital labelling scheme. http://\penalty0www.\penalty0nestle.\penalty0com/\penalty0Media/NewsAndFeatures/global-qr-codes. Accessed 7 Aug 2014

Nowak MA, Sigmund K (1998) Evolution of indirect reciprocity by image scoring. Nature 393(6685):573–577

Olson EL (2013) It's not easy being green: the effects of attribute tradeoffs on green product preference and choice. J Acad Mark Sci 41(2):171–184

Orme B (2005) Getting started with conjoint analysis: strategies for product design and pricing research. Research Publishers, LLC, Madison, WI

Özer Ö, Zheng Y, Chen K (2011) Trust in forecast information sharing. Manag Sci 57(6):1111–1137

Özer Ö, Zheng Y, Ren Y (2014) Trust, trustworthiness, and information sharing in supply chains bridging China and the United States. Manag Sci 60(10):2435–2460

Patagonia (2014) The footprint chronicles. http://www.patagonia.com/us/footprint. Accessed 7 Aug 2014

Prasad M, Kimeldorf H, Meyer R, Robinson I (2004) Consumers of the world unite: a market-based response to sweatshops. Labor Stud J 29(3):57–79

Reed II A (2004) Activating the self-importance of consumer selves: exploring identity salience effects on judgments. J Consum Res 31(2):286–295

Schweitzer M, Cachon G (2000) Decision bias in the newsvendor problem with a known demand distribution: experimental evidence. Manag Sci 46(3):404–420

Straughan RD, Roberts JA (1999) Environmental segmentation alternatives: a look at green consumer behavior in the new millennium. J Consum Mark 16(6):558–575

Thøgersen J, Haugaard P, Olesen A (2010) Consumer responses to ecolabels. Eur J Mark 44(11/12):1787–1810

Vermeir I, Verbeke W (2006) Sustainable food consumption: exploring the consumer "attitude–behavioral intention" gap. J Agric Environ Ethics 19(2):169–194

Part II
Profit-Driven Environmental Responsibility in Supply Chains: Opportunities

Chapter 4
By-Product Synergy: Productively Using Waste in Joint Production Operations

Deishin Lee

Abstract As raw material resources become more scarce and waste disposal becomes more costly, firms are increasingly focused on the effective use of raw materials, many of which are natural resources. By-product synergy is an operational model that leverages economies of scope to more effectively use natural resources, while simultaneously reducing waste. Processes are joined by feeding the waste stream of one process as input into another process. The operational, economic, and environmental implications of this joint production method are explored in this chapter.

4.1 Introduction

This chapter begins with a discussion on waste. Waste is a convenient entry point into a discussion on sustainability because it is an obvious symptom of an unsustainable process. The disposal of waste, typically in landfill or an incinerator, is economically and environmentally costly. However, the crux of what is unsustainable is the depletion of raw material resources needed to produce goods and provide services. These materials are being depleted because we are wasting them. We are wasting them because we have designed production systems to produce waste.

Every production system converts input into output using a process that organizes labor and equipment to perform tasks. Moreover, most processes are designed to produce a particular product. For example, in a smelting process,

D. Lee (✉)
Carroll School of Management, Boston College, 140 Commonwealth Ave., Chestnut Hill, MA 02467, USA
e-mail: deishin.lee@bc.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_4

the input raw materials, iron ore, coke, and limestone, are combined in a blast furnace that blasts high temperature air into the bottom of the furnace. This process produces pig iron, the desired output, but it also produces a waste stream called slag—a mixture of silicates and oxides.

From a product-oriented perspective, a process will always produce a desired output and an associated waste stream. This is because there is no product that encapsulates 100 % of the input material fed into the process that produced it—there is always a stream of material produced collaterally that is not encapsulated in the product. Thus, placing the smelting process in the context of steel production, pig iron is the desired process output and slag is the waste stream. However, if we take the process out of the product context, something magical happens—pig iron and slag simply become two outputs from the smelting process and the "product" and "waste" labels are eliminated. This is magical because it unleashes the potential to productively use everything that flows out of a process.

A shift in mindset from "How can we make steel better?" to "How can we make better use of iron ore?" is critical to opening up this opportunity. According to Gordon Forward, CEO of Chaparral Steel, the mindset shift from product-focus to process-focus was essential to reducing waste and improving sustainability for his company. If the organizational mindset is on steel production, it is difficult to envision non-steel products, even if the resources for producing these products are readily available. To remove that narrowing lens, Forward initiated the "100 % product" challenge—to make productive use of everything that flowed out of the production process. As a result, Chaparral Steel, in conjunction with a cement company, developed a process for using slag, the "waste stream" from the smelting process, to produce Portland cement (Forward and Mangan 1999).

In this chapter, we take a fresh look at waste. We review operational approaches for mitigating waste, and focus on a form of joint production—by-product synergy—that turns "trash into treasure."

4.2 Waste

Many words are used to classify physical material in supply chains: raw material, work-in-progress, finished goods, components, subassemblies, products, ... and waste. The feature that separates waste from other types of material is that it is unwanted. Given that it is unwanted, the sheer volume of waste is staggering. The U.S. Environmental Protection Agency estimates that in 2012, 251 million tons of municipal solid waste was generated in the U.S.—this equates to 1600 pounds of waste per person. A conservative estimate for industrial solid waste generated yearly in the U.S. is 7.6 billion tons.

Waste is problematic for a number of reasons. The disposal of waste, typically in landfill or an incinerator, is economically and environmentally costly. Moreover, once in landfill or incineration, these materials often become unrecoverable. For example, once incinerated, the precious metals in electronic devices cannot be recycled. Continuing to consume material of finite supply such as precious metals will logically end in depletion.

The underlying issue is that what has been deemed “waste” is usually material that can still be useful. In recognition of this fact, much effort has been expended to reclaim the usefulness of materials that end up in waste streams. Options for end-of-life (EOL) products include reuse, refurbish, remanufacture, or recycle. The first three options apply at the product level—the EOL product is processed for the intention of using it again in the product form. Recycling requires breaking down the product into component parts for the purpose of using the components or raw material in similar applications.

The common characteristic of these processes is that the intention is to get the waste back into a state where it can be used again in a function similar to the original. For example, paper is recycled back into pulp, which is used to make other paper products. Electronic devices such as mobile phones are remanufactured and sold for use again as mobile phones. The flow of material is circular—products flow “forward” to the end-user market, and at the end of life, they “reverse” flow to be processed (recycled, refurbished, or remanufactured), after which they flow forward again to a similar end-user market. Often the products enter a lower-tier market, e.g., office paper is down-cycled into newspaper, remanufactured electronic devices are sold at a discount in a secondary market.

The strategic and operational challenges in managing this circular material flow are studied in the Closed-Loop Supply Chain literature (see Atasu et al. 2008 for a review). One set of key challenges pertains to the logistics of the reverse flow of material. This includes changing consumer and firm behavior, and material processing logistics (cf. Fleischmann et al. 1997; Jayaraman et al. 2003; Savaskan et al. 2004). The Closed-Loop Supply Chain literature has also studied the market dynamics resulting from products that have been remanufactured or refurbished potentially competing with new products (cf. Majumder and Groeneveolt 2001; Ferguson and Toktay 2006; Ferrer and Swaminathan 2006).

However, before a product even reaches the end-consumer market, another type of waste is generated collaterally as part of the many processes required to make the product, but does not end up in the final product (e.g., slag from our earlier smelting example). This type of waste stream is arguably more problematic because the quantity is significant, and it is material that does not end up in the product *by design*. Therefore, it cannot be “re”-processed back into its original (or similar) form. This type of waste arises as a result of the linear structure of most production processes: raw material, labor, and capital are organized in a process for the purpose of producing a desired output product. The material that flows out of the process that is not encapsulated in the product, is deemed waste.

In this light, the notion of waste is simply a matter of perspective. In a process that is designed to produce product A, all other collaterally generated output not encapsulated in product A is waste by definition. However, that does not necessarily mean that the collaterally generated output is useless. From our earlier example, slag is produced as a waste stream in steel manufacturing. Once the steel is produced, the slag is useless for producing steel, however, it can be used productively as an input to making cement (National Slag Association 2014). By using steel slag as an input to cement production, economic and environmental benefits can be realized. First, the disposal cost can be avoided. Second, the slag substitutes for virgin raw material, thereby avoiding input cost. These avoided costs include the environmental cost of production activities as well as the economic cost.

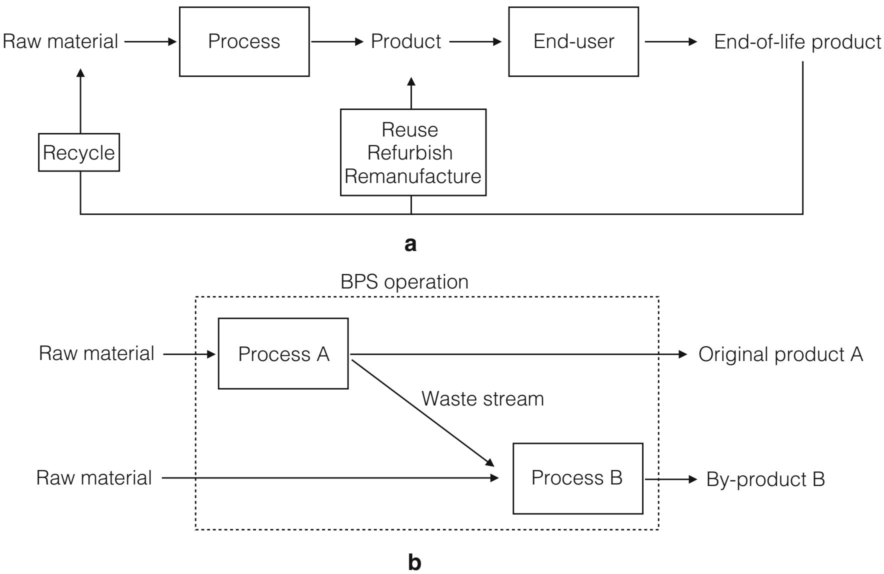

Fig. 4.1 Process flow diagrams for reverse supply chain and by-product synergy operations. (**a**) Reverse supply chain makes end-of-life products useful again in the same or similar supply chain, (**b**) by-product synergy converts the waste stream into a completely different product

4.3 By-Product Synergy

Waste is merely raw material in the wrong place.—Frederick Talbot

The use of a waste stream from one process as an input to another process is commonly referred to as *by-product synergy (BPS)* (USBCSD 2014). Essentially, a waste stream is converted into a by-product. Similar to recycling, remanufacturing, and refurbishing, BPS turns a waste stream into something productive. However, BPS differs in two important ways. First, BPS makes use of waste generated in a production process, not EOL products. Second, recycling, remanufacturing, and refurbishing utilize a reverse supply chain that processes EOL products so that they can be used again in the same or a similar manner (see Fig. 4.1a). BPS, on the other hand, converts a waste stream into another completely different by-product—the supply chain activities continue in the forward direction (see Fig. 4.1b). In essence, a BPS operation produces two (or more) products in one operation. Moreover, the two products use the raw material in a non-competitive manner, thus, operational synergy is created. BPS joins two or more processes together through a shared material resource, thus, it is a form of joint production.

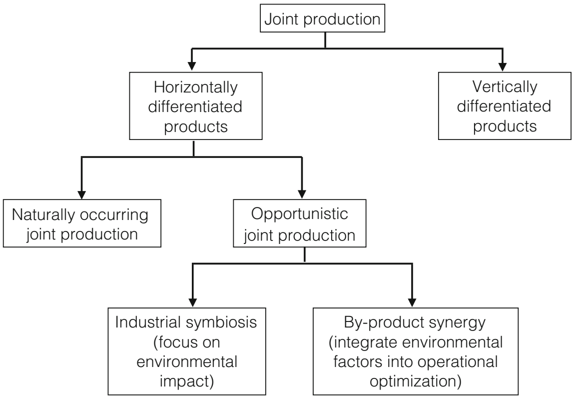

Fig. 4.2 Topology of joint production research

There is an emerging body of work in operations management that studies the joint production of multiple products in one operation. Chen et al. (2013) introduce the characterization of joint production operations as producing either horizontally or vertically differentiated products and provide a comprehensive review of joint production literature. In vertically differentiated joint production operations, products vary along the quality dimension. Higher quality parts typically command higher prices, but products of differing quality can be substituted for each other. For example, semiconductor manufacturing produces chips of varying quality, and higher quality chips can be substituted for lower quality chips. Earlier work focused on production optimization and inventory allocation among the various classifications (cf. Bitran and Leong 1992; Bitran and Gilbert 1994; Bitran and Dasu 1992; Hsu and Bassok 1999). More recent work has incorporated pricing (Tomlin and Wang 2008) and product line design (Chen et al. 2013) into the joint production analysis. Horizontally differentiated joint production operations produce products that are sold into different markets—the products do not compete and cannot substitute for each other (e.g., joint production of plywood and bark mulch). Operations management literature has studied horizontally differentiated joint production in various settings including oil refining (Dong et al. 2014), agribusiness (Boyabatli 2014), the palm industry (Boyabatli et al. 2014), and mining (Sunar and Plambeck 2014).

In the BPS setting, the waste stream from one process is used as input into another different process, thus, the products are horizontally differentiated. What separates BPS from other previously studied horizontal joint production operations is that the production synergy arises from the *opportunistic* use of a waste stream as input to another process. That is, the products produced in a BPS operation could be produced independently of each other, each using virgin raw materials (unlike, for example, the production of plywood and bark mulch, which are naturally produced together). However, by *joining* the processes and making productive use of a waste stream, disposal cost and raw material cost are avoided, thereby creating economic and environmental value. In the industrial ecology field, BPS is called industrial symbiosis. Industrial symbiosis is defined as "traditionally separate industries (engaged) in a collective approach to competitive advantage involving physical exchange of material, energy, water, and by-products" (Chertow 2000). The industrial symbiosis literature has focused on the environmental impact of specific firms that exchange waste materials, energy, and water (cf. Ehrenfeld and Gertler 1997; Chertow and Lombardi 2005; Zhu et al. 2007).

By comparison, the operations management literature on BPS integrates the environmental aspects of joint production into the optimization of the operation. Because BPS operations opportunistically use waste streams to substitute for virgin raw material, waste disposal and raw material costs are significant parameters in the operational, economic, and environmental impact analysis. Figure 4.2 shows the topology of research on joint production. In the following sections, we explore three operational settings where BPS can be implemented: manufacturing, service, and retail. In the manufacturing and service settings, waste generation is driven by the physical characteristics of the process. In these settings, the capacity or production quantity is the key decision because the quantities of the product and by-product are interdependent. In the service setting, however, demand is stochastic and therefore safety capacity also becomes an issue. In the retail setting, waste generation is driven by demand uncertainty. Retailers carry inventory to accommodate demand uncertainty, therefore, in the retail setting the appropriate safety inventory is critical. We describe the tradeoffs introduced by BPS in these three contexts and explain how they affect the optimal operating policy.

4.3.1 By-Product Synergy in a Manufacturing Setting

In a manufacturing setting, opportunities for BPS are created by leveraging multiple dimensions of raw material. This concept has long been in practice in agriculture. For example, the production of beef also yields leather from the hide of the cow. Moreover, the production of beef and leather are not in competition for the raw material resource (cow). In fact, the more beef produced, the more leather can be produced. Thus, waste (or by-product) generation is determined by the physical properties of the process. Using the terminology from Fig. 4.1b, beef would be original product A and leather would be by-product B.

The optimization of a BPS implementation in a manufacturing setting and how the firm can capture value from BPS are studied in Lee (2012). The original product and by-product are related through a quantity relationship: γ units of by-product B can be produced from the waste stream generated by the production of one unit of product A. The marginal cost of production for product A is c_A, and the cost to dispose of the waste generated by producing one unit of A is c_w. If the waste stream of A is used to make by-product B, the unit cost of conversion is c_B, and $\frac{c_w}{\gamma}$ in waste disposal cost is avoided. If product B is produced using virgin raw material, the unit cost is $c_r + c_B$, where c_r represents the cost of virgin raw material. Assume that the inverse demand curves for products A and B are $p_A = a - q_A$ and $p_B = b - q_B$, and consider the simple case where the firm is a monopolist.

For a firm currently making product A, a straightforward way to implement BPS would be to continue producing A business-as-usual and simply convert the entire waste stream into product B. However, this is likely to give suboptimal profits. In order to optimize the joint production operation, the firm can choose one of three operating regimes:

- *Partial conversion ($q_B < \gamma q_A$)*: Produce the quantity of product A that maximizes product A profit, and convert all or part of the waste stream into product B. In this operating regime, the firm's production is driven by A. Product B provides a service by "consuming" part of A's waste stream. Therefore, the cost of producing B is decreased by $(1/\gamma)c_w$.
- *Full-plus conversion ($q_B > \gamma q_A$)*: Increase the production of A above the optimal quantity for product A, and convert all the waste into product B. Additionally, source virgin material to make more product B. In this operating regime, the firm's production is driven by B. The production of A is bumped up to "feed" (waste) input to process B.
- *Exactly-full conversion ($q_B = \gamma q_A$)*: All the waste stream of A is used to produce B, and B is produced using only the waste stream of A. No waste disposal cost and no virgin raw material cost are incurred—the two processes are completely synchronized. In this operating regime, the quantity of A or the quantity of B may be increased above the optimal for each respective product in order to "feed" or "consume" waste.

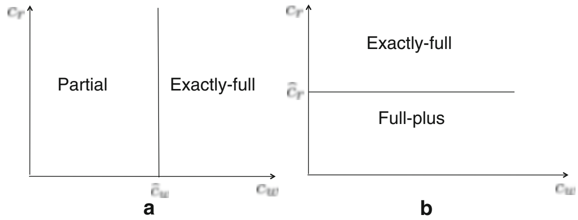

Fig. 4.3 The optimal operating policy under BPS in a manufacturing setting: $\hat{c}_w = \frac{\gamma(a-c_A)-(b-c_B)}{\gamma+1/\gamma}$, $\hat{c}_r = -\frac{\gamma(a-c_A)-(b-c_B)}{1+\gamma^2}$. (**a**) $\gamma \geq \frac{b-c_B}{a-c_A}$, (**b**) $\gamma < \frac{b-c_B}{a-c_A}$

BPS ties the two markets together in one operation, therefore, a straightforward diversion of the firm's waste stream misses the opportunity to leverage the tradeoff between the two markets. The constraint that binds the two markets together is that one unit of A can produce γ units of B. To fully take advantage of the operational synergy in the joint production process, we may have to sacrifice the profit from one product to boost the profit from the other. Figure 4.3 shows the firm's optimal policy (Proposition 2 in Lee 2012).

We see that the optimal operating policy is driven by three parameters that are central to the BPS value proposition: the waste to product ratio γ, the disposal cost c_w, and the cost of virgin raw material c_r. If $\gamma = (b - c_B)/(a - c_A)$, absent disposal and virgin raw material cost, the optimal quantity of B matches exactly the quantity that can be produced from the waste stream of the optimal quantity of A. In Fig. 4.3a, we see that if $\gamma > (b - c_B)/(a - c_A)$ (i.e., process A generates more than enough waste to feed process B), the parameter that drives the operating policy is disposal cost c_w. For high disposal cost (i.e., $c_w > \hat{c}_w$), exactly-full conversion is optimal—the optimal joint production policy is to increase the quantity of B above what is optimal for market B in order to consume the waste stream of A. For low disposal cost (i.e., $c_2 < \hat{c}_w$), it is not worth reducing the profit from B to consume A's waste stream, so partial conversion is optimal—some of A's waste stream is still disposed.

Figure 4.3b shows that if $\gamma < (b - c_B)/(a - c_A)$ (i.e., process A does not generate enough waste to feed process B), the parameter that drives the operating policy is virgin raw material cost c_r. For high material cost (i.e., $c_r > \hat{c}_r$), exactly-full conversion is optimal—the quantity of A is increased above what is optimal for market A in order to feed process B the input waste stream. For low material cost (i.e., $c_r < \hat{c}_r$), instead of increasing the output of A in order to feed B, virgin raw material is purchased to produce B.

The structure of the optimal operating policy shows that leveraging operational synergy between two process may imply a tradeoff between the profitability of the two products. Thus, the decision to implement BPS and how to manage a BPS operation should be made at a strategic level.

4.3.2 By-Product Synergy in a Service Setting

In a service setting, similar to manufacturing, waste generation depends on the physical properties of the process. However, customer demand (or arrival) is uncertain. Because the customer is an integral part of the service process, timing is critical. Thus, customer arrival uncertainty in a service setting is accommodated by setting processing capacity. The firm must set the processing capacity so that customers are served in a timely manner.

As customers are served, waste streams are generated that can be productively used. This form of by-product synergy is particularly relevant in reverse supply chains where there is recycling. For example, Ata et al. (2012) study a service setting where an organic waste recycler converts its methane gas waste stream into electricity. Note that although this joint production setting exists in a reverse supply chain context, the BPS process description in Fig. 4.1b still applies. Process A is the service process and process B is the process by which the methane gas waste stream is converted into electricity. Figure 4.4 shows the process flow diagram for the organic waste recycling BPS operation. The digestion process is the service process—customers with waste arrive at the facility and are served by the recycler who accepts the waste. Customers pay the recycler a per ton processing fee, commonly called a "tip fee," to accept the waste stream. If the recycler has enough capacity, it processes the waste in an anaerobic digester that converts the waste into compost. The digestion process reclaims the nutrients from the organic waste and

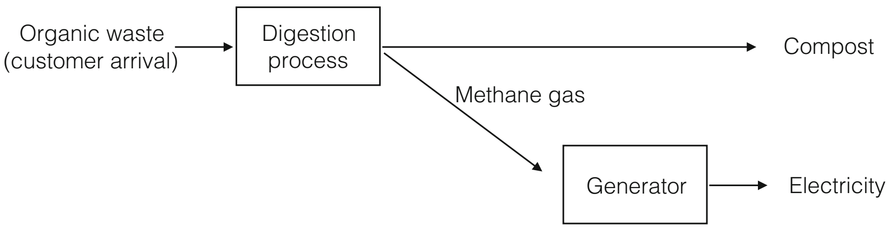

Fig. 4.4 By-product synergy in a service setting: organic waste recycling with energy recovery

the compost can be used in landscaping or agricultural applications. If the recycler does not have enough capacity, the recycler must pay a fee to dispose the waste (i.e., this is the penalty paid by the service provider for not having enough capacity). The methane gas "waste stream" is used to generate electricity.

In this BPS setting, avoiding waste disposal is not only critical to BPS value creation, it is the core value proposition of the business. The alternative would be to operate as a pure service process and landfill or incinerate the waste. Thus, unlike the manufacturing and retail settings, if there is sufficient capacity there is only exactly-full conversion—all the organic waste is fed into the digestion process, and the digestion process only takes the waste stream from the service process as input. The operational tension in this joint production process does not arise from the decision of how much waste to convert into by-product—all of it is converted if possible. Rather, the tension arises from how much capacity is needed and how to manage the capacity of a process that both serves the customer and produces the by-product.

In this service BPS setting, the synergy is determined by the biological characteristics of the digestion process. The longer a batch of organic material is digested, the more methane (electricity) can be produced. Letting m be the retention (processing) time of organic waste in the digester, the biological process is characterized by the function $g(m)$ that represents the amount of methane produced, where $g(m)$ increases at a decreasing rate. However, longer retention time reduces the capacity of the digester to accept organic waste input thereby limiting the revenue stream from the service process. Therefore, there is a tradeoff between the profit of the service product and the electricity by-product. The faster the digestion process (i.e., low retention time m), the higher the revenue from tip fees, but the lower the revenue from electricity generation. The optimal operating policy m depends on the characteristics of the waste generation process (i.e., organic waste arrivals) and the biological digestion process (Proposition 1 in Ata et al. 2012). We can also think of this tradeoff as a tradeoff between capacity efficiency and input efficiency. Whereas capacity efficiency is a measure of the number of customers (waste arrivals) served per unit time, input efficiency is a measure of the units of output (electricity) generated by a unit of input (organic waste).

4.3.3 By-Product Synergy in a Retail Setting

In a retail setting, waste is generated as a result of demand uncertainty. Demand uncertainty is typically accommodated by stocking safety inventory in a retail environment (vs. safety capacity in a service setting). However, this often leads to leftover products at the end of the selling period. These leftover products eventually become waste. Thus, the waste stream in a retail setting looks very different than in a manufacturing setting. In a manufacturing setting, the collaterally generated waste stream is material that is not encapsulated in the final product. In a retail setting, the waste stream consists of the product itself, but it is the leftover product that was not sold. The nature of waste generation in a retail setting affects how the firm makes operational decisions when BPS is implemented. Whereas BPS in a manufacturing setting is driven by the product to waste ratio, BPS in a retail setting is driven by demand uncertainty, which is captured by a probability distribution for demand.

BPS in a retail grocer setting is studied in Lee and Tongarlak (2015). Leftover inventory from the fresh produce department can be diverted to make prepared food. For example, avocados that become over-ripe and cannot be sold as fresh produce can be used to make guacamole in the prepared food department (other fresh items such as meat can also be used as input for prepared food). Lee and Tongarlak (2015) model a retail grocer who uses excess inventory from a primary process (e.g., fresh produce) as an input into a secondary process (e.g., prepared food). There is a steady state two-period process where the retailer places an order for fresh produce for sale in the first period. The excess inventory at the end of period 1 can be salvaged (or disposed) at a per unit value (or cost), or used as input to make a prepared food item for sale in period 2. If the prepared food item is made using *newly purchased* input, the per unit cost is higher than if it is produced using *excess* primary units. The demand for fresh produce and the prepared food item are both uncertain.

If the two processes operate independently, the optimal order quantities would simply be the classical Newsvendor solutions. If the retailer could use only the lower cost primary excess units to make the prepared food item, the optimal quantity in the secondary process would clearly increase. Analogous to the manufacturing setting, the analysis in Lee and Tongarlak (2015) shows that the optimal order-up-to level in period 2 consists of three regimes:

- *Partial conversion*: The primary process produces more than the number of excess units optimally used in the secondary process, therefore, there is only partial conversion.
- *Full-plus conversion*: All primary excess units are used as input to the secondary process and additional units are newly purchased.
- *Exactly-full conversion*: All primary excess units are used as input to the secondary process. However, no units are newly purchased. In this regime, the quantity of primary excess units exactly matches the order-up-to level.

The retailer's optimal order in the first period takes into account the opportunity to use primary excess units in the secondary process, therefore, the order increases above the classical Newsvendor quantity. As in the manufacturing setting, the profit from the primary process suffers under BPS because there is over-ordering to leverage the operational synergy. The decrease in primary profit is more than compensated by the increase in secondary profit.

In the retail setting, we see that three parameters are again central to the BPS value proposition: the uncertainty in primary product demand, the salvage value (or disposal cost), and the cost of newly purchased input. Excess primary units are only generated if primary demand is uncertain, therefore, the more uncertain demand is, the more synergy can be created in the BPS operation. As the primary product salvage value decreases (or equivalently, as disposal cost increases), the partial conversion operating policy is less likely to be used—more excess units will be converted into secondary units, increasing the benefit of BPS. As the cost of newly purchased units increases, the full-plus operating policy will be used less, implying that the secondary process relies more on excess primary units.

4.4 Rethinking the Way We Make Things

As seen in the three settings above, value is created in a BPS operation by jointly producing different products. That is, a BPS operation creates value by leveraging *economies of scope* (Panzar and Willig 1981). An operation that exhibits economies of scope produces multiple different products at lower cost than producing the products independently. The process synergy can only be created by producing *different* products that use the same raw material resource in a non-competitive way. Thus, the core process synergy that creates the economic benefit is what also creates the environmental benefit. In contrast, a single-product operation creates value by leveraging *economies of scale*. A fixed investment in labor or capital is made to produce a single product very efficiently. Value is created by using a specialized process to produce the *same* product in high volume. In an economies of scale operation, the core process characteristic that creates economic value by efficiently producing the product, also creates waste very efficiently.

Leveraging economies of scope to create value is an appealing idea, but a valid question is how significant the BPS operational model can be in terms of addressing sustainability issues. The potential is difficult to estimate, but there is some anecdotal evidence that the BPS model is continuing to spread. Organizations around the world are organizing regional BPS programs to bring companies together to share information about their waste streams. For example, the National Industrial Symbiosis Program (NISP) was established to promote BPS in the United Kingdom. In 8 years, NISP BPS projects achieved £1 billion in cost savings and £1.4 billion in additional sales, created or safeguarded over 10,000 jobs, recovered of 45 million tonnes of material, reduced of 39 million tonnes of carbon emissions, and saved 71 million tonnes (National Industrial Symbiosis Programme 2014). In the U.S., the U.S. Business Council for Sustainable Development has organized regional BPS programs in Chicago, Houston, Kansas City, New Jersey, and Puget Sound. In one BPS project, Dow Chemical Company piloted the joint production concept within its own company. With six manufacturing plants from the Gulf Coast participating in the initial study, $15 million of annual cost savings were identified in addition to an annual reduction of 900,000 MMBtu of fuel use and 108 million pounds of CO_2 emissions (U.S. Department of Energy 2005). In industrial settings, although there are promising signs, the future opportunities for BPS are difficult to estimate because the underlying process synergies are not well understood.

However, an area where joint production is a very natural (literally) operational model is agricultural systems. In a report on sustainable agricultural systems by the National Research Council, the study found that the input-intensive, predominantly single-product industrial model of agriculture that is currently pervasive is unsustainable (National Research Council 2010). In the same report, agroecology was identified as part of the transformative approach to improving sustainability of agricultural systems. Agroecology is "the study of the interactions between plants, animals, humans and the environment within agricultural systems" (Dalgaard et al. 2003). Agroecology applies ecological principles to agricultural systems, employing the biological synergies between different types of plants and animals in the production of food. For example, Polyface Farm produces beef, chicken, and eggs in a joint production operation that minimizes the need for synthetic inputs (Lee and van Sice 2011). Transforming even a fraction of the \$1 trillion U.S. food industry from single-product production to agroecology-based joint production would have significant economic and environmental impact.

Shifting towards BPS joint production models requires rethinking how we design and manage operations and supply chains. We need to understand the implications of the operating policies that will arise when products are jointly produced. We discuss below some BPS issues that are highlighted by extant research and propose areas for future research.

What New Tradeoffs are Introduced in the BPS Setting? BPS creates an interdependence of different products that is unlikely to be correlated with demand characteristics. This will naturally introduce tensions when making operational and strategic decisions. One key tradeoff that is introduced in a joint production setting is the tradeoff between the profitability of two (or more) products. A typical division of organizations within a firm is along product lines. However, a BPS operation produces multiple often very different products in one operation. The process owner of A would prefer to implement BPS in a way that treats process B as an alternative to waste disposal—simply convert all process A waste into product B. However, the synergy of the joint production process would not be fully exploited. Process A produces not only product A, but a valuable input for process B. Process B produces not only product B, but provides a valuable service for consuming the waste stream of process A. Managing the operational tradeoff between product-level profit and leveraging the process synergy is a decision that needs to be made at the strategic level, not at the product level. Moreover, it may even be the case that producing the original product A alone is not profitable for the firm, it requires jointly producing A and B in a BPS operation to be profitable (Proposition 3 in Lee 2012). This is an extreme case, but it underscores how compelling the synergy between the two processes can be.

Another managerial implication of BPS is that it may be optimal to increase the amount of waste that process A generates (e.g., increase γ in the manufacturing setting in Lee 2012). This insight is completely counter to operations management conventional wisdom which typically seeks to reduce the amount of waste generated by a process. It may not be possible to change the ratio of product to waste, however, when possible, it can be another lever for creating process synergy. For example, Cook Composites and Polymers (CCP) manufactures gel coat. To clean production equipment between batches, it uses styrene, an expensive chemical, which after use turns into a toxic waste stream. However, the waste styrene can be used to make a concrete coating product. In the linear process of producing gel coat, CCP seeks to minimize the use of styrene because it is expensive to purchase and dispose. However, if CCP implements BPS and uses the waste styrene to make concrete coating, it would be beneficial to use more styrene in the gel coat production process. This could simultaneously improve the quality of the gel coat process and provide more input material for the production of the concrete coating by-product (Lee et al. 2011). In another example, the benefits of increasing waste in the organic waste recycling setting are more intuitive. If the capacity of the digestion process is not a constraint, increasing the waste generated by the service process clearly increases the profit of the joint operation.

Another key BPS tradeoff is between input efficiency and capacity efficiency. As seen in Ata et al. (2012), squeezing more output from a unit of input may require sacrificing efficiency in processing capacity (this tradeoff is also studied in Plambeck and Taylor 2013). In a broader sense, BPS is about using raw material resources more efficiently. In order to achieve that objective, additional processing resources will likely be required, and this cost needs to be weighed against the benefits of higher input efficiency.

Overall, the tight operational coupling in a BPS process implies that some operational decisions should be made at the strategic level. Often, the profit of one product will be sacrificed to boost the profit of another. This affects the incentives and compensation of the organizations involved. The operational tradeoffs introduced by BPS create ripple effects throughout the organization and need to be considered when designing a joint production operation.

How can we Implement BPS in a Practical Manner? Implementing BPS *optimally* introduces organization complexities that may prove to be overwhelming. However, BPS can be implemented in simple ways that can still create economic and environmental value. For example, in the retail setting, the primary and secondary processes can operate independently, however, the waste stream of the primary process is made available to the secondary process to use optimally. The primary process does not "over-order" to benefit the secondary process, but some process synergy is still captured. Lee and Tongarlak (2015) analyze a hybrid-BPS implementation where the primary process operates to optimize its own profit, but its waste stream is opportunistically used by the secondary process. Although the profit is not as high as that in an optimal BPS implementation, total waste is lower. Most importantly, the two departments maintain their organizational autonomy. Exploring practical ways to implement BPS is an important area for researchers to collaborate with industry.

What are the Environmental Implications of BPS? BPS can reduce the environmental impact of producing products A and B in two ways. First, the environmental impact of disposing of A's waste stream can be mitigated. In a manufacturing setting and certainly in the organic waste recycling (service) setting, BPS reduces waste. This is generally considered a positive effect if the waste would otherwise have been landfilled or incinerated. However, there are other productive uses of waste that can compete with BPS. For example, a retailer or manufacturer can donate excess inventory (often receiving a tax credit). If donation were the alternative to BPS, BPS may actually increase total waste because the waste generated in a BPS operation is still more than if the firm donated excess inventory (cf. Lee and Tongarlak 2015).

The second way that BPS can reduce environmental impact is by reducing the quantity of virgin raw material produced. This could have significant impact for an energy intensive process such as cement production (National Slag Association 2014). If over-production in the food industry can be mitigated by reducing food wastage, this could also create significant environmental benefits (e.g., reduce fossil fuel usage, less deforestation for farmland, etc.). However, market dynamics change when process changes increase value. If the firm optimizes the joint production process taking advantage of cost reductions, the quantity of the jointly produced products may actually increase (i.e., the rebound effect). Therefore, the total environmental impact depends on the relative impact of the various processes in the BPS operation.

These examples reveal a conundrum underlying solutions that are designed to benefit both business and the environment. If there is a business advantage to be gained, typically the business will grow, and that can increase the (negative) environmental impact. This highlights an opportunity for regulatory mechanisms to complement the process synergy approach to environmental sustainability.

What are the Regulatory Implications of BPS? A regulatory mechanism that can be very effective for reducing waste generation is a disposal fee. This fee is generally levied on a per pound or per ton basis for material that is landfilled or incinerated. Other requirements such as composting for organic material are also de facto disposal fees because the firm needs to pay a service provider to process its waste in a particular way. In a single-product linear production process, the effect of the disposal fee is to increase the marginal cost of the product and thus reduce the production quantity and the associated waste stream. Waste disposal is mitigated, but at the cost of reducing production. However, in a manufacturing BPS operation, the effect of the disposal fee depends on the waste to product ratio γ. If the ratio is low, the disposal fee is irrelevant because all the waste is converted into by-product. Under these conditions, it may still be beneficial to have a disposal fee because high disposal cost may induce the firm to investigate the possibility of BPS to begin with. If the waste to product ratio is high, increasing the disposal cost induces the firm to increase the production of B in order to consume the waste stream of A. It is important to note, however, that instead of *reducing* production to reduce waste as in the single product operation, the BPS operation *increases* production.

The disposal fee and other regulatory mechanisms can be used effectively to incentivize firms to make productive use of their waste. However, once firms implement BPS, it is important for regulators to realize that the disposal fee can affect the effectiveness of BPS.

What are the Supply Chain Implications of BPS? A supply chain connects the joint production operation to the end user. Shifting from single-product to joint production will also have significant impact on how the supply chain is structured (distribution, inventory, retailing), and how the consumer views the end product. For example, Zhu et al. (2014) study how competition and consumer characteristics influence a firm's decision to implement BPS. The interdependence of disparate products through the production process will create interdependencies between disparate supply chains, and the implications of this are understudied in operations management.

Awareness of the possibility of BPS is already a significant step towards identifying opportunities. Intermediaries can play a key role in facilitating BPS exchanges by providing a trustworthy platform for information exchange. Intermediaries can also take a more active role by offering a service to firms to find uses for their waste streams (e.g., Dhanokar et al. 2014; Austin Materials Marketplace 2015; Encouraging Environmental Excellence 2015). Designing systematic ways to identify feasible BPS exchanges is critical to increasing opportunities to leverage joint production.

4.5 Conclusion

Production processes take input materials and transform them into output. There has been much effort expended to optimize the *processing resources* of firms, e.g., how to increase capacity utilization, reduce labor cost, increase labor efficiency, increase output rate. However, as *material resources* become more scarce and waste disposal becomes increasingly costly, firms are shifting their attention to how to more effectively manage the use of materials (e.g., natural resources). In a linear, single-product production system that creates value buy leveraging economies of scale, the ability to effectively use material resources is limited—the process produces waste streams by design. We need to rethink the way we make things. The BPS mindset forces us to cast aside our preconceived notions of process design—what the intended output is, what efficiency means, and how profitability should be measured. BPS operations leverage economies of scope to creatively and more effectively use what is rapidly becoming the binding constraint to many processes: our material resources.

References

Ata B, Lee D, Tongarlak M (2012) Optimizing organic waste to energy operations. Manuf Serv Oper Manag 14(2):231–244

Atasu A, Guide V, Van Wassenhove L (2008) Product reuse economics in closed-loop supply chain research. Prod Oper Manag 17(5):483–496

Austin Materials Marketplace (2015) Austin Materials Marketplace: facilitating business-to-business material reuse in Austin, Texas. http://austinmaterialsmarketplace.org/successes-new-ideas/. Accessed 16 May 2015

Bitran G, Dasu S (1992) Ordering policies in an environment of stochastic yields and substitutable demands. Oper Res 40(5):999–1017

Bitran G, Gilbert S (1994) Co-production processes with random yields in the semiconductor industry. Oper Res 42(3):476–491

Bitran G, Leong T (1992) Deterministic approximations to co-production problems with service constraints and random yields. Manag Sci 38(5):724–742

Boyabatli O (2014) Supply management in multi product firms with fixed proportions technology. Manag Sci. doi:10.1287/mnsc.2014.2055

Boyabatli O, Nguyen Q, Wang T (2014) Capacity management in agricultural commodity processing and application in the palm industry. Working paper. Singapore Management University

Chen Y, Tomlin B, Wang Y (2013) Coproduct technologies: product line design and process innovation. Manag Sci 59(12):2772–2789

Chertow M (2000) Industrial symbiosis literature and taxonomy. Ann Rev Energy Environ 25:313–337

Chertow M, Lombardi D (2005) Quantifying economic and environmental benefits of co-located firms. Environ Sci Technol 39(17):6535–6541

Dalgaard T, Hutchings N, Porter J (2003) Agroecology, scaling and interdisciplinarity. Agric Ecosyst Environ 100:39–51

Dhanokar S, Donohue K, Linderman K (2014) Repurposing Materials & Waste through Online Exchanges: Overcoming the Last Hurdle. Production and Operations Management, 24(9):1473–1493

Dong L, Kouvelis P, Wu X (2014) The value of operational flexibility in the presence of input and output price uncertainties with oil refining applications. Manag Sci 60(12):2908–2926

Encouraging Environmental Excellence (2015) Working together: E3 Ohio and the Ohio by-product synergy network. http://www.e3.gov/accomplish/ohio.html. Accessed 16 May 2015

Ehrenfeld J, Gertler N (1997) Industrial symbiosis in practice: the evolution of interdependence at Kalundborg. J Ind Ecol 1(1):67–79

Ferguson M, Toktay L (2006) The effect of competition on recovery strategies. Prod Oper Manag 15(3):351–368

Ferrer G, Swaminathan J (2006) Managing new and remanufactured products. Manag Sci 52(1):15–26

Fleischmann M, Bloemhof-Ruwaard J, Dekker R, van der Laan E, van Nunen J, Van Wassenhove L (1997) Quantitative models for reverse logistics: a review. Eur J Oper Res 103(1):1–17

Forward G, Mangan A (1999) By-product synergy. Bridge 29(1):12–15

Hsu A, Bassok Y (1999) Random yield and random demand in a production system with downward substitution. Oper Res 47(2):277–290

Jayaraman V, Patterson R, Erik R (2003) The design of reverse distribution networks: models and solution procedures. Eur J Oper Res 150(2):128–149

Lee D (2012) Turning waste into by-product. Manuf Serv Oper Manag 14(1):115–127

Lee D, Tongarlak M (2015) Converting retail food waste into by-product. Working paper. Boston College
Lee D, van Sice S (2011) Polyface: the farm of many faces. Harvard Business School Case 611-001, October 2010 (Revised October 2011)
Lee D, Toffel M, Gordon R (2011) Cook Composites and Polymers Co. Harvard Business School Case 608-055. June 2008 (Revised March 2011)
Majumder P, Groeneveolt H (2001) Competition in remanufacturing. Prod Oper Manag 10(2):128–149
National Industrial Symbiosis Programme (2014) Proven track record. NISP. http://www.nispnetwork.com/about-nisp/a-proven-track-record. Accessed 24 Dec 2014
National Research Council (2010) Toward sustainable agricultural systems in the 21st century. National Research Council of the National Academies. The National Academies Press, Washington, DC
National Slag Association (2014) CemStar process: slag usage raises productivity, operational efficiency, lowers emissions. National Slag Association. http://www.nationalslag.org/sites/nationalslag/files/documents/nsa_201-1_cemstar_technical_bulletin.pdf. Accessed 10 Aug 2014
Panzar J, Willig R (1981) Economies of scope. Am Econ Rev 71(2):268–272
Plambeck E, Taylor T (2013) On the value of input-efficiency, capacity-efficiency, and the flexibility to rebalance them. Manuf Service Oper Manag 15(4):630–639
Savaskan R, Bhattacharya S, Van Wassenhove L (2004) Closed-loop supply chain models with product remanufacturing. Manage Sci 50(2):239–252
Sunar N, Plambeck E (2014) Allocating emissions among co-products: implications for procurement, offsetting & border adjustment. Working paper. University of North Carolina, Kenan-Flagler Business School
Tomlin B, Wang Y (2008) Pricing and operational recourse in coproduction systems. Manag Sci 54(3):522–537
U.S. Business Council for Sustainable Development (2014) Materials marketplace. US-BCSD. http://usbcsd.org/materials. Accessed 21 Dec 2014
U.S. Department of Energy (2005) Dow Chemical Company: by-product synergy process provides opportunities to improve resource utilization, conserve energy, and save money. DOE, U.S. Department of Energy, Energy Efficiency and Renewal Energy. DOE/GO-102005-2153. https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/38478.pdf. Accessed 24 Dec 2014
Zhu Q, Lowe E, Wei YA, Barnes D (2007) A case study of the Guitang group. J Ind Ecol 11(1):31–42
Zhu Y, Dawande M, Gavirneni S, Jayraman V (2014) Competition and firms' willingness to implement industrial symbiosis. Working paper. Available at SSRN: http://ssrncom/abstract=2489460

Chapter 5
Responsible Sourcing

Vishal V. Agrawal and Deishin Lee

Abstract Consumer awareness and concerns regarding the environmental and social impact of the supply chains that produce the products they consume is increasing. Other stakeholders such as non-governmental organizations (NGO's) are also pressuring firms to improve the environmental and social impact of their supply chains. Therefore, in addition to producing high quality products at low cost, firms must ensure that their suppliers are able to supply parts that are produced using processes that adhere to environmental and social impact standards—that is, firms must source responsibly. This chapter discusses what it means to source responsibly and gives an overview of the challenges faced by firms and the mechanisms they can use to implement responsible sourcing.

5.1 Introduction

Most processes that produce goods or provide services rely on supply chains to produce components, ingredients, or subassemblies that are required to deliver the end product to the consumer. The design and execution of the processes in the supply chain determine the characteristics of the product that is eventually consumed by the end-user. From the consumer's perspective, the product characteristics that readily spring to mind are cost and quality (i.e.,

V.V. Agrawal (✉)
McDonough School of Business, Georgetown University, Washington, DC 20057, USA
e-mail: Vishal.Agrawal@georgetown.edu

D. Lee
Carroll School of Management, Boston College, Chestnut Hill, MA 02467, USA
e-mail: Deishin.Lee@bc.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_5

functional or aesthetic performance). These two dimensions clearly affect the consumer's utility from using the product. However, consumers are increasingly starting to care not only about characteristics inherent in the product they experience, but the process characteristics that created the product. In particular, consumers care about the environmental and social impact of the supply chain activities that produce the products they consume. Because process characteristics generate externalities, other stakeholders such as regulators and non-governmental organizations (NGO's) are also pressuring firms to improve the environmental and social impact of their supply chain processes. The use of mass and social media has further increased the influence of these stakeholders over the firm's decisions. Therefore, in addition to ensuring *product* characteristics (quality and cost), firms must ensure that their suppliers are able to adhere to *process* standards for environmental and social impact—that is, firms must source *responsibly*.

From the consumer's perspective, there are two key differences between product characteristics (focus of traditional sourcing) and process characteristics (focus of responsible sourcing). First, product characteristics are observable, but process characteristics are not. Second, product characteristics affect the consumer's use of the product directly, but process characteristics generally do not (and if they do, it may be a negative impact). Process characteristics often generate negative externalities that may have no direct impact on the consumer's use of the product, but have detrimental impact on the environment or society.

Consider the impact of supply chain processes on the environment. These activities can negatively affect the environment in two ways. First, they can deplete natural resources. In general, natural resources such as water, timber, soil, and wildlife can be renewable resources, but the rate at which production methods consume them can thwart a healthy replenishment cycle. Second, supply chains can produce harmful by-products (pollutants) that cause environmental damage that prevents organisms from flourishing in their natural ecosystems.

For example, the production in many food supply chains relies on industrial farming methods. These are typically large-scale monoculture (i.e., single crop) operations that rely on synthetic pesticides and fertilizer to increase yield. Nitrogen run-off from farms have been shown to pollute ground and surface water systems (Gardener and Drinkwater 2009). Poor crop rotation and tillage has also led to soil erosion, thereby reducing the fertility of the soil and its future productivity (Lobb 2008). Thus, this type of production method both damages the natural environment and depletes the natural productivity of the land. However, when consumers purchase industrially farmed fresh produce, they do not observe how the produce was grown, nor do they suffer directly from the negative impact on the land.

Supply chain activities also have a social dimension. For example, global supply chains can employ tens of thousands of workers. Ensuring fair and ethical treatment of those workers, particularly in developing countries where the legal infrastructure is weak, has proven to be challenging for multinational firms. In 2012, a fire broke out in the Tazreen Fashion factory in Dhaka, Bangladesh. Because of poor safety standards, 117 workers were killed in the fire (Bajaj 2012). Poor safety standards are clearly not reflected in the product, making the process defect unobservable to the consumer. The negative consequences of the process defect are also borne by those other than the consumers.

Because of the externalities generated by supply chain processes, regulators and NGO's can play a significant role in process improvement. For example, the Tazreen tragedy was covered widely in the news and consumers were appalled by the lack of safety standards and generally poor working conditions in the factory. Retailers who sourced from the factory were implicated, with consumer advocacy groups demanding that retailers be held accountable for worker mistreatment. The fire exposed the weak labor standards in the garment industry and even retailers who did not source from the Tazreen factory were ensnared in the ensuing public shaming, suffering negative reputational consequences. Since then, retailers have become active in setting working standards and transparency in the supply chain.

In a more positive example, advocacy groups have promoted the beneficial social impact of supporting supply chains with regional affiliations. The "buy local" movement first focused on fresh produce, then expanded to all food categories, and now includes all businesses. Buying local can mean a higher quality product (e.g., fresher food), but many proponents of the "buy local" movement also espouse the positive societal impact. Buying local supports the regional economy and the workers in the regional economy, resulting in a robust and thriving community. This is a benefit, albeit indirect, to the individual consumer who buys from local businesses. There is evidence that these arguments are changing consumer purchasing behavior, and thus firms' sourcing decisions (Lyon 2014).

Although process characteristics may not affect consumers' use of the product directly, they may still affect the utility consumers derive from using the product. For example, knowing that workers are paid a fair wage and work in safe operating environments may increase consumers' valuation for a product. Moreover, consumer interest for process standards can also stem from concern for their own long term well-being. For example, eco-labels such as "Certified Organic" for food production, "Safer Choice" for chemical products (cleaning products), and "Energy Star" for home appliances provide information to consumers about product properties that may not be readily observable through product use. Food produced following the criteria for organic certification and products designated Safer Choice are free of chemicals deemed harmful to human health, but these harmful effects cannot be discerned by ingestion or use.[1] Products that are Energy Star qualified use less energy and thus save the consumers operating cost, which can be significant in the long term.

[1] Note that organic farming methods also reduce the environmental impact of farm activities. Safer Choice products are also less harmful to the environment when disposed.

A case that highlights the ambiguity of process standards is the debate of the health effects of bisphenol-A (BPA). BPA is a synthetic compound used in consumer goods and studies have shown that it is an endocrine disruptor. In particular, the use of BPA in baby bottles was contentious. Canada and the European Union banned the use of BPA in baby bottles. Before the FDA offered an official position on the safety of BPA in this application, baby bottle manufacturers had already removed BPA from bottles in response to consumer demand. This case illustrates that even in the absence of regulation, consumer concerns about personal health and safety can influence a firm's decisions.

A challenging aspect of responsible sourcing is that firms face both upstream and downstream challenges. Upstream, the firm must ensure that suppliers adhere to process standards that cannot be verified by inspecting the part (in contrast to quality metrics). Downstream, the firm must convince consumers to adopt or potentially pay more for products whose "use" characteristics do not necessarily improve as a result of adherence to responsible process standards. In what follows, we first begin by discussing what it means to source responsibly and what unique challenges it poses compared to traditional sourcing. We subsequently provide an overview of the different mechanisms that firms can utilize to address these challenges and implementation issues in the context of responsible sourcing.

5.2 Challenges of Responsible Sourcing

In traditional sourcing, the emphasis is on product quality (i.e., conformance or performance quality) and cost, and the main implementation challenges involve how to design contracts or align bilateral incentives with upstream suppliers. Responsible sourcing not only exacerbates these challenges of traditional sourcing, but also introduces several unique challenges. We outline below the key challenges to responsible sourcing. Subsequently, in Sect. 5.3, we identify and discuss different mechanisms that can be used to address each of these challenges.

5.2.1 Multidimensional Sourcing Criteria

In addition to traditional product characteristics, a firm seeking to source responsibly must consider dimensions such as the social or environmental impact of supply chain processes. These additional criteria may introduce new tradeoffs and considerations. For example, a responsibly sourced product may have different or even lower performance quality. As an example, organic cotton may have a different texture from conventional cotton, and may be less desirable in certain applications.

A firm's decision of whether to offer a responsibly-sourced product, depends on factors related to both the upstream suppliers and the downstream consumers. The buyer must consider whether the upstream supplier is able to provide responsibly-sourced parts and at what cost. The buyer must also consider how much and how many consumers will value a responsibly produced product. Moreover, there is often uncertainty about the consumer's willingness to pay for a responsibly produced product, especially if the process standard does not improve the consumer's own experience with the product. For example, paying workers a fair wage may improve the social impact of clothing, but increases the cost of production. Consumers may not be willing to pay more for the responsibly produced product since the traditional quality measures may remain unchanged.

5.2.2 Multilateral Coordination

An important antecedent for a buyer to consider responsible sourcing is that suppliers must be willing and able to produce parts that adhere to the relevant social or environmental standards. In other words, a buyer is dependent on upstream suppliers to offer responsibly produced parts. This can be challenging in practice for several reasons.

First, adhering to responsibility standards typically increases the supplier's cost. There may be a fixed cost, e.g., for upgrading equipment or for a certification process. The ongoing production cost may also increase because of better material inputs, more expensive labor, or lower production rates. The supplier must be able to capture enough value (through transactions with the buyer) to compensate for the potential investment and cost increases necessary to achieve the responsibility standards. Therefore, a buyer needs to consider how to influence or incentivize the supplier to change its process and facilitate responsible sourcing.

Second, it is important to align the incentives across the supply chain. Typically, the involved parties act in their own self-interest and need to make coordinated decisions. Responsible sourcing requires that both buyers and suppliers are willing to make the required investments. However, this typically creates a "chicken and egg" situation: In order for the buyer to be able to source responsibly, suppliers must produce parts adhering to certain responsibility standards. In order for the supplier to do so, the buyer must be willing to source those parts. The interdependence of these decisions makes it challenging for all parties in the supply chain to change from the status quo.

5.2.3 Contracting Issues

Decisions regarding how to structure contracts can be challenging under traditional quality or cost based sourcing, but contracting issues are further exacerbated in the context of responsible sourcing. Product cost and quality are easier to measure and verify than the environmental or social measures that are relevant in the context of responsible sourcing. Assessing or verifying whether a product adheres to responsibility process standards requires monitoring throughout the entire supply chain. Given the global and fragmented nature of supply chains in today's world, this becomes very difficult. Therefore, contracting for responsible sourcing poses a significant challenge in practice.

5.2.4 Additional Stakeholders

Environmental and social externalities are created by supply chain activities and thus a firm must anticipate and consider the response of additional stakeholders such as regulators, NGO's, and consumer advocacy groups. The goal of these entities is to induce firms to undertake responsible sourcing. Even for firms that source responsibly, such entities are involved in monitoring supply chain activities to ensure that responsibility standards are upheld and firms do not misrepresent the responsibility levels of their products. Mechanisms that have been effectively used to influence firm behavior include publicizing a firm's environmental or social impact performance or violations, or organizing consumer boycotts of products. NGO's may also consider influencing regulators, who in turn, can implement legislation to incentivize firms to adopt responsible sourcing. Regulators may consider requiring that a firm's products adhere to minimum responsibility standards or mandate provision of information regarding sourcing of products such as that under the California Transparency in Supply Chains Act (California Senate 2010). Therefore, it is critical that firms anticipate the response and actions of these additional stakeholders when deciding whether and how to offer responsible products.

5.3 Mechanisms for Responsible Sourcing

We next consider mechanisms for addressing the challenges of responsible sourcing.

5.3.1 Multidimensional Sourcing Criteria

In the context of responsible sourcing, a firm has to balance the different tradeoffs between traditional product characteristics and responsibility-based process characteristics. Often these tradeoffs are manifested as a decision of which type of supplier to source from—one that produces according to responsibility standards and one that does not.

Guo et al. (2015) study this tradeoff—should a buyer source from a responsible supplier who is at higher cost, but adheres to the responsibility standards desired, or from a risky supplier who is cheaper but does not adhere to the standards? This decision is especially important when faced with a market with a socially-conscious consumer segment. Sourcing from a risky supplier may lead to a responsibility violation, causing a public event and a loss of demand from such consumers (e.g., as in the Tazreen Fashion factory fire example). Guo et al. (2015) study a firm's choice from the following sourcing policies: The firm can source only from the risky supplier and tolerate the exit of socially conscious consumers in case of a violation, or source from both suppliers to diversify their offerings, or only source from the responsible supplier and sell to the socially conscious consumers or all consumers. Guo et al. (2015) show that as consumers become more socially conscious, it may be beneficial for a buyer to shift from selling a responsibly-produced product to all consumers to only targeting the socially-conscious consumers, resulting in a lower quantity being responsibly sourced. Therefore, their results suggest that firms should carefully anticipate the changes in consumer preferences for responsibly produced products and consider how they should adapt their sourcing policy accordingly.

In a similar vein, Ata et al. (2015) study the sourcing decisions of a buyer in the fresh produce supply chain. Typically, the fresh produce supply chain is characterized by large (mainstream) suppliers that are located far from consumers. Retailers can also source from local suppliers (farms) who are closer to the consumers. However a challenge of sourcing from local suppliers is that they are typically capacity constrained. Therefore, retailers end up using local suppliers who are closer, as de facto responsive suppliers, i.e., place an order closer to demand realization. This is risky for a local supplier as it faces a less predictable demand. In order to encourage sourcing from local fresh produce suppliers, Ata et al. (2015) consider the following operational mechanisms: (1) Retailers can use intermediaries that act as an aggregator, which allows a group of local suppliers to decrease their uncertainty and make sourcing from them more attractive. (2) Retailers can utilize empty trucks returning from retail stores to the warehouse to collect fresh produce from the local suppliers (referred to as backhauling). An example of this is Walmart's Heritage Agriculture program, which uses backhauling to source locally. Such a program can lower the cost of sourcing locally, making local sourcing more attractive. (3) Walmart's Heritage Agriculture program also offers a purchase guarantee to buy a certain quantity from a local supplier. Ata et al. (2015) show that using a combination of backhauling and a purchase guarantee can benefit both the retailer and the local supplier.

Another important decision for a firm is how it should market or position its products with respect to their responsibility or sustainability level. Vedantam et al. (2014) study the recycled content claims often used by a firm on their product packaging or in their sustainability reporting. Typically, under such a claim, a firm discloses what fraction of their product is comprised of recycled content. The firm can source recycled content from the municipal supply, which is cheaper but constrained, or go out and collect recycled input on its own, which is more expensive. Should a firm use a time-specific or a time-averaged claim? In other words, whether to promise a certain fraction of recycled content in each product in every period, or an average fraction of recycled content across several periods. As averaging over time allows the firm to source less from the expensive collection source and rely more on the cheaper municipal source, a higher recycled content claim should be offered under the time average. In other words, choosing what may be perceived at glance to be a weaker claim, i.e., averaging over time, may actually lead the firm of offer a higher fraction of recycled content in its products.

5.3.2 Multilateral Coordination

A firm cannot unilaterally decide to offer a responsibly-sourced product. It depends on upstream suppliers to adhere to the required responsibility process standards and ensure a reliable supply of responsibly sourced parts. Therefore, an important decision for a firm in this context is how to coordinate or motivate its suppliers and other parties in the supply chain. We first discuss how firms should design their sourcing policies in this context. We subsequently discuss how responsible sourcing can be made feasible by collaborating with suppliers or fostering competition between them.

As discussed earlier, it may be costly for suppliers to switch to a sustainable or responsible process. The lack of supply of responsible products or parts may preclude a buyer from pursuing responsible sourcing. This supply problem can be further exacerbated by buyers who do not want to commit to buying the more expensive sustainable inputs, in case consumers are not willing to pay a premium for the products. However, sourcing policies can be used to influence an upstream supplier to switch to a sustainable process. A sourcing policy can be used to establish and communicate the firm's preference for conventional vs. responsible products and may also offer an incentive to suppliers to convert to sustainable practices.

Agrawal and Lee (2015) study the use of different sourcing policies observed in practice, where a buyer's sourcing policy can make explicit what kind of inputs it will source. This in turn can induce a supplier to switch to a sustainable process. For example, a buyer can adopt a *sustainable preferred* sourcing policy, where it commits to purchase sustainable inputs if the supplier switches to a sustainable process, but will still purchase conventionally produced inputs if the supplier remains with a conventional process. This type of policy is used by Chipotle in its "Food with Integrity" program. In contrast, under a *sustainable required* sourcing policy, the buyer will only purchase sustainably produced inputs. Stonyfield, an organic yogurt manufacturer, uses this type of stricter sourcing policy. Conventional wisdom would suggest that if a supplier does not prefer to switch under a non-committal policy, these sourcing policies would induce a supplier to switch. However, Agrawal and Lee (2015) show that whereas a *sustainable required* policy may induce a supplier to switch, a *sustainable preferred* policy may actually deter the supplier from switching.

Sourcing policies not only influence supplier behavior but also represent a product positioning statement. In other words, a sourcing policy links a buyer's upstream decisions pertaining to the supplier with its downstream decisions, which depend on consumer preferences. Therefore, in situations where a buyer can verify or ascertain adherence to environmental or labor standards, sourcing policies, if used correctly, may be an effective mechanism for responsible sourcing.

If there are multiple suppliers, a buyer can consider using competition between suppliers to spur development of more responsible products and processes. Alternatively, competing firms at the same supply chain level can also consider collaborating together to share costs and resources to develop a more responsible alternative.

Kraft and Raz (2014) investigate whether competing manufacturers should collaborate to develop a replacement for a potentially hazardous substance, instead of competing with each other. They show that it can be beneficial for the manufacturers to collaborate to develop a substitute even if the shared cost is higher than the sum of their individual costs. For example, if in the absence of collaboration, the manufacturers differ in their incentives to develop the replacement, i.e., only one of them prefers to develop it, they may benefit from collaborating to replace the substance. The results from Kraft and Raz (2014) highlight how competing manufacturers can benefit from collaborating together to replace hazardous substances (vs. competing on toxicity), leading to superior outcomes for consumers and the society.

In a similar vein, Karaer et al. (2015) study an innovative tool called Material IQ (MIQ) developed by GreenBlue, a non-profit organization, which encourages suppliers to share sensitive data regarding the chemicals in their products (for details, see chapter "Managing the Chemicals and Substances in Products and Supply Chains," by Kraft, Karaer, and Sharpe). This tool was aimed to provide a central source of information for manufacturers and retailers, as they make their sourcing decisions. The results in Karaer et al. (2015) show that such a tool increases the competition between the suppliers, which helps increase the environmental quality and manufacturer profits. However, this comes at the expense of increased competition between suppliers. Instead of fostering competition between suppliers, a manufacturer can share costs with a supplier to invest in improving environmental quality. If the manufacturer earns a sufficiently large premium, it benefits from cost sharing instead of fostering competition. If consumers are quite sensitive to the presence of hazardous substances, the manufacturer may even benefit from both adopting cost sharing and fostering competition.

Overall, competition and collaboration can be effective tools in influencing the development of replacements for hazardous substances used in consumer products. Whether competition or collaboration should be used depends on the brand differentiation between firms, supply chain structure, and the consumers' sensitivity to potentially hazardous substances in their products.

5.3.3 Contracting Issues

Verifying supplier adherence to environmental or labor standards is a significant challenge for buyers. Conventional contracting mechanisms typically used for traditional quality and cost measures cannot be directly implemented in the context of responsible sourcing. Instead, firms should combine them with other elements such as deferred payments, auditing, or require certification through eco-labels or standards.

5.3.3.1 Deferred Payments

Suppliers may have an incentive to misrepresent the characteristics of their products. However, in some cases, such a violation may be discovered at a much later date when the impact is significantly worse (e.g., adverse reputational effects when safety violations occur). Therefore, an effective mechanism can be to include a contractual clause that delays a portion of the payment.

Babich and Tang (2012) consider a setting where an upstream supplier has an incentive to save costs by adulterating or diluting a product with additives. They propose two different contractual mechanisms that a firm can use to deter a supplier from doing so: The firm could consider offering a deferred payment contract, where a portion of the payment to the supplier is withheld until a time in the future, contingent on that no product defects or violations are discovered in the meantime. Alternatively, a firm could rely on inspection, where the products are inspected immediately and the supplier is paid if no defects are discovered. Babich and Tang (2012) show that a firm does not gain any additional benefit from utilizing both deferred payments and inspection together. Instead, the firm should adopt contracts with deferred payments when inspecting products is costly or not accurate. In contrast, when the supplier has high financing costs, the buyer should instead use contracts with inspection terms.

An additional complication from a buyer's perspective is how to distinguish between different suppliers, when their responsibility performance are unobservable. In such a context, a potential solution may be to consider more sophisticated screening contracts to manage the risk of responsibility violations. Chen and Lee (2014) analyze how and when to utilize such contracts for responsible sourcing. Firms can offer contracts with two different payments: a fixed payment and a deferred payment contingent on whether a violation or breach by the supplier is discovered. A buyer can offer a menu of such contracts aimed to separate suppliers with different ethical levels, when directly observing their actions is not feasible. Chen and Lee (2014) show that a menu of contracts is effective for screening suppliers when the cost of violations is low. However, when the cost of violations is high, i.e., when sourcing responsibly is more critical, screening contracts with deferred payments are not effective for differentiating between suppliers. Instead, the firm should rely on simpler mechanisms augmented with other tools such as auditing, eco-labels or certification (see Sects. 5.3.3.2 and 5.3.3.3).

5.3.3.2 Auditing

Another important and commonly used mechanism is inspection or auditing of suppliers for noncompliance or violations. For example, Walmart has a compliance team that audits its suppliers and the results are directly used to determine whether to continue sourcing from a supplier (Plambeck and Denend 2010). There are a number of important issues to consider when using the auditing mechanism: How should audits/inspections be conducted to encourage compliance to environmental or social impact criteria? Are inspections or auditing effective for achieving the intended goal? What other decisions or strategies should be used in combination with auditing to increase responsible sourcing?

Plambeck and Taylor (2014) study how a buyer should audit its suppliers when its compliance with environmental and labor standards cannot be directly observed. In response to recent scandals related to violations in different industries, there has been an increase in the auditing conducted by buyers. While one may expect increasing auditing to be a good strategy, Plambeck and Taylor (2014) show that increased auditing may lead to an increase in effort by the suppliers to evade the audits, and reduce the detection of non-compliance. Therefore, firms should be wary of increasing auditing frequency because it may backfire and instead worsen labor and environmental conditions. Similarly, a supplier may decrease compliance efforts in response to NGO efforts to publicize violations or if the buyer provides a higher price to the supplier. Instead, Plambeck and Taylor (2014) suggest alternative mechanisms to avoid this undesirable outcome. For example, it may be better for a buyer to lobby the local government to require a higher minimum wage for workers or to coordinate its pricing and auditing decisions.

Xu et al. (2015) investigate the issue of child labor in the upstream supply chain, where it is very difficult, to detect if a supplier is using child labor. Moreover, firms are increasingly facing regulation regarding sourcing of products made with child labor. For example, the California Transparency in Supply Chains Act requires manufacturers in California to declare their efforts in combating child labor in their supply chains. In order to comply with this Act, buyers must disclose their auditing efforts to consumers. However, the disclosure also informs their suppliers. For buyers who do not conduct inspections, the suppliers would know that there is no probability of inspections or violations being discovered, leading to greater use of child labor. Therefore, efforts to require transparency from buyers sourcing from suppliers may backfire, and increase the use of such labor. Xu et al. (2015) instead suggest increasing consumer awareness to drive an increase in the price that can be charged for firms who conduct more inspections or to allow the firm to decide how much compensation should be paid to such labor detected during these inspections.

The above discussion highlights that an important aspect of utilizing auditing policies for responsible sourcing is to correctly anticipate and account for the supplier or manufacturer's incentives in response to auditing policies, thereby avoiding unintended consequences.

5.3.3.3 Use of Standards and Eco-labels

Eco-labels and process standards are becoming increasingly important as a mechanism for ensuring and communicating compliance with responsible practices that cannot be easily verified by inspection or use. For example, Walmart prefers sourcing seafood that meets the Marine Stewardship Council Certification (Plambeck and Denend 2010). As discussed earlier, Chen and Lee (2014) show that screening contracts with deferred payments are not effective when violations are costly. Instead, they suggest offering contracts with terms that differ based on certification. In particular, buyers can offer a menu of contracts for certified and uncertified suppliers and this may induce suppliers to voluntarily get certified. This is beneficial for the buyers as it allows them to differentiate between suppliers with different responsibility levels. Buyers can also choose a mandatory certification where they only contract with certified suppliers. In terms of choosing whether a buyer should choose mandatory or voluntary certification, Chen and Lee (2014) show that a mandatory certification may lead to lower sourcing cost for the buyer.

Ecolabels and standards while promising, also pose certain challenges in practice. Typically, when a product meets a standard, there may still be uncertainty about what information the standard conveys to the consumer, e.g., how stringent the standard is, or how much environment impact the standard imposes. This raises an important question for buyers. Should they require an ecolabel given such uncertainty regarding their stringency? Harbaugh et al. (2011) study this issue and show that due to this uncertainty, labels may not be very informative. In addition, when there are several different labels, it causes all of them to become less informative. As consumers may not know which standards are demanding, they might assume that the firm chooses to adopt the easiest one. Harbaugh et al. (2011) also show that firms with low environmental quality adopt the same labels as the firms with high environmental quality, but the firms with high environmental quality would like to differentiate themselves from others. This research provides an important caveat regarding the use of eco-labels and standards—although one may expect eco-labels to certify the environmental performance of a product, they may be uninformative and counterproductive if there is uncertainty among consumers regarding the stringency of the standard.

5.3.4 Additional Stakeholders

The main concern of those advocating responsible sourcing practices is the creation of negative environmental and social externalities by supply chain activities. Thus, additional stakeholders such as regulators, NGO's, and consumer advocates play an important role. A buyer has to anticipate the actions and responses from these stakeholders when deciding whether to source responsibly.

Firms should monitor consumer awareness and sensitivity for different responsibility dimensions of their products and any potential regulation that may occur in the near-term future. Kraft et al. (2013a) study such a situation where a firm is considering whether to develop a replacement substance for a potentially hazardous material in its product. An event may occur in the future which confirms the hazardous nature of the substance, and regulation that bans it may be improved. If a firm proactively replaces the substance before an event occurs, it can exploit the situation to gain higher profits due to increased demand. However, if a firm does not replace the substance and an event occurs, it risks losing customers. Kraft et al. (2013a) show that firms should indeed develop a substitute well in advance, motivated by the threat of regulation or a change in consumer awareness. However, it may not be good to implement a developed replacement immediately. Instead, firms may benefit from deferring its implementation to a later date. In the case where the firm operates in a competitive industry, it may benefit from immediately implementing the replacement.

Galbreth and Ghosh (2013) investigate the effect of consumer awareness regarding sustainability of products on competition between firms. They show that when firms compete by offering different products, i.e., one offers a conventional product and the other a sustainable product, both firms may benefit from increasing consumer awareness. In other words, even if a firm simply wants to offer a conventional product, increasing consumer awareness for sustainably sourced products may be beneficial. The reason is that increased consumer awareness increases the perceived differentiation between the sustainable and conventional products, thereby relaxing the competition between the firms.

Firms should also pay attention to how their decisions influence stakeholders such as NGO's. Kraft et al. (2013b) study how NGO's exert efforts to promote the development of replacement substances. An NGO can pursue two different strategies: it can choose to lobby the regulator to increase the chances of regulation being enacted, or it can influence the industry directly by increasing consumer and market sensitivity to the potentially hazardous substance. Kraft et al. (2013b) show that when firms are relatively homogenous and prefer to defer, NGO's prefer targeting the regulatory body. When only one firm replaces the substance, the NGO can leverage the competition between the firms and choose to target the market. Interestingly, lobbying to oppose an NGO's efforts may backfire for the firm. This is because the NGO will respond by increasing its efforts.

5.4 Conclusion

The inclusion of process characteristics into sourcing criteria has introduced a new set of challenges and tradeoffs for firms who seek to source responsibly. Two key differences that distinguish responsible sourcing from traditional sourcing criteria are that process characteristics are generally unobservable or unverifiable through product inspection or use, and the impact of supply chain processes typically do not affect the consumer directly, but rather generate externalities that negatively affect the environment or society. Ensuring adherence to these process characteristics poses new challenges to firms: multidimensional sourcing criteria, multilateral coordination, contracting issues, and interacting with additional stakeholders such as regulators, NGO's, and consumer advocacy groups. In this chapter, we provide a brief overview of these challenges and different mechanisms that can be used to address them. We hope that this chapter provides insights for firms regarding which factors to take into account when making decisions related to responsible sourcing.

Going forward, scrutiny of supply chain process characteristics will only increase, and the use of social media can rapidly turn a supply chain infraction into a brand nightmare for retailers and original equipment manufacturers. Although the literature has studied a number of mechanisms to address these challenges, it is but a start to a field which warrants both broader and deeper investigation. The environmental and social impact in different industries can be manifested in different ways, which would call for mechanism designs tailored for specific settings. The role of intermediaries for setting and enforcing supply chain standards is also another area for future research. As with cost and quality dimensions before, firms must find ways to change and align their supply chain activities to adhere to environmental and social standards, and operations management researchers can be instrumental in this process.

References

Agrawal V, Lee D (2015) The effect of sourcing policies on a supplier's sustainable practices. Working paper. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2601974

Ata B, Lee D, Tongarlak MH (2016) Mechanism for increasing sourcing from capacity-constrained local suppliers. Decis Sci doi:10.1111/deci.12204

Babich V, Tang CS (2012) Managing opportunistic supplier product adulteration: deferred payments, inspection, and combined mechanisms. Manuf Serv Oper Manag 14(2):301–314

Bajaj V (2012) Fatal fire in Bangladesh highlights the dangers facing garment workers. The New York Times. http://www.nytimes.com/2012/11/26/world/asia/bangladesh-fire-kills-more-than-100-and-injures-many.html?_r=1. Accessed 6 Mar 2015

California Senate (2010) The California transparency in supply chains act. Senate bill 657 http://www.leginfo.ca.gov/pub/09-10/bill/sen/sb_0651-0700/sb_657_bill_20100930_chaptered.pdf. Accessed 3 Aug 2015

Chen L, Lee H (2014) Mitigate supplier responsibility risk in emerging economies: an ethical sourcing framework. Duke University working paper

Galbreth M, Ghosh B (2013) Competition and sustainability: the impact of consumer awareness. Decis Sci 44(1):127–159

Gardener J, Drinkwater L (2009) The fate of nitrogen in grain cropping systems: a meta-analysis of ^{15}N field experiments. Ecol Appl 19:2167–2184

Guo R, Lee H, Swinney R (2015) The impact of supply chain structure on responsible sourcing. Working paper

Harbaugh R, Maxwell J, Roussillon B (2011) Label confusion: the Groucho Effect of uncertain standards. Manag Sci 57(9):1512–1527

Karaer O, Kraft T, Khawam, J (2015) Firm and nonprofit levers to improve suppliers' environmental performance. Darden Business School working paper

Kraft T, Raz G (2014) Competing on toxicity: the impact of supplier prices and regulation on manufacturers' substance replacement strategies. Darden Business School working paper

Kraft T, Erhun F, Carlson R, Rafinejad D (2013a) Replacement decisions for potentially hazardous substances. Prod Oper Manag 22(4):958–975

Kraft T, Zheng K, Erhun F (2013b) The NGO's dilemma: how to influence firms to replace a potentially hazardous substance. Manuf Serv Oper Manag 15(4):649–669

Lobb D (2008) Soil movement by tillage and other agricultural activities. In: Jorgensen SE, Fath B (eds) Encyclopedia of ecology, earth systems and environmental sciences. Academic, London, pp 3295–3303

Lyon J (2014) Buy local campaigns can actually supercharge sales. CNN Money. http://money.cnn.com/2014/03/28/smallbusiness/buy-local/. Accessed 6 Mar 2015

Plambeck E, Denend L (2010) Walmart's sustainability strategy. Stanford Graduate School of Business case OIT-71

Plambeck E, Taylor T (2014) Supplier evasion of a buyer's audit: implications for motivating compliance with labor and environmental standards. Working paper

Vedantam A, Iyer A, Lacourbe P (2014) An analysis of recycled content claims under demand benefit and supply uncertainty. Working paper

Xu Y, Cho S, Tayur S (2015) Combating child labor: incentives and information transparency in global supply chains. Carnegie Mellon University working paper

Chapter 6
The Impact of Supply Chain Structures on Corporate Social Responsibility

Paolo Letizia

Abstract Markets are paying increasing attention to the social and environmental impacts of business. As a consequence, the problem of incentivizing upstream firms in a supply chain (i.e., suppliers) to engage in Corporate Social Responsibility (CSR) activities has become of pivotal importance. Formal contracts may not serve the purpose, as CSR activities are not necessarily verifiable. In this chapter, we posit that incentives for CSR can be provided through the supply chain structure, which consists of the distribution of ownership rights over the assets of production, and involves horizontal and/or vertical alliances among supply chain members. To this end, this chapter illustrates the effects of supply chain structure on CSR adoption using three case studies. For each case, the chapter highlights the interplay of forces that arises as a result of the supply chain structure, such as pooling, free-riding, and countervailing power, and discusses their impact on incentivizing supply chain parties to invest in CSR.

6.1 Introduction

Corporate Social Responsibility refers to the commitment of firms to integrate social and environmental concerns in their business operations and interactions with stakeholders. Consumers are increasingly interested in goods that are produced in a responsible and sustainable way, i.e., taking into account the impact of the production of these goods on the environment and the society. Research has shown that they are also willing to pay more for such

P. Letizia (✉)
Assistant Professor of Business Analytics, Haslam College of Business University of Tennessee, 223 Stokely Management Center, 916 Volunteer Boulevard, Knoxville, TN 37996-0525, USA
e-mail: pletizia@utk.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_6

goods.[1] To respond to this market trend, downstream firms need to design proper incentives for their suppliers to invest in CSR activities. However, the benefits and/or revenues generated by CSR activities are often difficult to verify, as they might be either too indirect to value or deeply embedded in the core business of a company to be measured meaningfully. As a consequence, formal contracts specifying payments contingent on CSR performance may not be enforced in a court of law, and thus fail to provide the incentives to invest. As such, this chapter applies the *property rights* (PR) approach, first introduced by Hart and Moore (1990), to argue that incentives to invest in CSR can be provided through an appropriate design of the supply chain.

According to the PR theory, a firm in a supply chain corresponds to an asset of production, on which an investment can be undertaken. Having *ownership rights* over the asset means being entitled to decide who uses the asset and to receive payments generated by the use of that asset. A *supply chain structure* consists of an alliance between firms in the supply chain, where the ownership rights over the assets of production are assigned. There are various supply chain structures that can be observed in practice: market exchange of independent firms, horizontal and vertical alliances, and cooperatives, which represent firms vertically integrated. Different structures may create different incentives for firms to invest in CSR. This chapter studies how the supply chain structure affects CSR investments on the assets of firms in the supply chain.

We consider a supply chain with two upstream suppliers and one downstream processor. Each party can create extra revenues by investing in CSR. If a CSR investment is taken both upstream and downstream, the total additional revenues generated by CSR activities are augmented by an exogenous factor, as it demonstrates to consumers that the whole supply chain is committed to respect the planet and people. Within this setting, we study three business cases and compare their supply chain structures. For each case, we identify supply chain forces such as *pooling*, *free-riding*, and *countervailing power*. The interplay of these forces determines the incentives for investing in CSR.

Pooling is a horizontal alliance between suppliers who agree to jointly own assets and share revenues generated by CSR investments. This pooling of revenues can result in *free-riding*, where one supplier decides not to invest and takes advantage of the other supplier's investment. Hence, pooling discourages suppliers to invest in CSR. The horizontal alliance of suppliers, however, can increase the bargaining power of the upstream tier against the

[1] Several surveys have reported that consumers do value CSR activities and are willing to pay a higher price for the corresponding products. Ferreira et al. (2010) states that "consumers perceived greater benefit and value in the offer of the socially responsible firm, and were showed to be willing to pay 10 % more for its product, judging this price differential as being fair". In a similar vein, Grimmer and Bingham (2013) finds that consumers are more willing to purchase products from companies perceived to have a higher environmental performance at each stage of the product value chain.

downstream tier of the supply chain. As a consequence, through an alliance, two suppliers may appropriate a larger share of the revenues generated by the processor. This phenomenon, known as *countervailing power*, generates positive incentives for suppliers to invest in CSR. Given the interplay of pooling, free-riding, and countervailing power, we denote the supply chain structure that creates the highest number of incentives to invest in CSR as *efficient*.

This chapter contributes to the streams of literature on *incentives* for CSR activities and on *incomplete contracts*. A few recent papers have considered the problem of incentivizing suppliers to engage in socially responsible operations. Chen and Lee (2014) propose a delayed payment contract to mitigate the supply responsibility risk. Xu et al. (2014) study several strategies to mitigate suppliers' use of child labor, such as internal inspections of the suppliers' sites, high wholesale prices, and support from third-party organizations. Kim (2014) considers the environmental performance as determined by the interplay between inspections performed by a regulator and noncompliance disclosure by a production firm. These articles, however, do not consider the impact of the supply chain structure on CSR investments. There are only a few works that study this aspect. Bagnoli and Watts (2003) analyze how CSR activities are affected by the structure of the market and competition. Mendoza and Clemen (2013) study how the incentives for CSR given by competing buyers to their suppliers are affected by suppliers sharing. This chapter departs from the previous literature by considering not only horizontal and/or vertical alliances but also ownership rights.

The supply chain literature on incomplete contracts is quite recent and still developing. Some works have modeled long-term contracts, which are incomplete by nature, as contractual terms are likely to be renegotiated, especially in the presence of unforeseen contingencies. For instance, Plambeck and Taylor (2007a) consider the case where demand is uncertain at the time the contract is signed. In Plambeck and Taylor (2007b) the authors propose contract renegotiation as a way to give more purchase flexibility to the buyer. A few papers have also adopted the property rights approach but they are empirical [see for instance Novak and Eppinger (2001) and Williams et al. (2002)]. This chapter takes an analytical approach instead.

The remainder of this chapter is organized as follows. In Sect. 6.2, the property rights approach is introduced as an alternative way to traditional contracts to incentivize the parties to undertake CSR investments. Section 6.4 illustrates three business applications of the property rights approach and Sect. 6.5 contains a few concluding remarks.

6.2 The Theory of Property Rights (PR)

Consider a set of N firms and a stylized 2-period model. Using terminology from cooperative game theory, a subset $J \subset N$ of firms is referred to as a *coalition*. Firms may undertake costly investments in period 1, and attain revenues through trade in period 2. It is assumed that in period 1 the investing parties cannot contract on the allocation of the revenues generated in period 2. There are two reasons for this. First, the revenues generated through investments may be attributed to other factors, which would deprive the investing party of the ability to claim payments as determined by the contract. Second, contracts are necessarily *incomplete*, due to (1) the costs of specifying all the relevant contingencies, (2) the difficulties of negotiating the responsibilities of all parties in all contingencies, and (3) the costs of monitoring the contract (Grossman and Hart 1986; Williamson 1979).

The PR theory provides an approach to study cases where parties are to be incentivized to undertake an investment, but contracts cannot be used or are somehow ineffective for this objective. This approach posits that the future return on an individual's current investment depends on his *ownership rights* over the asset of production. The owner of an asset is assumed to have the right to exclude others from the use of that asset; in case of contract renegotiations or disputes, the owner has the right to appropriate revenues generated through use of the asset.[2]

To understand the impact of ownership rights on the willingness to invest by a business player, consider a situation where player X wants to use a machine initially owned by player Y.[3] One possibility is for X to buy the machine from Y; another possibility is to rent it. If contracting costs are zero, the two players can sign a rental agreement that would be as effective as a change in ownership. In particular, the rental contract may specify exactly what X can do with the machine, when he has access to it, what happens if the machine breaks down, what rights he has to use the machine, and so on. Given this possibility, it is unclear why changes in asset ownership ever need to take place. In a business context where there are positive transaction costs, however, renting and owning are no longer economically equivalent. If contracts cannot be written or are incomplete, not all the uses of the machine will be specified in all possible eventualities. The economic question then arises: Who chooses the unspecified uses? A reasonable approach is that the owner of the machine has this property right; that is, the owner has the residual rights of control over the machine. For example, if the machine breaks down or requires modification and the contract is silent about this contingency, the owner can decide how and when the machine is to be repaired or modified. It is now possible to understand why it might make sense for X to buy rather than to rent the machine from Y: if X owns the machine, he will have all the residual rights of control. Put differently, if the machine breaks down or needs to be modified, X can ensure that the machine is repaired or modified quickly, so that he can continue to use the machine productively. Knowing this possibility, X will have a greater economic incentive to look

[2] Empirical support for the idea that noncontractible investments are influenced by asset ownership can be found in a number of papers, including Woodruff (2002) and Acemoglu et al. (2010).

[3] This example is adapted from Mahoney (2005).

after the machine, to learn to operate the machine properly, and to acquire other machines that create a synergy with his machine. In the end, any kind of investment on the machine would make much more sense when the machine is owned rather than rented by the investing player.

According to the PR approach, the owners of an asset of production are the individuals that will be able to claim all the revenues generated by the use of that asset for themselves. When the revenues in period 2 are generated thanks to the previous investments, the supply chain parties will engage in a bargaining process with the objective of allocating the revenues. The outcome of such bargaining must have the following characteristics:

- Allocation of revenues is unique
- Revenues will be fully allocated among players
- Players who did not contribute to revenues receive a zero allocation
- Identical players receive identical allocations.

The Shapley value is an allocation scheme that jointly satisfies the properties above,[4] and is thus used by Hart and Moore (1990) in the formulation of the property rights approach. The Shapley value of player i can be computed as

$$S_i = \sum_{J \subseteq N \setminus \{i\}} \frac{|J|!(|K| - |J| - 1)!}{|K|!} (v(J \cup \{i\}) - v(J)), \tag{6.1}$$

where the *characteristic function* $v(J)$ represents revenues generated by coalition J. In other words, the Shapley value computes the expected contribution of firm i to coalition J, where the expectation is taken over all coalitions to which i might belong. An example of computation of the Shapley value is provided in the Appendix.

6.3 The Model

The supply chain consists of two upstream suppliers and one downstream processor, i.e., $N = 3$. Let x_1, x_2, and x_3 denote the CSR investment decisions of supplier 1, supplier 2, and the processor, respectively, in period 1. For simplicity, x_i can take on a value of either 0 or 1 for $i = 1, 2, 3$, where $x_i = 1(0)$ if and only if party i does (does not) invest. Contingent on the CSR investments, the parties generate revenues in period 2. Specifically, supplier 1 and 2 will generate revenues equal to A and B, respectively, whereas the processor will generate revenues equal to C.

[4] See Kemahlıoğlu-Ziya and Bartholdi (2011) about the Shapley value being a fair mechanism of expected excess profit allocations when retailers agree to pool their inventory.

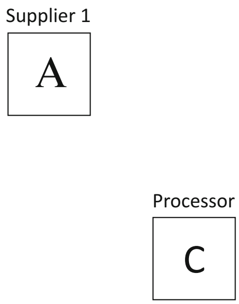

Fig. 6.1 The supply chain

However, no investment in period 1 implies zero revenues in period 2. To capture suppliers' heterogeneity, we assume the revenues generated by the two suppliers may differ, and without loss of generality, require $B < A$. Figure 6.1 depicts the three members of the supply chain, and specifies the revenues that each party generates in period 2 through a CSR investment in period 1.

Given the increasing traceability of goods, consumers value CSR activities at each stage of the supply chain. Thus, we assume that CSR investments from both the supplier and the processor augment the revenues by a factor $s > 1$. The factor s is referred to as a *vertical synergy in CSR*. For instance, if supplier 1 and the processor invest in CSR, the total revenues will be equal to $s(A + C)$, instead of $(A + C)$. Finally, to complete the model we assume that the costs of the CSR investment are given by k_i, $i = 1, 2, 3$.

In the next section we show an application of the property rights to a simple example.

6.3.1 A Simple Example

Consider a supply chain with only one supplier and one processor, i.e., $N = 2$. Managers wonder whether integration between the two firms would incentivize investments in CSR. To answer this question, the three supply chain structures reported in Fig. 6.2 should be compared, where a cross in the box denotes that the party has ownership rights over the asset.

Structure I represents a market exchange, where both the supplier and the processor own an asset of production and are independent. Structures II and III are cooperatives, where the assets of production are owned by only one member of the supply chain. In the supplier cooperative (i.e., structure II), the supplier forward integrates the processor, whereas in the customer cooperative (i.e., structure III), the processor backward integrates the supplier.

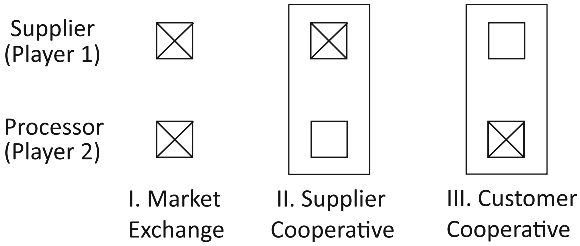

Fig. 6.2 Supply chain structures

To apply the property rights approach and compare the structures, we need to determine characteristic functions and Shapley values for each structure. The characteristic function, $v(J)$, can be computed considering that (1) player 1 and 2 generate revenues A and C, respectively, by investing in CSR, (2) the revenues generated in a cooperative are appropriated by the firm who has ownership rights over the assets, and (3) the total revenues of the cooperative are augmented by the vertical synergy s if both supplier and processor invest in CSR. Assuming each party invests in CSR, the characteristic function, $v(J)$, can be computed as shown in Table 6.1.

Table 6.1 Characteristic functions in the three supply chain structures if all parties invest in CSR activities

Supply chain structure	$v(\{1\})$	$v(\{2\})$	$v(\{12\})$
I	A	C	$s(A+C)$
II	$A+C$	0	$s(A+C)$
III	0	$A+C$	$s(A+C)$

The Shapley value assigns each player his expected marginal contribution as a coalition member. In this example the two possible coalitions are $\{12\}$ and $\{21\}$, to which player 1 contributes $v(\{1\})$ and $(v\{12\} - v(\{2\}))$, respectively, whereas player 2 contributes $(v\{12\} - v(\{1\}))$ and $v(\{2\})$, respectively. The average of these two contributions provides the Shapley value for each player. The Shapley values of the two players in the three supply chain structures are reported in Table 6.2.

Table 6.2 Shapley values of supplier and processor for the three supply chain structures

Supply chain structure	Supplier	Processor
I	$[(s+1)A+(s-1)C]/2$	$[(s+1)C+(s-1)A]/2$
II	$[(s+1)(A+C)/2]$	$[(s-1)(A+C)]/2$
III	$[(s-1)(A+C)]/2$	$[(s+1)(A+C)]/2$

Clearly, if one party does not invest, the revenues will be equal to zero and the vertical synergy in CSR will not materialize, so that $s = 1$. Given the cost k_i of the investment of party i, it is straightforward to derive the 2-stage sequential game of complete information for each supply chain structure. Figure 6.3 depicts the extensive form of the game for structure I, where, in sequence, the supplier and the processor decide about their CSR investments, and attain profits given by the difference between the Shapley values and the costs of the CSR investments.

Depending on the values of k_1 and k_2, the sub-game perfect equilibrium for each structure can be derived. For structure I, if the investment costs ($k_1 \leq [(s+1)A + (s-1)C]/2$ and $k_2 \leq [(s+1)C + (s-1)A]/2$) are low, both the supplier and the processor [i.e., $(x_1, x_2) = (1, 1)$] will invest, realizing total supply chain profits $\mathit{\Pi}_{SC} = s(A+C) - k_1 - k_2$. If k_1 is sufficiently high ($k_1 > [(s+1)A+(s-1)C]/2$), only the processor will invest and realize $\mathit{\Pi}_{SC} = C - k_2$. Likewise, if k_2 is sufficiently high ($k_2 > [(s+1)C + (s-1)A]/2$), only the supplier will invest and realize $\mathit{\Pi}_{SC} = A - k_1$. Finally, if the investment costs are both sufficiently high, there will be no investments and the supply chain profits will be equal to zero. The sub-game perfect equilibrium for structure I is reported in Fig. 6.4.

The same procedure can be applied to derive the sub-game perfect equilibrium for structures II and III. The *efficient* structure results in the highest number of CSR investments, and so generates the highest supply chain profits. To facilitate the comparison, Fig. 6.5 shows the sub-game perfect equilibrium of all the structures for $A < C$ and $s < (3A + C)/(A + C)$. If the investment costs are either sufficiently low or sufficiently high, no structure will be strictly preferred as both the supplier and the processor will either invest or not invest, respectively. However, there is an area with intermediate values of k_1 and k_2, where structure I is uniquely efficient. In fact, structure

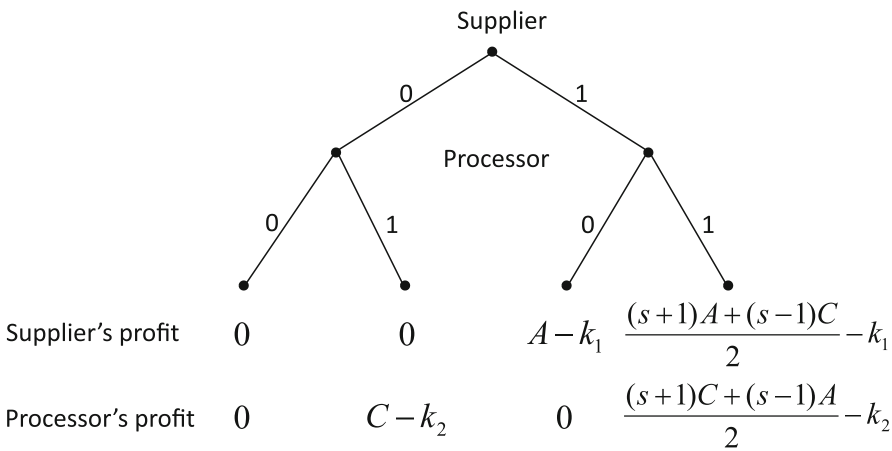

Fig. 6.3 Extensive form of the game corresponding to structure I

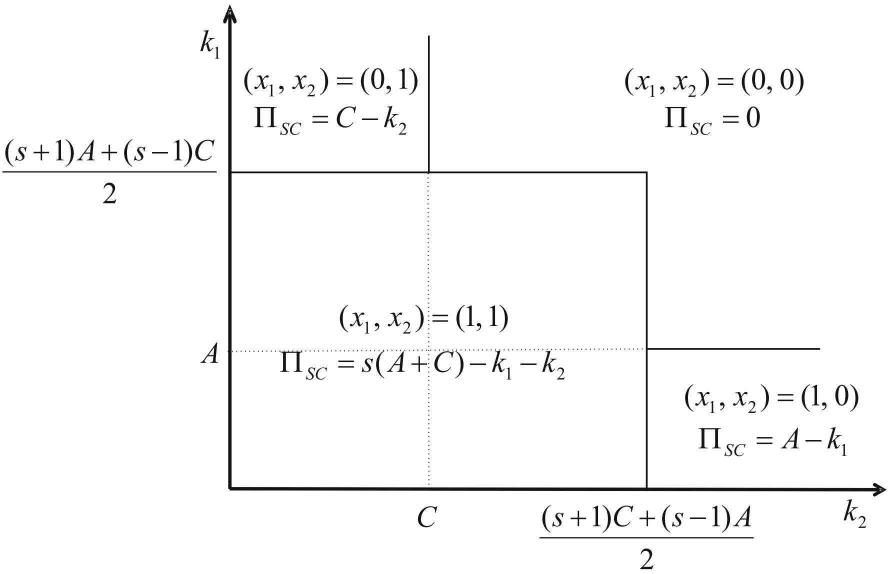

Fig. 6.4 Sub-game perfect equilibrium for stcture I

I allocates a fair share of the revenues to both parties. As a consequence, the supplier and the processor both have an incentive to invest in CSR in structure I, whereas one of the two loses this incentive in structures II and III. For $k_2 < [(s+1)(A+C)]/2$, moving in the direction of increasing values for k_1 we observe an efficiency pattern where structures I and II are initially equally efficient, then structure II dominates structure I, and finally, structure I and III are equally efficient. The intuition for this pattern goes as follows. As k_1 increases, the two structures I and II allocate sufficient revenues to the supplier, and so allow him to invest in CSR. However, structure II allocates larger revenues to the supplier than structure I; thus, if $[(s+1)A+(s-1)C]/2 \leq k_1 \leq sA+(s-1)C$, structure II will be uniquely efficient. When k_1 becomes very large (i.e., $k_1 > sA+(s-1)C$), then the supplier will not invest in either structure. In this case, structures I and III again emerge as the efficient structures because they provide an incentive to the processor to invest in CSR.

6.4 Business Applications

The purpose of this section is to describe applications of the property rights approach to cases in which companies need to provide incentives for CSR investments. The focus is to study how these incentives depend on the structure of the supply chain rather than on ineffective performance-based contracts.

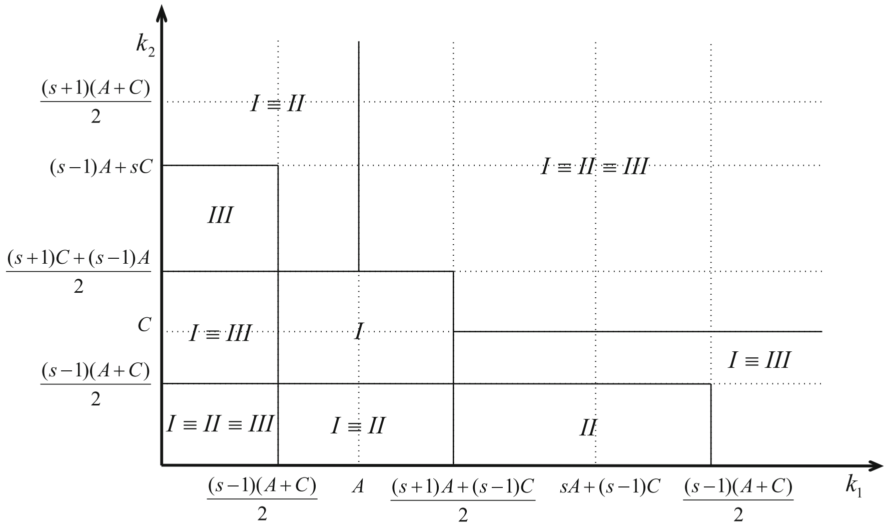

Fig. 6.5 Efficient supply chain structure for $A < C$ and $s < (3A + C)/(A + C)$

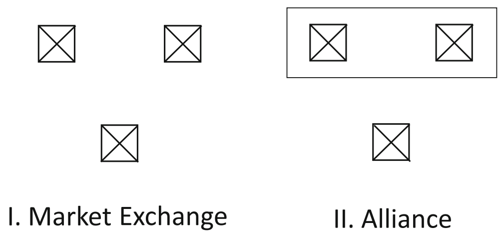

Fig. 6.6 The supply chain structures of poultry farmers in the Netherlands

6.4.1 Horizontal Alliances: The Case of Poultry Farmers in the Netherlands

The Dutch poultry sector is among the best in the world. It offers excellent products and equipment, as well as integrated system solutions to contribute to sustainable food safety on a worldwide scale. Dutch egg farmers have taken a lead in developing animal-friendly housing and sustainable production and processing technologies. Recently, however, egg farmers have been in economic difficulty as the returns on their investments do not seem to cover the sunken investment costs. Van der Heijden (2013) reports that poultry farmers in the Netherlands are very fragmented, and as a consequence, their bargaining power against downstream retailers is limited. CSR investments in the poultry sector have led to an increase in production costs, which amount to 7.5¢ per egg. However, downstream retailers such as Albert Heijn only pay 4.5¢ per egg, whereas one egg is sold to consumers for 17¢. This setting is clearly not sustainable. It is expected that Dutch egg farmers will put a limit, if not a definitive stop, to their investments in CSR activities in the poultry industry.

To understand how the poultry farmers should be incentivized to undertake CSR investments, we compare the two structures in Fig. 6.7: the Market Exchange in structure I corresponds to the case of fragmented poultry farmers, whereas the Alliance in structure II corresponds to the case of farmers that have pooled their assets of production in order to increase their bargaining power with the processor.

To compare the two supply chain structures we need to compute the characteristic functions for each coalition within the supply chain. In the Alliance structure both farmers have property rights over an asset of production; thus, each of them will be able to appropriate a portion of the total revenues generated upstream. For simplicity, let the suppliers split the upstream total revenues evenly, so that $v(\{1\}) = v(\{2\}) = (A + B)/2$. The expressions of the characteristic functions are reported in Table 6.3.

Assuming all parties invest in CSR, Table 6.4 reports the Shapley values for the two suppliers and the processor.

There are two main forces that emerge from the expressions of the Shapley values:

- *Pooling*: This is the effect of the two suppliers sharing the use of their production assets and the associated revenues. In structure II, as $v(\{1\}) = v(\{2\}) = \frac{A+B}{2}$, each supplier can benefit from the revenues generated by the other supplier. This pooling effect can lead to *free-riding*, as a supplier might attain positive revenues even without undertaking any CSR investment.
- *Countervailing power*: This is the effect of the two suppliers gaining more bargaining power against the processor, due to their alliance in structure II. This effect is apparent by comparing Shapley values of the processor in structure I and II. In fact, as $(2s + 1)C/3 > (s - 1)C/2$, the processor can retain a higher portion of his revenues in structure I than in structure II.

The two forces above have contrasting effects on the suppliers' CSR investments. Pooling resources might discourage investments as each supplier might conveniently choose to free-ride. Instead, the countervailing power solicits investments upstream as the two suppliers can appropriate a larger share of the revenues generated by the processor, due to their alliance. The interplay between these two forces determines the efficiency of the supply chain structures. As a thorough analysis would be very involved,we just develop the intuition about the results.[5]

If k_3 is sufficiently high (i.e., $k_3 > (s - 1)(A + B)/2 + (s + 1)C/2)$, the processor will not be motivated to invest. In this case, the Market Exchange

[5] See Letizia and Hendrikse (2016) for a full comparison between the two structures.

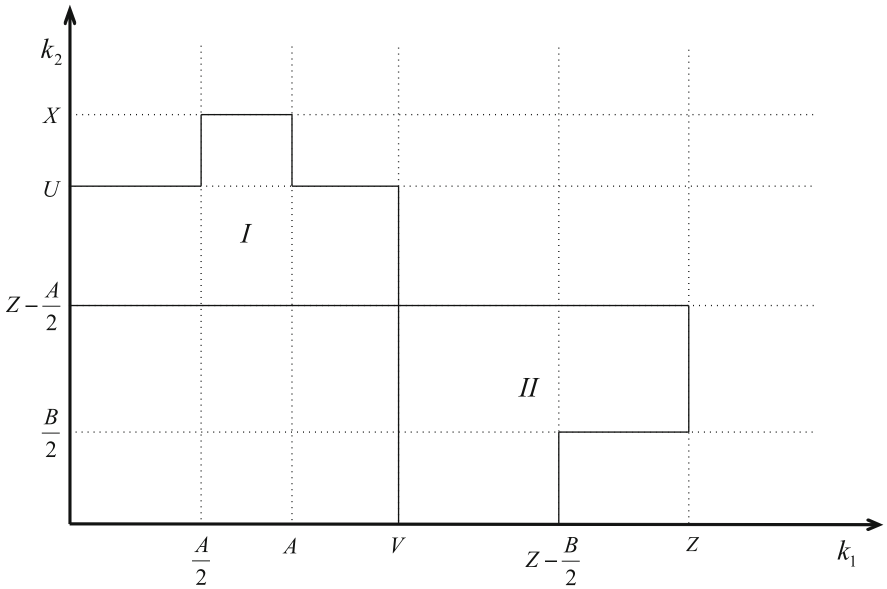

Fig. 6.7 The efficient supply chain structure for the poultry farmers in the Netherlands for $k_3 < \frac{(s-1)B}{2} + \frac{(s+1)C}{2}$. We have used the following notation: $X = \frac{(s+1)B}{4} + \frac{(s-1)C}{4}$, $U = \frac{(s+1)B}{2} + \frac{(s-1)C}{6}$, $Z = \frac{(s+1)(A+B)}{4} + \frac{(s-1)C}{4}$, and $V = \frac{(s+1)A}{2} + \frac{(s-1)C}{6}$

Table 6.3 Characteristic functions for all the coalitions in the two supply chain structures of the Dutch poultry farmers, assuming $x_i = 1$, $i = 1, 2, 3$

Supply chain structure	$v(\{1\})$	$v(\{2\})$	$v(\{3\})$	$v(\{12\})$	$v(\{13\})$	$v(\{23\})$	$v(\{123\})$
I	A	B	C	$A+B$	$s(A+C)$	$s(B+C)$	$s(A+B+C)$
II	$\frac{A+B}{2}$	$\frac{A+B}{2}$	C	$A+B$	$s\left(\frac{A+B}{2}+C\right)$	$s\left(\frac{A+B}{2}+C\right)$	$s(A+B+C)$

Table 6.4 Shapley values of the members of the supply chain for the two structures of the Dutch poultry farmers, assuming $x_i = 1$, $i = 1, 2, 3$

Supply chain structure	Supplier 1	Supplier 2	Processor
I	$\frac{(s+1)A}{2} + \frac{(s-1)C}{6}$	$\frac{(s+1)B}{2} + \frac{(s-1)C}{6}$	$\frac{(s-1)(A+B)}{2} + \frac{(2s+1)C}{3}$
II	$\frac{(s+1)(A+B)}{4} + \frac{(s-1)C}{4}$	$\frac{(s+1)(A+B)}{4} + \frac{(s-1)C}{4}$	$\frac{(s-1)(A+B)}{2} + \frac{(s-1)C}{2}$

structure will be more efficient than the Alliance structure, as the latter is penalized by the pooling effect and, because the processor does not invest, it cannot benefit from the countervailing power. If k_3 is sufficiently low (i.e., $k_3 < (s-1)(A+B)/2 + (s+1)C/2$), the Alliance structure can emerge as the efficient structure. If k_1 is sufficiently high, supplier 1 will not invest and supplier 2 will be confronted with an important trade-off in structure II: on one hand, if he invests, he will have to share a portion of his revenues with the non investing supplier 1; on the other hand, by investing, he can appropriate a large portion of the processor's revenues due to the countervailing power effect. Figure 6.7 shows that there are regions in the plane k_1k_2 where it is better for the egg farmers to implement structure II rather than structure I to invest in CSR.

The analysis establishes that structure II will solicit more CSR investments than structure I when k_2 and k_3 are sufficiently low and k_1 is sufficiently high. These conditions appear to correspond to the case of the poultry farmers in the Netherlands. In fact, the task of the egg processor is limited to advertise the adoption of practices of ethical sourcing for his products, and the costs of this advertising are reasonably low. Supplier 1 might be the supplier with a large volume of eggs and so CSR investments will be very costly. For supplier 2, the investment cost is reduced as it involves only a low number of poultry. In fact, there is empirical evidence that in the Netherlands low volume egg farmers were undertaking CSR investments whereas large volume ones were not (see Van der Heijden 2013). Unilateral transactions between small egg farmers and large processors resulted in a situation where the processor was paying a low price per egg to a farmer whose post-investment marginal cost per egg had substantially increased. In the end, small egg farmers stopped their CSR investments altogether. The analysis above shows that an alliance between them might provide new incentives for CSR activities. In fact, by forming horizontal alliances, small egg farmers can gain more bargaining power with their downstream processors, and so they would be more motivated to undertake CSR investments.

6.4.2 Forward Integration: The Case of FrieslandCampina

FrieslandCampina is one of the world's five largest dairy companies. It is recognized as a champion of CSR activities in the Netherlands (Van Riel and Ederer 2011), especially with respect to the health and welfare of livestock, and the sustainability of its production chains (reduction of water and energy usage, consumption of green energy, etc.). The supply chain and organization structure of FrieslandCampina is of pivotal importance for achieving its CSR goals. The company started with small farms joining together to form associations (Friesland Foods) in order to gain greater market power for the sale of their milk. These associations started to form supplier cooperatives that owned a downstream milk processor. The local cooperatives merged to form bigger regional cooperatives and finally in 2008, the dairy cooperatives Friesland Foods and Campina merged to form the cooperative FrieslandCampina. More recently, the company has also started to supply milk from external suppliers, who are required to comply with certain sustainability standards. The company's CSR activities started after the 2008 merger and have been increasing with the involvement of external suppliers. The FrieslandCampina's 2012 CSR report outlines the company's increasing commitment to high quality, sustainability, and transparency standards throughout the entire chain, as represented by the company motto, "from grass to glass".

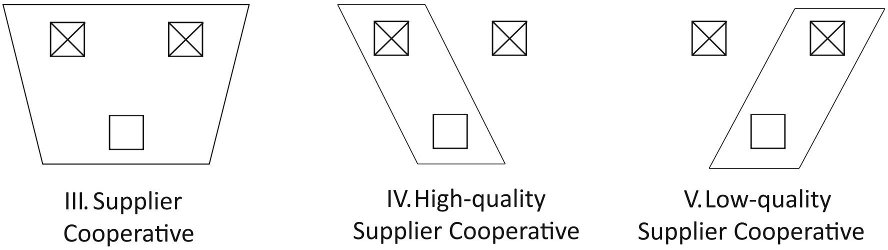

Fig. 6.8 The supply chain structures of FrieslandCampina

The evolution of the supply chain structure of FrieslandCampina is reported in Fig. 6.8. When Friesland and Campina merged, they formed a supplier cooperative as shown in III. When the cooperative started to supply milk from external suppliers, the supply chain structure shifted to either structure IV or V, depending on whether the internal supplier was of higher or lower quality, respectively, than the external supplier.

To understand how these structures affect incentives for CSR activities, we need to determine the characteristic functions for all possible coalitions in these structures. The following observations are in order. First, the processor in a cooperative does not have ownership rights over the asset ofproduction

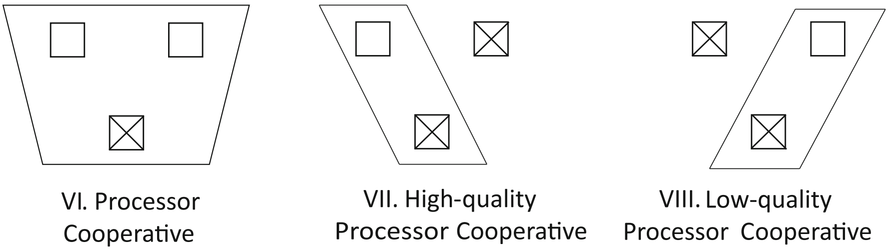

Fig. 6.9 The supply chain structures of StarBucks coffee suppliers

and will thus not be able to claim a portion of the ex-post revenues, i.e., $v(\{3\}) = 0$. Second, the two suppliers in structure I both have ownership rights over the assets of production, so they are both entitled to a portion of the revenues. For simplicity, we assume an even allocation of the revenues between the two suppliers. As a consequence, $v(\{1\}) = v(\{2\}) = (s(A + B + C))/2$ in structure III. Notice that this allocation of revenues may create free-riding within a cooperative. In fact, both supplier 1 and 2 will attain a portion of the revenues if one of them invests in CSR and the other does not. Finally, the processor in a cooperative is not allowed to process milk for an external supplier without the involvement of the cooperative supplier; thus, $v(\{2\}) = B$ in structure IV, and $v(\{1\}) = A$ in structure V. Assume each party invests, i.e., $x_i = 1$, $i = 1, 2, 3$. The characteristic functions for all the coalitions in the structures of FrieslandCampina are reported in Table 6.5. Given the characteristic functions, we can compute the Shapley value for the two suppliers and the processor in each structure, as reported in Table 6.6.

Table 6.5 Characteristic functions for all the coalitions in the three supply chain structures of FrieslandCampina, assuming $x_i = 1$, $i = 1, 2, 3$

Supply chain structure	$v(\{1\})$	$v(\{2\})$	$v(\{3\})$	$v(\{12\})$	$v(\{13\})$	$v(\{23\})$	$v(\{123\})$
III	$\frac{s(A+B+C)}{2}$	$\frac{s(A+B+C)}{2}$	0	$s(A+B+C)$	$\frac{s(A+B+C)}{2}$	$\frac{s(A+B+C)}{2}$	$s(A+B+C)$
IV	$s(A+C)$	B	0	$s(A+B+C)$	$s(A+C)$	B	$s(A+B+C)$
V	A	$s(B+C)$	0	$s(A+B+C)$	A	$s(B+C)$	$s(A+B+C)$

Table 6.6 Shapley values if all parties invest

Supply chain structure	Supplier 1	Supplier 2	Processor
III	$\frac{s(A+B+C)}{2}$	$\frac{s(A+B+C)}{2}$	0
IV	$s(A+C) + \frac{(s-1)B}{2}$	$\frac{(s+1)B}{2}$	0
V	$\frac{(s+1)A}{2}$	$s(B+C) + \frac{(s-1)A}{2}$	0

To assess the efficiency of the structures, we start by comparing supply chain structures IV and V, which differ in terms of ownership of the asset within the cooperative. The high-quality supplier owns the asset of the downstream processor in supply chain structure IV, whereas the low-quality supplier owns it in structure V. This difference does not matter for the equilibrium investment choices of the suppliers and the processor. In fact, the processor does not own assets in either structure, and will therefore never choose to invest. As a consequence, the vertical synergy in CSR cannot materialize, i.e., $s = 1$. Without the benefit of this synergy, the suppliers' investment decision depends only on the profits generated by that investment, i.e., on the difference $A - k_1$ for supplier 1 and $B - K_2$ for supplier 2. Proposition 1 states this result.

Proposition 1. *Supply chain structures IV and V are identical in terms of equilibrium investment decisions:*

1. *The processor does not invest in CSR;*
2. *Supplier* 1 *invests in CSR if* $k_1 < A$*;*
3. *Supplier* 2 *invests in CSR if* $k_2 < B$.

Given the result in Proposition 1, we will use the notation $IV \equiv V$ to mean that these two structures produce the same outcomes in terms of investment decisions. Thus, our search for the efficient structure needs to consider just one of them.

We can now extend our analysis to structure III, which is identical to the previous ones in terms of ownership of the assets, but is different in terms of vertical and horizontal relationships. In structure III, the processor has no asset ownership and will not invest. The relationship here is different as both suppliers are now part of the same cooperative with no external supplier present. The association between suppliers implies a pooling of the revenues: if both suppliers invest, each will receive revenues equal to $\frac{A+B}{2}$. This means that even without investing, a supplier will get revenues equal to half of those generated by the other supplier (free-riding). As a consequence, each supplier will be willing to incur at most the cost of his contribution to the upstream joint revenues, i.e., supplier 1 will invest only if $k_1 < A/2$, whereas supplier 2 will invest only if $k_2 < B/2$. As a result, the two suppliers in structure III are less willing to invest in CSR than those in structures $IV \equiv V$. We can summarize these results in the following proposition:

Proposition 2. *Supply chain structure III is never uniquely efficient.*

A managerial implication of Proposition 2 is that FrieslandCampina will invest more in CSR if the cooperative supplies dairy products from both internal and external suppliers, as $IV \equiv V$ dominates III. The intuition is that the presence of external suppliers creates competition upstream, which reduces the negative effect of free-riding by internal suppliers.

6.4.3 Backward Integration: The Case of Starbucks Corporation

Starbucks Corporation is the largest coffeehouse chain in the world. The company has set a series of ambitious CSR goals, especially in the area of ethical sourcing, consisting of responsible purchasing practices, farmer support, industry collaboration, and community development programs.[6] In an attempt to expand its ethical sourcing initiatives, Starbucks' suppliers purchased a few coffee farms in Costa Rica and in the Yunnan province in China, where they could provide direct guidelines to farmers to grow coffee in a way that is

[6] See Starbucks Global Responsibility Report—Goals and Progress 2013, available at http://\penalty0globalassets.starbucks.com/assets/98e5a8e6c7b1435ab67f2368b1c7447a.pdf.

more beneficial to both people and the planet ("green coffee"). The Starbucks' coffee suppliers formed a cooperative with their farmers but in some cases they also needed to supply coffee from external farmers. To create incentives for ethical sourcing, Starbucks believed it was crucial that the farmers could claim a sufficiently large share of the payments made throughout the supply chain for green coffee. In the words of the CEO Howard Schultz,"Starbucks requires economic transparency: suppliers must demonstrate how much of the price that we pay for green coffee gets to the farmers".[7]

The different supply chain structures between the Starbucks' coffee supplier (i.e., the processor) and the farmers (i.e., the suppliers) are reported in Fig. 6.9. The cooperative structure where the farmers are entirely backward integrated corresponds to structure VI. The structures where the coffee processor supplies coffee from both internal and external suppliers correspond to structures VII and $VIII$, depending on whether the internal supplier is of higher or lower quality, respectively, than the external supplier.

To evaluate the characteristic functions, we consider that the external supplier can create synergy in CSR with the processor, as the latter has ownership rights on the asset of production. As a consequence, $v(\{23\})$ in structure VII and $v(\{13\})$ in structure $VIII$ are both equal to $s(A+B+C)$. The derivation of the characteristic functions for all the other coalitions is straightforward, and their expressions are reported in Table 6.7.

Table 6.7 Characteristic functions for all the coalitions in the three supply chain structures of Starbucks Corporation, assuming $x_i = 1$, $i = 1, 2, 3$

Supply chain structure	$v(\{1\})$	$v(\{2\})$	$v(\{3\})$	$v(\{12\})$	$v(\{13\})$	$v(\{23\})$	$v(\{123\})$
VI	0	0	$s(A+B+C)$	0	$s(A+B+C)$	$s(A+B+C)$	$s(A+B+C)$
VII	0	B	$s(A+C)$	B	$s(A+C)$	$s(A+B+C)$	$s(A+B+C)$
$VIII$	A	0	$s(B+C)$	A	$s(A+B+C)$	$s(B+C)$	$s(A+B+C)$

Regarding the Shapley values, it is apparent that the processor in structure VI will appropriate all the revenues, whereas he will have to share a portion of them with supplier 2 in structure VII and with supplier 1 in structure $VIII$. The Shapley values are reported in Table 6.8.

To proceed with the analysis, consider that structure VI is a cooperative where only the processor has ownership rights over the assets of production. Thus, only the processor will invest in CSR. Structures VII and $VIII$ have a comparative advantage in CSR investments over VI, as the external supplier has ownership rights on the asset and thus has an incentive to invest. The following result then is straightforward.

[7] See Starbucks website `http://www.starbucks.com/responsibility/sourcing/coffee`.

Table 6.8 Shapley values if all parties invest

Supply chain structure	Supplier 1	Supplier 2	Processor
IV	0	0	$s(A+B+C)$
V	0	$(s+1)B/2$	$s(A+C)+(s-1)B/2$
VI	$(s+1)A/2$	0	$s(B+C)+(s-1)A/2$

Proposition 3. *Structure VI is never uniquely efficient.*

Proposition 3 provides a rational for why the suppliers of Starbucks Corporation vertically integrated some coffee farmers in the region of Yunnan in China but also kept a few external suppliers. In fact, structures VII and $VIII$ weakly dominate structure VI in terms of efficiency. This is due to the presence of external suppliers which attracts a higher number of CSR investments than the customer cooperative where all suppliers are vertically integrated with the processor.

The comparison in efficiency between structures VII and $VIII$ is more complicated because ownership rights over the assets are allocated at both the upstream and the downstream tiers of the supply chain. The intuition, however, is straightforward. The revenues generated in these two structures, in fact, depend only on the investment decisions of the external supplier and the processor. When we compare structures VII and $VIII$, we can observe that a high investment cost for a noninvesting supplier does not affect the efficiency of the corresponding structure. More specifically, a high k_1 will not hurt structure VII as supplier 1 would never invest there. The same reasoning applies for a high k_2, which cannot negatively impact the revenues of structure $VIII$ as supplier 2 would never invest there. The following result then is straightforward.

Proposition 4. *Supply chain structure VII dominates supply chain structure VIII in terms of efficiency if k_1 is sufficiently high and k_2 is sufficiently low.*

Proposition 4 establishes that it is better to integrate the farmer whose investment cost in CSR is very high. The external farmer, instead, should incur low costs to invest in CSR activities. If we combine the results of Propositions 3 and 4, we can assert that in the case of backward integration an external supplier provides better incentives for CSR investments than an internal supplier, unless the associated investment cost is too high. Using a similar analysis one could also compare the structures of FrieslandCampina and Starbucks Corporation to establish under which conditions forward integration is more efficient than backward integration and vice-versa.

6.5 Conclusions

Today, firms can strengthen their competitive position by showing to the markets that their products are produced through business practices, policies, and resources which are respectful of society and the environment. As a consequence, the problem of effectively inducing firms to engage in CSR has become of pivotal importance. Providing incentives through formal contracts, however, would not serve the purpose, due to the difficulty of linking financial performance to the adoption of CSR activities and, more generally, to contract incompleteness. In this chapter, we have taken a property rights approach to argue that incentives for CSR can be provided through the supply chain structure, that consists of a distribution of ownership rights over the assets of production, and involves various types of alliances among supply chain members.

By analyzing three business cases, we have identified the supply chain forces that determine the efficiency of supply chain structures. In particular, the first case shows that the fragmented poultry market in the Netherlands confers too much bargaining power to the processor and as a result, the egg farmers have no incentive to invest in CSR. By forming an alliance, the farmers would be able to claim a larger stake of the chain revenues (due to their countervailing power), and thus be more incentivized to invest in CSR activities. The case of FrieslandCampina shows that the alliance among farmers is detrimental if the processor does not have ownership rights. In fact, the benefit of countervailing power vanishes here, as the processor is not motivated to invest in CSR, whereas the pooling of resources among farmers results in free-riding. By supplying milk from external farmers, FrieslandCampina introduced competition upstream and created new incentives for farmers to invest in CSR. The case of Starbucks shows that backward integration is not effective in incentivizing CSR activities, as the farmers would not invest without ownership rights over their assets. The presence of external suppliers is beneficial instead, as they are owner of their assets and may decide to invest in CSR to achieve synergy between the upstream and downstream tiers of the supply chain.

In sum, this chapter provides insights on the provision of incentives in situations where contracts cannot serve the purpose. CSR investments are a perfect example of these situations because they are not verifiable in a court of law. In the words of Norman and MacDonald (2004), the insurmountable obstacle for verifying CSR activities is that "it is in principle impossible to find a common scale to weigh all of the social 'goods' and 'bads' caused by firms". Further, from a practical point of view, it would be very unlikely to get broad agreement (analogous, say, to the level of agreement about accounting standards) for any such proposed common scale. Our approach could also be applied to the context of emerging markets, as ineffective judicial systems and other institutional voids would again make contracts an ineffective instrument for incentivizing firms. We hope our work can spark further research in these directions.

Acknowledgements I thank George Hendrikse for introducing me to the area of incomplete contracts. I am grateful to Atalay Atasu for his invitation to write this chapter, and for his insights and comments that have improved its exposition.

Appendix

The Use of the Shapley Value in Cooperative Game Theory

The Shapley value is one of the main solution concepts in cooperative game theory. A cooperative game consists of two ingredients: players and payoffs. An n-person game in characteristic function form is defined by a pair $(N, v(\cdot))$, where N is the set of players and $v(\cdot)$ is the characteristic function. The characteristic function assigns a value to every nonempty subset (or *coalition*) of the set of players. This value has to be interpreted as the benefit or cost that will be established when the players in the coalition cooperate. The characteristic function form describes the strategic situation. Consider the following three-players shoe game:

$$v(\{1,2,3\}) = 1, \quad v(\{1,3\}) = v(\{2,3\}) = 1, \quad v(\{1,2\}) = 0,$$
$$v(\{1\}) = v(\{2\}) = v(\{3\}) = 0,$$

which describes a scenario where player 1 and 2 own one right-hand shoe each, while player 3 owns a left-hand shoe. The game then is such that the value of a matched pair of shoes is 1, while an unmatched pair is worth 0. The Shapley value for player i can be computed as the average of the marginal contribution of player i to its predecessors for all the possible orderings of players. In the shoe game there are six possible orderings of the players: $\{1,2,3\}$, $\{1,3,2\}$ $\{2,1,3\}$, $\{2,3,1\}$, $\{3,1,2\}$, and $\{3,2,1\}$. The marginal contributions of player 1 to the predecessors in each of the orderings is, respectively: 0, 0, 0, 0, 1, 0 as player 1 brings a worthy contribution only when he is preceded by player 3 and the left-hand shoe had not already been matched by player 2. The Shapley value for player 1 then is 1/6. Following a similar procedure, one can determine the Shapley value of players 2 and 3, equal to 1/6 and 2/3, respectively.

References

Acemoglu D, Griffith R, Aghion P, Zilibotti F (2010) Vertical integration and technology: theory and evidence. J Eur Economic Assoc 8(5):989–1033

Bagnoli M, Watts SG (2003) Selling to socially responsible consumers: competition and the private provision of public goods. J Econ Manag Strateg 12(3):419–445

Chen L, Lee HL (2014) Mitigate supplier responsibility risk in emerging economies: an ethical sourcing framework. Working paper

Ferreira DA, Avila MG, de Faria MD (2010) Corporate social responsibility and consumers' perception of price. Soc Responsib J 6(2):208–221

Grimmer M, Bingham T (2013) Company environmental performance and consumer purchase intentions. J Bus Res 66(10):1945–1953

Grossman SJ, Hart O (1986) The costs and benefits of ownership: a theory of vertical and lateral integration. J Polit Econ 94(4):691–719

Hart O, Moore J (1990) Property rights and the nature of the firm. J Polit Econ 98(6):1119–1158

Kemahlıoğlu-Ziya E, Bartholdi III JJ (2011) Centralizing inventory in supply chains by using Shapley value to allocate the profits. Manuf Serv Oper Manag 13(2):146–162

Kim SH (2014) Time to come clean? Disclosure and inspection policies for green production. Working paper

Letizia P, Hendrikse G (2016) Supply chain structure incentives for corporate social responsibility: An incomplete contracting analysis. Working paper

Mahoney JT (2005) Economic foundations of strategy. Sage, Thousand Oaks, CA

Mendoza AJ, Clemen RT (2013) Outsourcing sustainability: a game-theoretic modeling approach. Environ Syst Decis 33(2):224–236

Norman W, MacDonald C (2004) Getting to the bottom of "triple bottom line." Bus Ethics Q 14(2):243–262

Novak S, Eppinger SD (2001) Sourcing by design: product complexity and the supply chain. Manag Sci 47(1):189–204

Plambeck EL, Taylor TA (2007a) Implications of breach remedy and renegotiation design for innovation and capacity. Manag Sci 53(12):1859–1871

Plambeck EL, Taylor TA (2007b) Implications of renegotiation for optimal contract flexibility and investment. Manag Sci 53(12):1872–1886

Van der Heijden T (2013) Elk ei kost de boer drie cent. NRC Handelsblad 25

Van Riel M, Ederer P (2011) FrieslandCampina create, care, change together. EFAS business case for IFAMA forum. http://www.innovationgrowth.com/fileadmin/innovationgrowth/\penalty0publications/\penalty088055FrieslandCampinaCreateCareChangeTogetherIFAMA2011PeerEderer.pdf

Williams T, Maull R, Ellis B (2002) Demand chain management theory: constraints and development from global aerospace supply webs. J Oper Manag 20(6):691–706

Williamson OE (1979) Transaction-cost economics: the governance of contractual relations. J Law Econ 22(2):233–261

Woodruff C (2002) Noncontractible investments and vertical integration in the Mexican footwear industry. Int J Ind Organ 20(8):1197–1224

Xu Y, Cho SH, Tayur S (2014) Combating child labor: incentives and information transparency in supply chains. Working paper

Chapter 7
Servicizing in Supply Chains and Environmental Implications

Vishal V. Agrawal and Ioannis Bellos

Abstract Recently, a new type of innovative business models have been developed based on the premise that economic value is not necessarily associated with the production and distribution of products, but rather with the use and functionality that the products can offer. It has been argued that such models, often referred to as *servicizing* business models, may have a positive impact on the environment because they can enable firms to achieve both economic and environmental sustainability. However, they may also present unique implementation challenges because they require the business-as-usual relationship between the different partners in a supply chain to change from product-based to use- or function-based. In this chapter, we outline a taxonomy of different servicizing business models observed in practice, based on different operational characteristics. Based on these characteristics, we also provide an overview of the reasons why servicizing may improve environmental performance. More importantly, we also provide a discussion of why servicizing may backfire and lead to worse environmental outcomes due to the firm and/or consumer decisions. Finally, we identify implementation challenges that may prevent the adoption of servicizing business models in practice.

V.V. Agrawal (✉)
McDonough School of Business, Georgetown University, Washington, DC 20057, USA
e-mail: Vishal.Agrawal@georgetown.edu

I. Bellos
School of Business, George Mason University, Fairfax, VA 22030, USA
e-mail: ibellos@gmu.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_7

7.1 Introduction

The idea of a utilization-focused economy, which puts an emphasis on how products are used as opposed to how they are produced, distributed, or disposed, was first introduced by Stahel (1994). In particular, it was argued that firms should focus on optimizing the use rather than the production of goods because such a focus can result in higher resource efficiency, which can be both economically and environmentally beneficial.

The argument in favor of a utilization-focused economy implies that products should be viewed as having a mere ancillary role in creating value for the firms and their customers. This view motivated further inquiry into the potential benefits of use- or function/outcome-based business models. Along these lines, White et al. (1999) introduced the term *servicizing* to describe business models, whose economic value is largely generated through product-based services.

In recent years, servicizing business models have expanded in scope and have become increasingly popular in both B2B and B2C settings. Examples of successful servicizing models include Michelin's Fleet Solutions (Michelin 2015), Xerox's Managed Print Services (Xerox 2015), Philips' Lighting Solutions (Philips 2011), Rolls-Royce's TotalCare solutions (Rolls-Royce 2015), Atlas Copco's Contract Air service (Atlas Copco 2015), Amazon's Web Services (Amazon 2015), Quaker's chemical management services (Quaker Chemical Corporation 2015), and Zipcar's car sharing program (Zipcar 2015b), to name a few. Although this list is by no means exhaustive, it indicates the diversity of industries in which servicizing has been implemented.

Interestingly, regardless of the scope or the industry, the aforementioned business models share in common the fact that no product ownership rights are transferred from the firm to the end-user. Firms are compensated based on the extent that customers use the products or on the outcome/function that the products provide each time they are used. For instance, in the examples mentioned above, Philips, Michelin, and Xerox charge customers on a per-lux provided, per-mile driven, and per-page printed basis, respectively (see Table 7.1 for a summary).

Table 7.1 Companies implementing servicizing business models

Company	Type of offering	Pricing structure
Michelin	Fleet solutions	Pay-per-mile driven
Xerox	Managed print services	Pay-per-page printed
Philips	Lighting solutions	Pay-per-lux provided
Rolls-Royce	Engine maintenance services	Pay-per-hour flown
Atlas Copco	Contract air service	Pay-per-m^3 of air compressed
Zipcar	Car sharing service	Pay-per-hour reserved
Amazon Web Services	Cloud computing	Pay-per-GB transferred
Quaker Chemical Corp.	Chemical management services	Shared savings contract

One of the main reasons that servicizing has been gaining traction in practice is that it has been viewed by many as a business strategy that can promote environmental sustainability (Rothenberg 2007). Specifically, it has been argued that the pricing structure (i.e., the pay-per-use pricing) and the fact that firms maintain ownership of the products may lead firms and customers to reduce their production volume and product use, respectively. This would support the view of servicizing as a "green" practice. However, as we highlight in the rest of this chapter, taking a holistic view of the firms' and the customers' decisions may reveal environmental drawbacks associated with the implementation of servicizing. In Sect. 7.3, we discuss the reasons why servicizing may or may not improve the environmental performance of a supply chain.

In the context of a supply chain, servicizing can be particularly beneficial because it can possibly facilitate the alignment of the incentives of the different supply chain partners. This is illustrated by Reiskin et al. (1999) in the context of chemical supply chains, where a buyer's objective to minimize the quantity of "indirect" materials (e.g., solvents that do not become part of the final product but are only needed during the production process) conflicts with the supplier's objective of maximizing the volume of materials sold (see Fig. 7.1). A servicizing agreement, such as a shared saving contract, based on which the gains from a reduction in the use of indirect materials are shared between a supplier and a buyer has been shown by Corbett and DeCroix (2001) to increase supply chain profits.

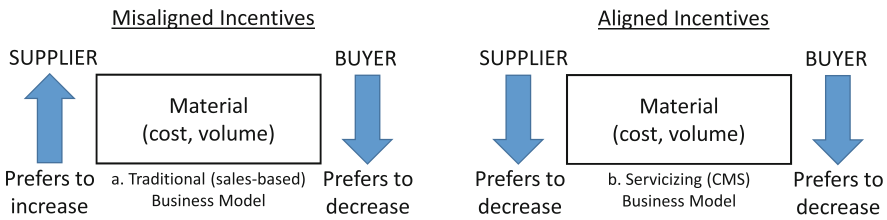

Fig. 7.1 From selling chemicals to selling chemical management services (CMS) (adopted from Reiskin et al. 1999)

However, the fact that servicizing changes the business-as-usual relationship between the different partners in a supply chain from product-based to use- or function-based may also create implementation challenges. In particular, the misalignment of the incentives of a supplier and a buyer may actually be exacerbated in a "servicized" supply chain. For instance, the preference for a smaller quantity of products is even stronger from a buyer's point of view when offering servicizing. This is because the buyer is paid on a per-use basis only, which limits the amount of fixed (i.e., product purchase) cost that can be transferred to the customers, since higher pay-per-use prices may not allow customers to meet their usage needs. Of course, this preference is at conflict with the supplier's objective to sell more products or charge a higher wholesale price. In Sect. 7.4, we identify the challenges that may actually hinder the servicizing of supply chains.

7.2 Operational Taxonomy of Servicizing Business Models

It is often tempting to construct an all-encompassing definition that tries to characterize what servicizing is. However, this attempt at generality may result in masking the intricacies of servicizing business models and in understating their differences. For instance, in Sect. 7.1, we mentioned that the key characteristic of servicizing business models (as opposed to conventional sales models) is that the firm typically maintains ownership of the products and customers pay on a per-use basis. However, this argument does not imply that all servicizing models have the same structure. Given the diversity of contexts where servicizing is observed in practice, it is important to provide a clear and detailed taxonomy of servicizing business models, based on the structural characteristics that distinguish them. Such a taxonomy can help a firm identify how "servicized" its current model is and which operational levers it can use to further servicize their business model. Towards this end, a firm needs to answer the following questions, which are based on an aggregation of the most common characteristics of successful servicizing models observed in practice. Table 7.2 provides a summary of the taxonomy of servicizing models, which is explained in detail in what follows. This taxonomy has been developed by building on the definition of servicizing as outlined in Toffel (2008).

Table 7.2 Structural characteristics of different business models

	Conventional business models		Servicizing business models		
	Selling of products	Leasing of products	Print services, pay-for-performance	Sharing programs, rentals	CMS, pure services services
Firm owns the product	✘	✔	✔	✔	✔
Pay-per-use	✘	✘	✔	✔	✔
Firm bears the operating cost	✘	✘	✘	✔	✔
Resource pooling	✘	✘	✘	✔	✔
Firm is the "end-user"	✘	✘	✘	✘	✔

Who Owns the Product? The necessary condition that a business model must meet in order to qualify as a servicizing business model is whether the ownership of the product remains with the firm[1] rather than with the customer. In other words, customer ownership of the product indicates a conventional sales-based business model. This also implies that offering after-sales services through traditional maintenance contracts where the customer owns the product and the firm charges a fixed or cost-plus fee for labor and/or parts may not qualify as a servicizing strategy. In other words, making the shift to servicizing requires a more significant structural change in the business model than simply diversifying a firm's offerings through auxiliary services.

As mentioned earlier, the ownership of the product is not the only characteristic of servicizing. Consider the model of product leasing for example. Under an operating lease agreement the firm maintains ownership of the product and by charging a fixed fee allows each customer to use a product for a given period time. From a customer's point of view, however, other than not acquiring ownership of the product, comparing leasing to a conventional sales model does not yield any major differences.[2] This brings us to our next characteristic: pricing.

How is Pricing Structured? Since under most servicizing business models, the firm maintains ownership of the product, the basis of the transaction is no longer the product but rather the use or function provided. As explained before, the consumers are charged on a per-use level. For instance, customers of Zipcar are charged based on the total number of hours they reserve a car. It is not uncommon for the customers of a servicizing model to have to pay a fixed fee as well. However, such a fee tends to be significantly smaller than the selling price that a customer would have to pay in order to buy the product under a conventional sales model. For instance, in the case of Zipcar customers pay an annual fee of $60 in order to gain access to the fleet of cars and then pay as low as $8 per hour they reserve a car (see Zipcar 2015a).

The pricing scheme used in some servicizing models can be more involved. For instance, in the chemical sector a new type of "shared-savings" contract has emerged according to which both the firm and the customer benefit from a reduction in the overall consumption of chemicals (see Corbett and DeCroix 2001). In this case, the pricing structure is linked to (the reduction of) the use (i.e., consumption) of the products. Additionally, in the aviation sector Rolls-Royce provides engine maintenance services through performance-based agreements under which payment is linked to the engine uptime. Such agreements are also referred to as "power-by-the-hour" in practice. No fees are charged for materials or spare parts used to ensure the operability of the

[1] The firm may be a manufacturer or a third-party provider who acquires products from a manufacturer.

[2] The reason we do not categorize product leasing as a servicizing business model stems from the fact that the pricing (most commonly in the form of fixed monthly payments) under leasing is to a greater extent related to the length of the lease and to a lesser extent to the actual use or function of the product.

engines. In the defense sector, following the Department of Defense's guidelines, contractors have also been implementing what is known as performance-based logistics (see Booz Allen Hamilton 2005).

Who Bears the Operating Cost? Another characteristic is whether the firm chooses to cover a portion or all of the operating cost associated with the use of the product. This is also related to the pricing. Although use/function-based pricing is considered one of the necessary conditions for servicizing models, determining who to hold responsible for the operating cost of the product does not alter the nature of the business model. Nonetheless, in practice we observe different approaches. That is, servicizing firms may choose to cover the product's operating cost or not.

Assuming responsibility for the product's operating cost can possibly foster the impression of a hassle/worry-free and all-inclusive offering. Along these lines, Zipcar covers the operating cost of the vehicles (i.e., cost of gas). Under Rolls-Royce's pay-for-performance contract, however, the customer is responsible for the operating cost of the engines. This is also the case under Xerox's Managed Print Services, where customers incur the electricity cost associated with the operation of the printers. In several cases, the firm's decision of whether to directly assume or to delegate the responsibility of the operating cost to the customer is limited by the technical feasibility of monitoring, reporting and payment mechanisms. For instance, assuming responsibility for a printer's electricity cost would probably require Xerox to install additional modules that monitor and report detailed electricity consumption along with the corresponding electricity rates. However, the perceived benefits from doing so may not justify the associated implementation costs.

Is Resource Pooling Feasible? Another important characteristic is whether it is possible for a servicizing firm to meet customers' usage needs through a common pool of (fewer) products. The answer depends to a large extent on the industry and to a smaller extent on the efforts of the firm. For instance, car sharing provides an example of a business model where the firm can exercise such resource pooling. This is possible since not all customers request a car at the same time. On the other hand, it may be more difficult for Xerox to satisfy the needs of multiple customers through a common pool of printers. One of the reasons is that each customer may require physical access to at least a certain number of printers. However, streamlining its customers' processes and information flow may allow Xerox to better allocate printing capacity and, therefore, to decrease the number of printers it dedicates to each customer. An important thing to note is that although the ability to pool firm resources is more prevalent in servicizing models, lack of it does not disqualify a business model from being considered as servicizing.

Who Applies the Solution? Some servicizing business models may change the fundamental relationship between a firm and a customer, in that the firm may assume complete responsibility for the customer's operations. In this case, customers delegate part of their operations to a firm with specialized skills, which is now responsible for taking all necessary actions (e.g., purchasing material, maintenance of the equipment) to ensure delivery of the final outcome (e.g., painted products). Regardless of the industry, the firm, which may have considered itself a manufacturer, effectively assumes the role of a service provider. This has been the case in the chemical sector where in recent years suppliers have been increasingly providing chemical management services (Reiskin et al. 1999).

7.3 The Green Potential of Servicizing(?)

In order to evaluate the environmental performance of any business model, the total environmental impact created during the production, use, and disposal phases of the product's lifecycle has to be analyzed. The total environmental impact in each phase is determined by the firm's decisions (e.g., pricing, resource pooling) and how customers respond to such decisions. It is straightforward to see that if a business model leads to lower impact in one phase, this does not necessarily imply that it will also lead to lower impact in the rest of the phases. As a result, understanding the environmental performance of a business model requires analyzing the effect on the overall environmental impact, which is the aggregation of the total environmental impact in each phase. The overall environmental impact may be primarily influenced by a certain phase of the lifecycle, based on the product type. For example, the majority of the environmental impact of printers happens during the use phase (see Xerox 2010). Moreover, in addition to the per-unit impact of a product in each life cycle phase, the total environmental impact of a business model depends on the firm decisions that influence the volume of production or use. Therefore, a more nuanced approach is needed to determine how each of the main aspects of servicizing may influence its overall environmental performance.

In what follows, we present the main drivers of the environmental performance of servicizing business models. For each driver, we present both sides of the coin. That is, instead of only describing why a certain aspect may be environmentally beneficial, we also outline the reasons as to why the same aspect may lead to adverse environmental effects when the firm and customer decisions are accounted for. This is not an attempt to be pessimistic, but to convey that the environmental potential of servicizing is not as straightforward and that the firm's decisions may actually undermine it. By being aware of this, firms and environmental groups can be more cognizant of when a servicizing business model actually has the potential to lead to superior environmental outcomes, instead of backfiring by leading to higher environmental impact.

7.3.1 Pay-per-Use Pricing

By selling the use instead of the ownership of a product, a servicizing firm effectively transforms the costs that customers incur from a fixed basis to a variable basis. The customer is now charged for every additional unit of usage due to the per-use pricing charged by the firm, which is not the case under a conventional sales business model. This may result in customers curtailing their use of the product, leading to lower use impact under a servicizing model. Consider Zipcar's business model as an example. Customers with moderate usage needs may actually find it beneficial to relinquish car ownership and satisfy their needs only through car sharing, under which it is likely they will drive less due to the higher hourly cost. We should note that in this case, the environmental benefits will also be in the production phase due to the possibly smaller quantity of cars required to be produced (we remind the reader about the pooling benefits of car sharing we mentioned earlier; see Bellos et al. (2016) for a treatment of the car sharing business model).

This reduction in use may be amplified by the fact that payments are more immediate and apparent to the user of the product. That is, even if the pay-per-use price under servicizing is the same as the operating cost that customers incur when they own the product, the fact that pay-per-use pricing imposes transparency and accountability may discourage the use of the product. For instance, charging on a per-page-printed basis may require creating a thorough monitoring system that displays detailed printing activity, along with the associated costs, of each user. In the same spirit, customers of Zipcar have their credit cards charged immediately after their reservation, something that when owning a car would happen only at refueling and after several trips.

However, the effect of pay-per-use pricing may not always be environmentally beneficial. Specifically, we need to consider the fact that transforming the fixed cost to variable may enable customers, whose low usage needs do not justify the purchase of a product, to use a product through servicizing. This may increase the overall number of adopting customers, which then may increase the overall product use and the number of products required to meet customers' needs. It is clear that such an increase may result in both higher production and use impact, thereby rendering servicizing environmentally inferior to conventional sales models (for a thorough treatment see Agrawal and Bellos 2015). Consider car sharing as an example: It can be appealing not only to customers who are contemplating relinquishing car ownership but also to customers who normally rely on more environmentally-friendly modes of transportation (e.g., public transportation) to cover their mobility needs. If these customers use a car through a sharing business model, this may lead to worse environmental outcomes (see Bellos et al. 2016).

7.3.2 Resource Pooling

As we have explained before, pooling refers to the firm's ability, under certain servicizing models, to pool its resources and to satisfy customers' needs through fewer products. The benefits of such resource pooling are fairly straightforward. The firm can create the same customer value by using fewer resources, less energy and material. This supports the move towards a utilization-focused economy where the impact during the production and, as an extension, the disposal phase is minimized.

Upon first glance, the environmental benefits of resource pooling seem to be rather straightforward. However, is it possible that one of the most environmentally-beneficial aspects of servicizing could backfire and result in higher environmental impact?. To answer this question we need to take a holistic view of the firm's and the customers' decisions and not treat them in isolation. This is because the firms make pricing and production decisions and customers respond to such decisions. Along these lines, pooling can affect the firm's pricing decisions, which subsequently can determine customers' decisions of whether to adopt or how much to use the product. Specifically, through pooling the firm can potentially enjoy savings in its total production cost as it does not need to provide each customer with a dedicated product. This may enable the firm to lower the pay-per-use price it charges in order to incentivize more customers to adopt a product or to increase the extent to which they use a product. However, this lower price may lead to greater adoption, and thus, higher production and/or product use. This implies that resource pooling may instead lead to a higher environmental burden (see Agrawal and Bellos 2015).

7.3.3 Product Design

The fact that under most servicizing models the firm retains ownership of the products and that it is compensated on a per-use or per-function basis may also incentivize changes in the design of the products. For instance, under a TotalCare maintenance agreement Roll-Royce is paid based on the number of hours that the engines are actually flown. Under such a program, in order to maximize revenue it is in the best interest of Rolls-Royce (but also in the best interest of their customers) to ensure maximum engine availability. Besides using best maintenance practices, an important prerequisite to this would be improving product reliability. It has been shown by Guajardo et al. (2012) that servicizing agreements such as pay-for-performance do incentivize manufacturers to improve the reliability of their products. Improvements in product reliability, of course, also benefit the environment because they lead to less frequent product replacement, which decreases the impact due to production and disposal. The same argument can also be made regarding the durability of the products. Namely, it is in the firm's best interest to maximize the duration of time for which it utilizes the same products, which is clearly also beneficial for the environment.

Another product design choice that the firm may determine based on whether it offers a servicizing or a conventional sales model is product efficiency. Product efficiency is particularly important under servicizing because a more efficient product leads to lower operating costs associated with the use of the product, and the firm's revenue is directly linked to the extent that customers use the products. The firm may also have an additional incentive to offer higher-efficiency products if it is the one who bears the operating cost. However, research has shown that the extent to which the firm improves the efficiency of its products depends on the strength of resource pooling. Specifically, Agrawal and Bellos (2015) show that if pooling is not feasible, then the firm offers lower efficiency products under a servicizing model. This result is reversed if resource pooling is feasible, which allows the firm to invest in higher-efficiency products. Therefore, servicizing does not always result in higher efficiency products. As a matter of fact, offering servicizing may actually be the reason for producing lower-efficiency products. We revisit the effect of efficiency and how it can possibly lead to lower environmental performance in Sect. 7.3.5.

7.3.4 Product Stewardship

Product stewardship is an approach that advocates for greater responsibilities of the producing firms in decreasing their environmental footprint throughout the *entire* lifecycle of their products (see U.S. Environmental Protection Agency 2012). In Europe this approach has taken the form of an official policy known as Extended Producer Responsibility (EPR; see Lifset et al. 2013; European Commission-DG Environment 2014). The objective of this policy is for firms to internalize the environmental cost of their products and foster a systems-thinking approach so that opportunities for reducing the environmental impact are identified from the early stages of design to the production, distribution and end-of-life stage of products. Most EPR policies focus on incentivizing firms to recover and reuse their products. The obvious benefits of recovery and reuse are the decrease in the number of products disposed in the landfills and, consequently, the decrease in the number of products that need to be produced to meet customer needs.

Note that under servicizing, a firm automatically maintains ownership of the product, achieving an important premise of EPR (White et al. 1999). Moreover, this may reduce the challenges faced by the firm in order to comply with EPR. This is because any recovery and reuse objectives can be satisfied at a much lower cost compared with a conventional sales model. However, this seemingly straightforward environmental advantage of servicizing comes with a caveat. By retaining ownership of its products, the firm has better control of the secondary market, which it can possibly eliminate by disposing its products in the landfill. Clearly, this would negate the environmental advantage that servicizing offers. See Agrawal et al. (2012) for a thorough treatment of these trade-offs in the context of leasing.

7.3.5 Rebound Effect

In Sect. 7.3.3 we described the different mechanisms through which servicizing may incentivize firms to produce products of higher or lower efficiency. The latter was implicitly assumed to be undesirable. The reason is that traditionally efficiency has been associated with environmental benefits such as energy savings. Therefore, environmentally conscientious firms ought to always offer products of higher efficiency. However, this is not as straightforward of an issue. The culprit is what researchers have named the *rebound effect*. According to the rebound effect, technological improvements that increase the efficiency of a resource may also result in an increase in the overall usage of the resource (see Greening et al. 2000). This means that by improving the efficiency of a product a firm may actually encourage customers to use the product more, which can be environmentally detrimental. But what is the role of servicizing in this case?

In Sect. 7.3.3 we mentioned that Agrawal and Bellos (2015) find that the efficiency that firms choose for their products depends on whether resource pooling is feasible. In particular, they find that servicizing may indeed result in products of higher efficiency, but at the same time it may dampen the rebound effect because of the pay-per-use pricing structure used by the firm. Under some conditions, higher efficiency may lead to lower usage under servicizing because the firm charges a sufficiently high pay-per-use price for a more efficient product. Namely, servicizing can be a mechanism that moderates the rebound effect, thus enhancing the environmental benefits of higher efficiency. Therefore, when determining the efficiency of their products, firms should also account for the rebound effect and possibly use servicizing as a means to moderate its occurrence.

The above discussion provides an overview of how the different operational characteristics and decisions influence the environmental performance of servicizing, which is summarized in Fig. 7.2.

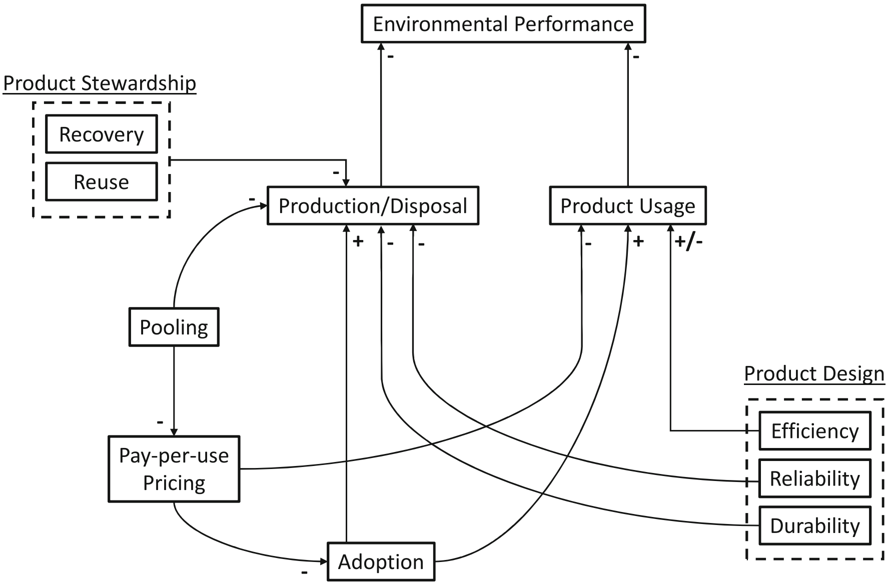

Fig. 7.2 Drivers of the environmental performance of servicizing (Each *arrow/arc* indicates a "standalone" (i.e., assuming all else being equal) influence. The *signs next to each arrow/arc* indicate the direction of this influence. For instance, higher pay-per-use price would most likely result in a smaller number of customers adopting the use of the product. Therefore, the *arc* that connects Pay-per-use pricing with Adoption has the "−" sign. However, larger adoption increases the quantity of products produced. Hence, Adoption is linked to Production/Disposal with a "+" sign.)

7.4 The Challenges of Servicizing the Supply Chain

The previous section focused on the drivers that determine the environmental performance of servicizing. However, even if a servicizing business model is environmentally superior, this is moot if the firm does not find it profitable. For that reason, in this chapter we look at implementation challenges that servicizing firms may encounter as they consider adopting servicizing. Regardless of type of the firm (i.e., whether the firm is a manufacturer or a third-party provider), the type of the product or the maturity of the industry, the mere act of servicizing will introduce the firm to at least some of the following challenges.

So far in this chapter, we have treated servicizing and conventional sales models as two extreme choices for the firm. In practice, however, it is likely to find that firms offer a "hybrid" business model, where the firm not only sells products but also sells the use/function of the products. Namely, a firm may offer both sales and servicizing options and have customers select their preferred option. It is more likely to observe such models being offered by manufacturing firms that want to diversify their offerings, but nothing precludes third-party providers from also providing such a combination. Offering both business models enables the firm to attract a more diverse customer base through better price discrimination. For instance, when simply selling products the firm may not attract customers with low-usage needs. It can do so by offering servicizing since it will charge on a per-use only basis.

While potentially more profitable, the simultaneous offering of both models may create additional challenges. In particular, the firm needs to price its models such that it does not cannibalize its own demand. For instance, having customers who typically buy a product switch to buying the use of the product may result in lower profitability. Although demand cannibalization is not an issue unique to servicizing (e.g., every firm that sells more than one product type faces the risk of demand cannibalization), managing it can be particularly difficult in a servicizing context (for a recent treatment see Agrawal and Bellos 2015).

Similarly, another critical issue when the firm offers both sales and servicizing options is whether and how the firm should offer a line of products. That is, a firm may have to decide whether to use the same or different types of products through the different business models. The differentiation of the products could be based on their efficiency level. In this case, if the firm chooses to offer a line of products with different efficiencies, the question is whether to offer the higher or lower-efficiency product to the customers who choose the sales or the servicizing model. Again the fact that each model uses a different pricing structure and that under servicizing the firm may be the one bearing the operating cost may complicate the product line decisions. We should note that, as we have already discussed in Sect. 7.3.3 reliability and durability can be additional dimensions based on which the firm may decide to differentiate its products.

Another layer of complexity is added when we consider a supply-chain context. In addition to deciding whether to offer a servicizing model, a sales model or both, the firm has to evaluate different supply chain structures. For instance, the firm could choose among: (1) selling products through a retailer and offering servicizing through a direct channel, (2) selling products through a retailer and offering servicizing through the same or a different retailer, (3) offering only servicizing through a retailer or through a direct channel, or (4) selling to a retailer who may choose to offer either or both models. Regardless of the structure, however, the misalignment of incentives may be exacerbated in a supply chain that includes servicizing because of the different nature of the transaction (i.e., quantity-based vs. use-based) and, for that reason, possible coordination issues may be more difficult to address. For studies on the effect of servicizing on the supply chain profitability, we refer the reader to Corbett and DeCroix (2001), Corbett et al. (2005), Kim et al. (2007).

As the firm maintains the ownership of the product, it is exposed to the risk of adverse selection and moral hazard (Toffel 2008). Adverse selection refers to the fact that a certain type of customers, which is unknown to the firm, may find it beneficial to choose servicizing. For instance, it is customers that extensively (ab)use a product who may be most interested in participating in a servicizing maintenance agreement since it is the firm's responsibility to ensure the operability of the products. Moral hazard refers to the fact that it is difficult to control the effort that a customer exerts during the use of the product. As one may expect, a customer who owns a product cares more about its resale value and, therefore, exerts more effort and care in using and maintaining it than a customer who uses a product under a servicizing model. We refer the reader to Toffel (2008) for a detailed discussion of these issues.

Finally, under servicizing a firm may face challenges stemming from internal employee resistance. The most common source of such a resistance is the firm's salesforce, who may find a transition to servicizing problematic due to the incentives structure. The reason is that typically the salesforce is compensated on a commission basis, based on the volume of products sold or the value of each transaction. However, these incentives cannot be used for servicizing models because the transaction is not product-based and/or the customer's eventual usage may be difficult to quantify at the start of the transaction and as it may be distributed over a longer period of time. Therefore, different performance metrics and incentives would be required to motivate the salesforce for servicizing business models.

7.5 Conclusions

Servicizing has been positioned as an innovative strategy through which firms can transform their business models to achieve economic and environmental sustainability. This chapter takes a closer look at this strategy and focuses on examining what differentiates servicizing business models from the more conventional sales models.

It is true that academic and managerial interest in the topic of servicizing has been growing for the past several years. However, the message regarding the potential of servicizing as a business model can seem to be muddled in a plethora of definitions and different contexts. For that reason we take a "unifying" approach that attempts to describe in the least theoretical way possible what servicizing is, what its key differentiators and operational determinants are, and what challenges a firm may face during the implementation of servicizing. We motivate our discussion based on examples of firms with successful servicizing models. Our intention is not to provide a exhaustive survey of research or business practices, but rather to convey in a structured manner our argument that servicizing should not be treated as business as usual but rather as an innovative way of conducting business with distinct operational and structural characteristics.

One of the main reasons that servicizing has attracted the attention of researchers and practitioners is its purported potential as a green business model. For that reason we devoted a significant part of this chapter on describing the key arguments for the environmental superiority of servicizing. More importantly, we also provided a discussion of the counter-arguments for why servicizing may lead to higher environmental impact. This provides a sobering view to the claims in practice that servicizing may lead to greatly improved environmental outcomes. We hope that this chapter provides a framework for firms and environmental groups to assess the environmental benefits of servicizing.

References

Agrawal V, Bellos I (2015) The potential of servicizing as a green business model. Forthcoming in Manag Sci. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2325218

Agrawal V, Ferguson M, Toktay LB, Thomas V (2012) Is leasing greener than selling? Manag Sci 58(3):523–533

Amazon (2015) Amazon EC2 pricing. Amazon web services. http://aws.amazon.com/ec2/pricing/

Atlas Copco (2015) Contract air: air-over-the-fence service for compressed air or gas. Atlas Copco. http://www.atlascopco.us/usus/products/air-and-gas-compressors/1524845/1546129/

Bellos I, Ferguson M, Toktay LB (2016) To sell and to provide? The economic and environmental implications of the auto manufacturer's involvement in the car sharing business. Working paper. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2372406

Booz Allen Hamilton (2005) Performance-based logistics perspective. Booz Allen Hamilton. http://www.boozallen.com/media/file/performance-based-logistics-perspective.pdf

Corbett C, DeCroix G (2001) Shared-savings contracts for indirect materials in supply chains: channel profits and environmental impacts. Manag Sci 47(7):881–893

Corbett C, DeCroix G, Ha A (2005) Optimal shared-savings contracts in supply chains: linear contracts and double moral hazard. Eur J Oper Res 163(3):653–667

European Commission-DG Environment (2014) Development of guidance on extended producer responsibility (EPR). European Commission. http://ec.europa.eu/environment/waste/\penalty0pdf/\penalty0target_review/Guidance%20on%20EPR%20-%20Final%20Report.pdf

Greening L, Greene D, Difiglio C (2000) Energy efficiency and consumption—the rebound effect—a survey. Energ Policy 28(6):389–401

Guajardo J, Cohen M, Kim S, Netessine S (2012) Impact of performance-based contracting on product reliability: An empirical analysis. Manag Sci 58(5):961–979

Kim S, Cohen M, Netessine S (2007) Performance contracting in after-sales service supply chains. Manag Sci 53(12):1843–1858

Lifset R, Atasu A, Tojo N (2013) Extended producer responsibility: national, international and practical perspectives. J Ind Ecol 17(2):162–166

Michelin (2015) Michelin fleet solutions. Michelin. http://www.michelintruck.com/services-and-programs/michelin-fleet-solutions/

Philips (2011) Philips lighting solutions. Philips. http://www.lighting.philips.com/pwc_li/main/\penalty0application_areas/assets/solutions/Philips-Lighting-Solutions-Brochure-HR.pdf

Quaker Chemical Corporation (2015) Chemical management services. Quaker Chemical Corporation. http://www.quakerchem.com/our-solutions/chemical-management-services/

Reiskin E, White A, Johnson Kauffman J et al (1999) Servicizing the chemical supply chain. J Ind Ecol 3:19–31

Rolls-Royce (2015) TotalCare. Rolls-Royce. http://www.rolls-royce.com/civil/services/totalcare/

Rothenberg S (2007) Sustainability through servicizing. MIT Sloan Manag Rev 48(2):83–91

Stahel W (1994) The utilization-focused service economy: resource efficiency and product-life extension. In: Allenby B, Richards D (eds) The greening of industrial ecosystems. National Academy Press, Washington, DC

Toffel M (2008) Contracting for servicizing. Working paper. http://papers.ssrn.com/\penalty0sol3/\penalty0papers.\penalty0cfm?abstract_id=1090237

U.S. Environmental Protection Agency (2012) Wastes-resource conservation-conservation tools. U.S. EPA. http://www.epa.gov/epawaste/conserve/tools/stewardship/basic.htm

White A, Stoughton M, Feng L (1999) Servicizing: the quiet transition to extended product responsibility. Tellus Institute, Boston

Xerox (2010) Life cycle assessment of a solid ink printer compared with a color laser printer. Xerox. http://www.office.xerox.com/latest/887WP-01U.PDF

Xerox (2015) Managed print services. Xerox. http://www.services.xerox.com/xerox-managed-print-services/enus.html

Zipcar (2015a) Washington DC rates & plans. Zipcar. http://www.zipcar.com/dc/check-rates

Zipcar (2015b) Zipcar wheels when you want them. Zipcar. http://www.zipcar.com/

Part III
Profit-Driven Environmental Responsibility in Supply Chains: Operational Perspectives

Chapter 8
Bike-Share Systems

Ashish Kabra, Elena Belavina, and Karan Girotra

Abstract Major cities—including New York, Paris, and London—have implemented bike-share systems to increase the use of sustainable modes of transportation. In this chapter we discuss the operational challenges of implementing such systems and also provide design recommendations. Critical decisions when implementing bike-share systems are the number of bikes and the number of docking points. For a proposed system, these quantities are determined as a function of the imbalance in demand flow (i.e., of demand asymmetry) in different directions. We show how this asymmetry affects decisions about the number of bikes and docking points and also about the frequency with which bikes should be reallocated from full stations to empty ones. The importance for users of the accessibility to stations and their bike-availability are the key determinants of how many daily trips a system attracts and hence of that system's optimal design. We describe an empirical study that determines user behavior in a central Parisian bike-share system and then suggest an alternate design which can increase the number of trips by almost 29 % for the same amount of resources in number of bikes based on user behavior parameters that we estimate.

A. Kabra (✉) • K. Girotra
INSEAD, Fontainebleau, France
e-mail: ashish.kabra@insead.edu; karan.girotra@insead.edu

E. Belavina
University of Chicago Booth School of Business, Chicago, IL, USA
e-mail: elena.belavina@chicagobooth.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_8

8.1 Introduction

Increasing populations and their need for mobility have led to traffic woes in major cities around the world. Most of these cities do not comply with clean-air requirements. Growing congestion on roads and longer travel times also take a huge economic toll: some €2883 for the average Paris resident and nearly €17 billion in annual costs to the French economy. Even as building infrastructure of local trains and buses helps reduce congestion and pollution, encouraging bike trips for short distances can be viewed as a means to serve the "last mile" travel needs and thus to increase reliance on public transit systems. Bike-sharing schemes are a healthy, and eco-friendly form of transport.

There are currently more than 535 bike-sharing systems in operation across North America, Europe, and Asia, where each system comprises stations spread throughout a service region. Every station consists of a certain number of docking points, which are the only places that bikes can be parked. Users who subscribe to the service can access bikes from any station and then drop off the bike at the same or any other station. The price per use of the service can be set to reflect pick-up and drop-off locations as well as use durations. Such service charges vary from system to system but are typically marginal for short trips; most system revenue derives from subscription fees and sponsorship.

Ridership in many of the implementing cities has fallen short of expectations. Most systems focused on the aspects of bike design and technology choice, which have been largely perfected. However, the operations aspects remain a challenge. Even though many bike-sharing schemes have emerged around the world, little is known about exactly how different factors affect the system's capacity decisions. Various rules of thumb are used when deciding on the number of bikes, stations, docking points per station, and reallocation frequencies required to serve an estimated number of users. For instance, the feasibility report for London's bike-sharing program proposed using 1.7 docking points for each bike in the system (i.e., as used by the Vélib' system in Paris).[1]

The objectives of this chapter are first to characterize operational decisions (the optimal number of bikes, docks and reallocation frequencies) in a bike-sharing system and then to derive empirically how consumers are affected by operational improvements in the system's accessibility and availability.

Toward that end, we look at the effect of demand—in particular, of demand asymmetry—between different stations on the optimal number of bikes and reallocation frequency. At a station, the demand for incoming and outgoing bikes is seldom balanced. One reason is that, even if the flow of a city's commuters is balanced over a day, it may be that one of the commuter

[1] http://content.tfl.gov.uk/cyclehire-scheme-feasibility-full-report-nov2008.pdf.

directions can be substituted with other modes of transportation. Also, this phenomenon can vary depending on the weather, the city's topography, and traffic conditions. Another factor affecting demand (im)balance is intertemporal variation. It is common for there to be high demand toward city centers in the morning hours and from them in the evening. As a result, most bike-share systems have mechanisms for reallocating bikes among the stations during the day or night hours. To analyze the effects of these factors on system efficiency, we define a system's *asymmetry* as the sum of (the positive parts of) the demand imbalances at individual stations. We find that an increase in asymmetry requires an increase in the number of bikes, docks, and reallocation frequency, where each of these three values is proportional to the square root of the asymmetry measure. System operational expenses due to bikes, docks, and the fixed costs of reallocation are also proportional to the square root of asymmetry, but the variable costs of reallocation are directly proportional to asymmetry. Finally, when accounting for demand uncertainty, we formulate capacity decisions regarding bikes and docks using newsvendor-style expressions.

Further analysis is based on an empirical model for estimating commuter responses to station density and to levels of bike availability. This model is based on a "random utility choice" model of spatially distributed commuters and is estimated via usage data on the Vélib' bike-sharing system in Paris. The data comprise more than 22 million observations of real-time information on the number of bikes at a station in central Paris, which corresponds to about 2.5 million bike trips. Using this data, we find that a 10 % in the distance of a commuter's travel to a bike-sharing station increases system use by 6.7 % and that a 10 % increase in bike availability increases system use by nearly 12 %. These findings suggest that the current Parisian system could benefit from those estimates, which would enable managers to balance the cost of system improvements against the expected benefits of increased ridership. Our estimates could also serve as inputs for the design of new systems. We further illustrate their use by comparing ridership among various station network designs that differ along two dimensions: the density (or closeness to commuters) of the stations, and the availability (on average) of bikes. We show that altering the system design parameters for central Paris could increase bike ridership by almost a third (29 %).

We remark that the issues considered in this chapter are not specific to bike-sharing systems. The notions of demand asymmetry, accessibility, and availability all apply directly to car-sharing systems and to on-demand taxi-hailing apps like Uber, Lyft, and EasyTaxi. Similar trade-offs are involved in the design of retail chains and in a hotel chain's locations.

Next we present a stylized analytical model to illustrate the effect of asymmetry on the optimal reallocation frequency and number of bikes. This is followed a description of our empirical study for estimating commuter responses to station density and bike availability. The chapter is based on work reported in Kabra et al. (2015a,b).

8.2 Model

In this section we present a stylized model to illustrate the impact of asymmetry of demand in a system on the number of bikes, docks and the reallocation costs.

Cost Parameters A system operator incurs a cost of c_b per bike per unit time in the system. The bikes that are used in the system are usually expensive because they must be robust to high-intensity use. The maintenance and repair of bikes also adds to this cost. Moreover, some bikes have to be replaced after breaking down or being vandalized. Since all these costs are proportional to the number of bikes in the system, we will use a combined amortized measure of cost per bike per unit time to reflect this.

Docking points are used to park the bikes in stations, and they incur costs of procurement, maintenance, and repair. They also occupy space with high opportunity costs. We use an amortized measure of all these costs per docking point per unit time, which is denoted by c_k.

Whenever bikes are to be reallocated, a fleet of trucks must be arranged. This process involves a significant fixed cost in addition to a variable cost (i.e., per reallocated bike). We use c_r to denote this variable (per-bike) cost; the fixed cost per reallocation cycle is denoted K_r. Every unit of demand that is not instantaneously satisfied is assumed to be lost. Each unit of "outgoing" demand lost when a station is empty incurs a system penalty p.

Decision Variables In our model, each reallocating operation brings the system to a state such that each station has q_i bikes. The total number of bikes in the system is denoted by N_b. Each station consists of certain number of fixed docking points at which returning bikes are deposited. As already mentioned, minimizing system penalties will require that bikes be reallocated. Finally, T denotes the time between reallocations.

Demand Process Every station will see an inflow of demand for renting bikes, which we denote by $\mu_i(t)$. A demand process is not completely described by the arrival rate at a station, since we must also identify the destinations of that demand. We will use r_{ij} to denote the probability of a demand at station i that requires a bike be transferred to station j. We shall use R to denote the matrix $[r_{ij}]$.

The primitive variables defined so far can now be used to construct our measure of asymmetry. The asymmetry in demand *at a station* i at time t is given by $\alpha_i(t) = \mu_i(t) - \sum_j \mu_j(t) r_{ji}$. The asymmetry *in the system* at time t is given by the sum of absolute imbalances at each station: $\alpha(t) = \sum_i \alpha_i(t)^+$.

We further simplify all demand processes to be constant over time so that $\mu_i(t) = \mu_i$; similarly, α_i and α denote (respectively) the constant station level and the system-level demand asymmetries. In addition, we start by assuming that travel from any station i to j is instantaneous—and that so is the reallocation process. Finally, we assume that all demand loss is due to stock-outs and ignore "blocking" (later we relax these travel-time and "blocking" assumptions).

At time 0, each station has q_i bikes; as time proceeds to t, each station has $e_i\left(t\right)$ bikes. If $e_i\left(t\right)$ approaches 0 then station i loses outgoing demand, and the cumulative demand lost at station i is given by $z_i\left(t\right)$. Note than when station i "stocks out", $dz_i(t)/dt \neq \mu_i(t)$. That is, not all the outgoing demand will be lost because some of it can be satisfied by the incoming demand (i.e., from other stations to this station). The processes $z_i\left(t\right)$ and $e_i\left(t\right)$ are related to vectors $\mathbf{q}$ and $\boldsymbol{\alpha}$ by the following set of equations:

$$\begin{aligned}
\boldsymbol{\alpha}t - \mathbf{q} + \mathbf{e}\left(t\right) &= \left(\mathbf{I} - \mathbf{R}\right)'\mathbf{z}\left(t\right), \\
\frac{d}{dt}z_i\left(t\right) &\geq 0 \quad \forall i, \\
z_i\left(0\right) &= 0, \\
e_i\left(t\right)\frac{d}{dt}z_i\left(t\right) &= 0, \\
e_i\left(t\right) &\geq 0;
\end{aligned}$$

$\mathbf{I}$ is the identity matrix. If we assume $\mathbf{R}$ is irreducible, then (by Theorem 7.30 in Chen and Yao 2001) there exists a unique pair of $(\mathbf{e}, \mathbf{z})$ given by the reflection mapping (Φ, Ψ) such that $\mathbf{e}\left(t\right) = \Phi\left(\mathbf{q} - \boldsymbol{\alpha}t\right)$ and $\mathbf{z}\left(t\right) = \Psi\left(\mathbf{q} - \boldsymbol{\alpha}t\right)$. At time T, the reallocation process kicks in and resets the system to a state that is equivalent to time 0. The cost of operating the system per unit time is given by

$$C\left(\mathbf{q}, T\right) = \frac{1}{T}\left(c_b T \sum_i q_i + c_r \sum_i \left|q_i - e_i\left(T\right)\right| + K_r + p \sum_i z_i\left(t\right)\right).$$

Characterizing Φ and Ψ is not always possible and in general only algorithmic solutions are known. However, if we set the penalty cost high enough $(\min_i[p/(1 - r_{ii})] \geq 2\sqrt{K_r c_b/\alpha} + c_r)$, so that the optimal solution to above expression precludes any stock-outs, then one can derive the optimal number of bikes at station i,

$$q_i^* = \alpha_i^+\sqrt{\frac{K_r}{c_b\alpha}},$$

the total number of bikes,

$$N_b^* = \sqrt{\frac{K_r\alpha}{c_b}},$$

and the optimal reallocation time,

$$T^* = \sqrt{\frac{K_r}{c_b\alpha}}.$$

For the overall system, the optimal cost is

$$C^*(\mathbf{q}, T) = 2\sqrt{K_r \alpha c_b} + c_r \alpha.$$

We note that if T were exogenous, q_i^* would be given by

$$q_i^*(T) = \alpha_i^+ T$$

The solutions could be extended to include blocking under similar conditions as above that penalty costs (for "stock outs" and "blockings") are high enough. In that case, the optimal station size (number of docks),

$$\kappa_i^* = |\alpha_i| \sqrt{\frac{K_r}{(c_b + 2c_k)\,\alpha}},$$

the total number of docks

$$N_\kappa^* = 2\sqrt{\frac{K_r \alpha}{c_b + 2c_k}},$$

and the expressions for all other optimal quantities are obtained by replacing c_b with $c_b + 2c_k$. For instance, the total cost rate is now written as

$$C^*(\mathbf{q}, T) = 2\sqrt{K_r \alpha\,(c_b + 2c_k)} + c_r \alpha.$$

We may observe from these characterizations that the optimal number of bikes and the optimal reallocation frequency $1/T^*$ are inversely proportional: the more bikes in the system, the less often one must reallocate. Any increase in demand asymmetry α increases both the number of bikes and the reallocation frequency. The increase in each factor is proportional to the square root of proportional increase in asymmetry. This finding reflects the economies of scale in system operation. Although the fixed costs (due to bikes, docks, and reallocations) increase in a square-root manner with asymmetry, the variable cost increases linearly. The system's economies of scale will therefore depend on which of $\sqrt{K_r c_b}$ or c_r dominates the cost structure.

So far we have assumed that bikes travel instantaneously from i to j. Now suppose instead that bikes travel at a finite rate, so that t_{ij} captures the travel time from station i to station j. From Little's law we know that in this case, if every station is serving bikes at the rate of μ_i, then the number of bikes en route from i to j is $\mu_i r_{ij} t_{ij}$. Given our assumptions, it follows that the total number of bikes required under nonzero interarrival times is $N_b = \sqrt{K_r \alpha / c_b} + \sum_i \sum_j \mu_i r_{ij} t_{ij}$.

8.2.1 Single-Station Analysis

The preceding formulation restricts us to obtaining interpretable results in regions where the penalty cost is sufficiently high. We now take a different approach to determining the optimal number of bikes and docking points in each station: considering each station in isolation and with exogenous reallocation time. We account for uncertainty in demand rates $\mu_i(t)$.

Assume that the penalty costs are s (resp., s_b) for each unit of outgoing (resp., incoming) demand lost. We don't use penalties p and p_b from before because each unit of demand lost at a station will have repercussions in behavior at other stations; hence s and s_b will generally not be the same as p and p_b. Uncertainty about μ is resolved at the start of each reallocation period so that the demand rate at each station remains constant in that period. This procedure is similar to the multidimensional newsvendor networks approach of Van Mieghem and Rudi (2002).

In this case, the optimal number of bikes at station i, or q_i, is given by

$$q_i^* = F^{-1}_{\alpha_i^+ T}\left(\frac{s - (c_b + c_k)\,T}{s}\right)$$

and number of docks κ_i is given by

$$\kappa_i^* = F^{-1}_{\alpha_i^+ T}\left(\frac{s - (c_b + c_k)\,T}{s}\right) + F^{-1}_{\alpha_i^- T}\left(\frac{s_b - c_k T}{s_b}\right).$$

In this setting, the inverse terms could be interpreted as ratios of underage and overage costs. One example is that for unmet outgoing bike demand the cost is $s-(c_b + c_k)\,T$ whereas, if bikes are available in excess, then the overage cost is $(c_b + c_k)\,T$.

8.3 Empirical Analysis

We now look more closely at what drives consumer demand. Previously we assumed that demand was exogenous to system characteristics. Here we posit two main drivers of consumer demand: *accessibility*, or how far one must walk to access a station; and *availability*, or the likelihood of finding—at the time of need—a usable bike at a nearby station. In what follows we describe the data, the overview of estimation strategy, and present our findings.

8.3.1 Data Description

We use data from the Vélib' bike-sharing system in Paris. Vélib' is one of the most popular such systems in the world, and it has served as a design model for many of the new bike-share systems in North America and Europe. Of the 20 Paris districts, we use data from the most central 10 districts, where demand density is highest. Our data consists of every-two-minute observations of the number of bikes at each of the 349 stations in central Paris. The data are compiled using the Vélib' availability interface for a period of 4-months starting May 2013. We restrict the analysis to weekdays, for which the pattern is probably different than for weekends. The data set contains 22 million "snapshots".

Using this high-frequency data, we construct one of our variables of interest: *Station-level use in a given two-minute interval*. This variable is equal to the number of bikes taken out when a station is stocked in and is equal to zero when the station is stocked out. Figure 8.1a shows the average use at a station when it has available bikes; the size of the bubble corresponds to the magnitude of average use. We observe that normally a station's use increases in its isolation from other stations. Estimating a station-level reduced-form model might seem to confirm the logical consequence that participation rates increase in response to greater distances to stations (or that commuters prefer stations that are farther away). However, those conclusions do not follow because the higher use at such stations reflects not only increased distance but also the station's greater service area.

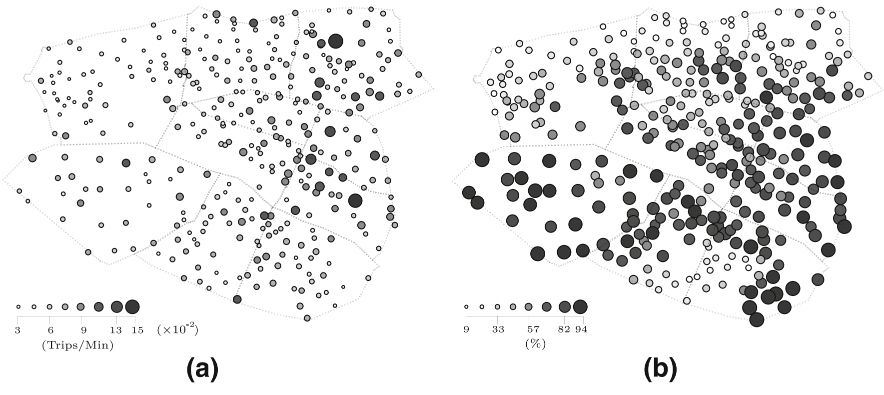

Fig. 8.1 Vélib' stations: usage and bike availability. (**a**) Average station-use; (**b**) average bike availability

Next we construct the study's independent variables. The distance that a commuter at any location must travel to a reach a station is defined as the straight-line distance to each station's GPS coordinates. A station's bike availability at a monthly level is the average of its fraction of 2-min intervals that are stocked in. Figure 8.1b depicts each station's average bike availability. Note that the stations in district 7 (lower left in the figure) exhibit much greater bike availability than do the stations in district 8 (just above district 7)—even though these two districts feature similar station-use levels. District 7 is home to many government buildings and centers of power, which could indicate that system operators set availability levels endogenously based on unobserved system characteristics. We will account for such potential endogeneity in our estimation.

8.3.2 Empirical Model

In our model, the effect of distance is that of the potential customer's walking distance, which is both station and commuter specific. It would be ideal to have data on commuter origin location for every trip—that is, at the station $\times$ commuter $-$ location level. Yet even system operators seldom have data at this level, and neither do we. One way to circumvent this issue would be by using a station-level reduced-form model, in which case the distance effect could be proxied by the distance of an average commuter to the focal station (e.g., "25 % of the distance to the nearest station"). Recall our previous comment, though, that any distance proxy will also reflect the influence of changes in the station's service area. We could, in theory, devise proxies capable of separating these two opposed effects; however, in each case a major challenge would be to account for the design's two-dimensional spatial structure. Even for bike availability, which is a station-specific measure, a simple station-level model would be inadequate because the use observed at each station includes not only the demand at that station but also the overflow demand from nearby, stocked-out stations. Moreover, a nearby station's greater bike availability would reduce use at the focal station, an effect that would have to be weighted by distance between the stations. Thus accounting for such spatial dependence between unobservable factors renders this approach even more difficult.

Our empirical model for commuters is a choice model between differentiated products. In this context, the products are different stations of various distances from a commuter and with different historical levels of bike availability; other factors include unobservable stations as well as time and district characteristics. Our parameters of interest are commuter sensitivity to distance and historical bike availability. The model and estimation procedure is built on work of Berry et al. (1995) and Davis (2006).

Since we do not observe commuters' origins, we create a density model of those locations. Each commuter makes a choice among those nearby stations that are stocked in (i.e., not stocked out). Given the parameters, the utility model gives us the probability of the focal commuter using a bike from station f. Aggregating the probabilities so derived and then multiplying them by modeled density yields our predicted demand as a function of utility parameters.

This model does not suffer from the independence of irrelevant alternatives (IIA), a property that troubles simpler models (e.g., a multinomial logit model). The reason is that commuters are heterogeneously located, which ensures that—when one station is stocked out—most of the outflow demand is satisfied by nearby rather than distant stations. Models with the IIA property predict, unreasonably in this case, that one station's stock out will increase the resulting demand at other stations in proportion to their respective base levels of demand.

Our model reflects the impact of bike availability in two ways. First is the *long-term* effect of bike availability. Being able to count on finding a bike at a station allows the commuter to plan an itinerary and, more generally, to make well-informed decisions about other, long-term choices (e.g., owning a car). The use of a bike-share system will increase with the likelihood of finding a bike at a nearby station, or with that station's average bike availability. The second effect is a *short-term* effect of bike-availability. When a station stocks out, commuters can no longer make trips from that station. But those trips need not be lost to the system, since some of the affected commuters may decide to use bikes from a nearby (stocked-in) station. Such behavior is a function of the distance to nearby stations (and their bike availability) and of other fixed station, time properties. The fraction of commuters who substitute—upon finding their preferred station stocked out—account for the *short-term* effect of bike availability.

The estimation process we employ is related to the nested fixed point procedure in Berry et al. (1995). A naive implementation of that procedure would be computationally too expensive; the stock-out status of stations changes frequently, and a new probability of using a station must be computed for each commuter in each of the system's stock-out states. In sum: the data's high frequency, the large number of (simulated) commuters within the service region, and the iterative nature of the estimation together render this procedure computationally infeasible. But neither would it be appropriate to use shorter spans of data, since station use exhibits considerable variation and so a fairly wide span of data is needed for robust estimation.

We therefore propose a different aggregation model that allows us to use changing choice-sets for our estimation. We can aggregate all observations at a station for time periods when the same of set of stations in the system are stocked-in and for same "time-window" and month. We notice however that the system could have as many as $2^{\#\text{stations}}$ different stock-out states, and the data indicate that many of these states are realized. Hence this level of aggregation does not materially reduce the number of computations. However, we observe that station use is not affected by the stock-out states of all other stations but only by those of nearby stations. We therefore aggregate observations of each station at the level of a local stockout-state i.e.

for time periods when stock-out state of *nearby* stations is the same (and for same "time-window" and month). The result is some loss of information, since multiple states of nearby stations can coincide (during a given time interval) with one state of the focal station. Once we have carefully accounted for that possibility, the resulting computational gain is exceptional.

8.3.3 Results

Reducing distances between stations and commuters by 10 % leads, on an average, to a 6.65 % increase in system use. Increasing bike availability by 10 % leads to a 11.73 % increase in system use in long-term. Of this, the short-term effect is 9.56 %.

8.4 Implications

In this section, we discuss in more detail the implications of the foregoing analyses.

The design of a bike-sharing system involves a few key decisions, of which the first is how many bikes the system should have overall. This decision directly raises the question of how many docks should the system have for a given number of bikes. If the system does not have enough bikes then stations will be sparsely located and have low levels of bike availability, defeating the purpose of and potential demand for a bike-share system. More bikes and docks will accommodate a greater number of trips, but the associated costs mount rapidly. The bikes are expensive owing to durability demands, and the cost of bikes and docks accounts for most of the system's fixed costs. It is therefore important to get these numbers right.

8.4.1 Effect of Demand Asymmetry

As mentioned previously, the demand for incoming and outgoing bikes is hardly ever balanced at a given station. We define asymmetry at the system level as the sum of positive part of the imbalance of demand at individual stations. Because demand is asymmetric, many bikes end up at stations where they are not needed. Neutralizing the effect of this asymmetry requires that system operators frequently reallocate bikes from full stations to empty ones.

We demonstrated in Sect. 8.2 that the system's required number of bikes is equal to the product of system-level asymmetry and the average time between subsequent reallocation operations. To see the intuition behind this result, consider a system with only two stations, A and B. Assume that there is no travel time between these stations and assume that, every minute, station A sees two more outgoing bikes than incoming bikes. At the same time, the corresponding difference at station B is -2 bikes/min. Now suppose that bikes are reallocated every 10 min. If station A starts with 20 bikes and station B with 0 bikes then, after 10 min, both the stations will have catered to all the demand and station A (resp., B) will be left with 0 bikes (resp., 20 bikes). A reallocating operation will refill so that station A has 20 bikes and station B has none. So this example shows the total number of bikes required being equal to the product of system-level asymmetry (2 bikes/min) and the reallocation interval (10 min).

The number of bikes that the reallocating operation leaves at each station depends on the station's asymmetry. If the asymmetry at a station is positive (i.e., if outgoing demand exceeds incoming demand), then its number of bikes is the product of its asymmetry and reallocation levels; if asymmetry is negative, then *no* bikes are stocked at the station because it will have a net inflow of bikes.

The number of bikes required by a system is linearly increasing in its asymmetry—provided the reallocation interval is unchanged. However, that interval is a decision variable whose value could be changed in response to changes in demand asymmetry. Assume that the cost of a reallocating operation consists of a fixed cost plus a variable cost that is proportional to the number of bikes reallocated. Our model then shows that, when asymmetry increases, it is optimal for the system (1) to increase the number of bikes by a factor equal to the square root of the increase in asymmetry and (2) to reduce the reallocation interval by that same factor. Throughout any such manipulation, the total number of bikes remains equal to the product of system-level asymmetry and reallocation interval. The system's fixed costs increase with the square root of asymmetry upon adjustment of the reallocation interval; otherwise, they increase linearly. The variable cost due to a reallocating operation is directly proportional to the system's asymmetry level.

8.4.2 Effect of Travel Time Between Stations

So far we have assumed that the travel time and distance between stations is zero. Thus any decrease in a station's number of bikes leads to an instantaneous increase in their number at some other station. Nonzero travel time has the effect of delaying this process and entails that, at any given time, some bikes will be "on the road" (i.e., having left the origin station but not yet reached a destination station). In our setup, the number of such *in-transit* bikes is given (according to Little's law) by the product—at the system level—of the average trip duration and the average number of trips on each route, therefore on route i to j, its $\mu_i r_{ij} \tau_{ij}$ (see Little 1961 and

Cachon and Terwiesch 2009). For instance, if the average trip duration is 20 min and if (on average) 100 trips start every minute, then there are 2000 bikes in transit. So besides the previously calculated number of needed bikes (i.e., asymmetry multiplied by reallocation interval), the system will have to add 2000 more.

8.4.3 Effect of Uncertainty of Demand

Although we have assumed that demand is deterministic, there is actually quite some uncertainty in both the outgoing and the incoming demand at each station. Since asymmetry is the difference between outgoing and incoming demand, it follows that the average value of station asymmetry will be the difference in the average of outgoing and incoming demands. The stations' asymmetry levels will be distributed around this mean value, and demand uncertainty could either raise or lower the number of bikes needed at a station (owing to our $\alpha_i^+ T$, i.e., "positive value of asymmetry $\times$ reallocation interval" formula). In this case, the optimal number of bikes can be determined by viewing the focal station in a newsvendor framework. Each station with positive asymmetry starts with a certain fixed number of bikes, which are depleted at the rate of asymmetry (a random variable). Following a reallocation interval, if the net realized asymmetry is higher than the number of bikes then a penalty is incurred for lost demand. This penalty cost includes the loss of future trips owing to commuter dissatisfaction as well as the environmental effects from the commuter using some other (and less eco-friendly) mode of transport. This downside is equivalent to the newsvendor framework's "underage" cost. In contrast, if the realized value of total asymmetry within a reallocation interval is lower than the starting number of bikes and if some of the bikes are not used, then an "overage" cost has been incurred. This overage cost is the cost of holding each extra bike during the reallocation interval, which can be derived by amortizing a bike's purchase and maintenance costs over its useful lifetime. A station's optimal number of bikes is then given by the *inverse* of asymmetry's cumulative distribution function at the *ratio* of the underage cost to the sum of underage and overage costs. Much as in a newsvendor model, here an increase in the penalty (underage) cost of bikes will lead to more bikes at a station whereas an increase in their holding (overage) cost will lead to fewer of them.

8.4.4 Number of Docks

We now address the decision concerning how many docking points to install. To identify this number, we use the deterministic demand setting. The number of docks is a function of the number of bikes in the system and its demand characteristics (asymmetry). Docks are required so that the commuter can either pick up a bike or drop it off after use. Thus, the number of docks at each station should be equal to the absolute value of station asymmetry. If asymmetry is positive, then the number of docks equals the number of bikes a station has immediately *after* a reallocation process. If asymmetry is negative, so that there is an incoming (net) flow of bikes, then the optimal number of docks is equal to the number of this station's bikes just *before* the reallocation process takes them all away. Note that the total number of docks is twice that of the number of bikes actually at the station. For bikes that are in transit, the number of docks required would vary between one and two times the number of bikes depending on whether these bikes end up where they start or at a different station. When taking demand uncertainty into account, we get newsvendor styles expressions in distribution of asymmetry much like number of bikes.

8.4.5 Station Locations

We have examined, for a particular station location, the decisions regarding how many bikes and docks to acquire and how often to reallocate the bikes. We can assume that demand is known at a given location, but allowing locations to vary would naturally result in demand also varying. Having stations close to commuters makes them more likely to adopt and use bike-share systems compared to other alternative modes. How much of demand can be encouraged by altering the proximity of stations is an empirical question. Using real-time data on the number of bikes at stations in central Paris, Kabra et al. (2015a) find that 6.7 % more bike-sharing trips occur for every 10 % reduction in distance between stations.

8.4.6 Bike Availability

Bikes can be checked out of a station only if it has available bikes. The proportion of time for which bikes are available at a station can be used as its measure of bike availability. Kabra et al. (2015a) identify two effects of low bike availability. One is the short-term effect due to stock-outs. Recall that, in such cases, some commuters do end up using a nearby station. The authors find that only 4.4 % of stocked-out commuters go to nearby stations, so the short-term effect of a 10 % increase in bike availability is about a 9.6 % (10–4.4 % of 10 %) increase in the number of trips. In the longer term, greater bike availability enables commuters to plan itineraries and may incentivize changes in commuting behavior and increased use of the bike-share system. They report a nearly 12 % increase in the number of trips for every long-term increase of 10 % in bike availability.

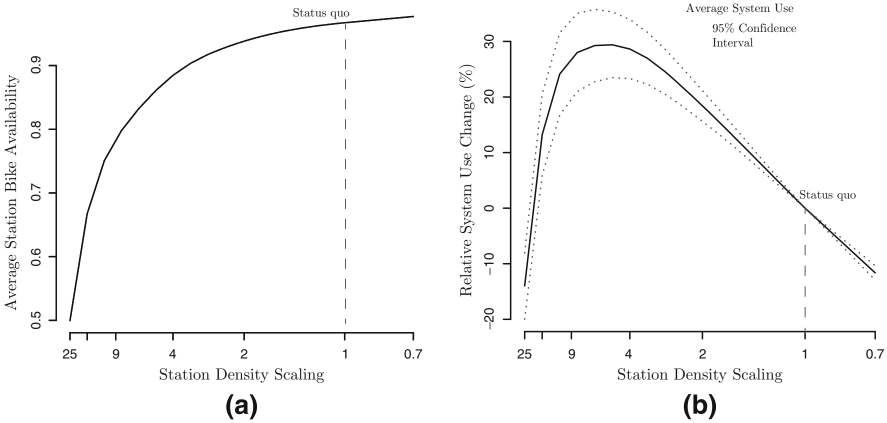

Fig. 8.2 Density–availability simulation and counterfactual system use. (**a**) Effect of station density on bike availability; (**b**) counterfactual system-use for alternate station network designs

8.4.7 Balancing the Demands of Accessibility and Availability

Although bike-share users prefer high station density and bike availability, a system operator must trade off making the system more accessible (lower distances) against making it more available (higher bike availability). Thus, for a given number of bikes, the operator chooses between designs featuring larger but fewer stations and those featuring smaller but more stations. On the one hand, stations of larger *size* naturally handle more demand and so, by a pooling effect, their bike availability is higher on average (Cachon and Terwiesch 2009). On the other hand, a larger *number* of stations makes the system closer to both the starting and destination points of a typical commute and hence more accessible. The optimal station design depends, in turn, on the relative extent to which commuters prefer one of these two aspects. We take current design as the status quo and test for the effect of changing station density (the number of stations) on the number of trips. Figure 8.2a plots the trade-off curve between station density and bike availability. On each x-axis, the status quo station density (i.e., the current design) is set to 1; the curve shows the resulting average bike availability when station density is changed by the x-axis factor. Reduced station density does increase bike availability levels—although that marginal increase is decreasing (in the density reduction). System use under each combination of station density and bike availability is plotted in Fig. 8.2b, which shows that higher levels of system use can be achieved (albeit with less bike availability) by locating stations more densely. In the case of central Paris, Kabra et al. (2015a) find that the optimal design involves making the system dense enough to increase the number of system trips by 29.41 %. Most of these gains are achieved by making the system from two to four times more dense; returns to this strategy are diminishing after that point.

8.5 Conclusion and Future Directions

This chapter discusses some early work in the nascent field of bike-sharing systems. Many city governments have begun to take a more analytical and data-driven approach to the operations management of these systems. We have described how (asymmetrical) demand and also travel times affect the optimal number of bikes and docks as well as the optimal frequency of reallocating operations. We also examined data-driven tools for designing stations that, for a given number of bikes, best cater to the anticipated trips. An important topic not covered here is the use of algorithms to manage both vehicle routing and the process of reallocating bikes; see Schuijbroek et al. (2013) and Raviv et al. (2013) (and references therein) for solution approaches to the process of reallocation of bikes. We hope that this chapter has demonstrated the importance of an operational perspective on the design of sustainable public transportation systems. We believe there are also ample opportunities for investigating how bike-sharing systems interact with other public transit systems. Insights on such matters could help city governments make better plans for the design and capacity of these systems.

References

Berry S, Levinsohn J, Pakes A (1995) Automobile prices in market equilibrium. Econometrica 63(4):841–890

Cachon G, Terwiesch C (2009) Matching supply with demand, vol 2. McGraw-Hill, Singapore

Chen H, Yao DD (2001) Fundamentals of queueing networks: performance, asymptotics, and optimization. Springer, New York

Davis P (2006) Spatial competition in retail markets: movie theaters. RAND J Econ 37(4):964–982

Kabra A, Belavina E, Girotra K (2015a) Bike-share systems: accessibility and availability. Chicago Booth Research Paper (15-04)

Kabra A, Belavina E, Girotra K (2015b) Effect of demand asymmetry on the design of bike-sharing systems. Work in Progress

Little JD (1961) A proof for the queuing formula: $L = \lambda w$. Oper Res 9(3):383–387

Raviv T, Tzur M, Forma IA (2013) Static repositioning in a bike-sharing system: models and solution approaches. EURO J Transp Logist 2(3):187–229

Schuijbroek J, Hampshire R, van Hoeve WJ (2013) Inventory rebalancing and vehicle routing in bike sharing systems. Under Review. Tepper School of Business Working Paper 2013-E1, Carnegie Mellon University, Pittsburgh, PA

Van Mieghem JA, Rudi N (2002) Newsvendor networks: inventory management and capacity investment with discretionary activities. Manuf Serve Oper Manag 4(4):313–335. doi:10.1287/msom.4.4.313.5728

Chapter 9
Biofuel Supply Chain Network Design and Operations

Michael K. Lim and Yanfeng Ouyang

Abstract The rapidly growing biofuel industry poses considerable challenges to its supply chain network design and operations. In this chapter, we introduce key characteristics of the biofuel supply chain that comprises of feedstock production, biomass logistics, biofuel production and distribution. We then discuss the recent literature on biofuel supply chain models. Using an illustrative biofuel supply chain model to facilitate the understanding of the core trade-offs in this context, we discuss various issues including logistics network optimization, transportation and inventory management, uncertainty management, land use competition, governmental policies, and the resulting environmental and social impacts.

9.1 Introduction

In 2013, the United States was the largest consumer of crude petroleum oil, accounting for about 21 % of worldwide consumption (i.e., 18.5 million barrels per day out of 88.9 million barrels consumed worldwide), more than half of which was imported from about 80 countries (U.S. Energy Information Administration 2014). The majority of consumption occurs in the transportation sector, especially the light-duty vehicles Americans drive every day which rely

M.K. Lim (✉)
Department of Business Administration, University of Illinois at Urbana-Champaign, 1206 S. 6th St., Champaign, IL 61820, USA
e-mail: mlim@illinois.edu

Y. Ouyang
Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL 61801, USA
e-mail: yfouyang@illinois.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_9

almost exclusively on oil. Such heavy reliance raises two major issues: energy security and environmental sustainability. With increasing oil consumption and dependence on foreign oil imports, the U.S. government has made energy security a key priority. Increasing oil consumption also implies considerable impact on the environment, since transportation-related emissions represent about one third of the total greenhouse gas (GHG) emissions in the U.S. and are considered to be a critical contributor to global climate change.

To help alleviate these issues, the U.S. government is firmly supporting the development of biofuel production as one of the ideal alternatives for transportation fuel. Biofuel is converted from renewable resources such as crops or other naturally grown biomass into a form of bioethanol or biodiesel that can be used as a gasoline additive to supplement the petroleum-based fuels. With the great potential that biofuels offer, the U.S. Congress enacted the Energy Independence and Security Act (EISA) in 2007 (Energy Independence and Security Act 2007) "to move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, vehicles, to promote research on and deploy GHG capture and storage options, and to improve the energy performance of the Federal Government, and for other purpose." Congress further announced the Renewable Fuel Standard (RFS) mandate (U.S. Department of Energy 2005) and its revision (known as RFS2, U.S. Department of Energy 2011) as action plans, requiring the annual production of renewable fuel to reach 36 billion gallons by 2022, as shown in Fig. 9.1.

The majority of currently produced renewable fuels are conventional biofuels, also referred to as the first-generation biofuels. The primary feedstocks for conventional biofuels are agricultural crops such as corn and sugarcane. Advanced renewable fuels include cellulosic biofuel, often referred to as the second-generation biofuels. The two main feedstock sources of cellulosic biofuels are dedicated energy crops and non-edible agricultural crop residues. Dedicated energy crops include herbaceous energy crops, such as switchgrass and miscanthus, and woody energy crops, such as fast-growing hardwood trees and hybrid poplars. These are perennial crops that require certain years to reach full productivity. Non-edible agricultural crops include corn stover and wheat straw. In particular, corn stover is likely to be one of the major crop residue feedstocks as approximately 80 million acres of corn are grown in the U.S. On smaller production scales, biodiesel derived from oil seeds of soybeans, canola, and palm is another form of renewable fuel. There are other advanced biofuels derived from various sort of feedstocks including algae and aquatic crops, or any other form of biofuels that may exist in the future.

One important difference between conventional and advanced biofuels is that the raw material (biomass feedstock) for conventional biofuels directly competes against food production whereas advanced biofuels are produced from non-food sources. In addition, advanced biofuels are typically more environmentally-friendly than the typical conventional biofuels. For

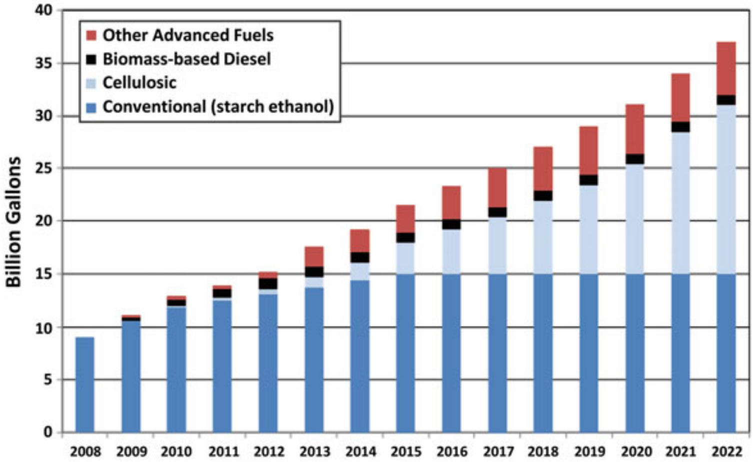

Fig. 9.1 Renewable fuel volume consumption mandated (Source: United States Department of Energy, Energy Efficiency and Renewable Energy, Alternative Fuels Data Center, http://www.afdc.energy.gov/laws/RFS.html)

example, the EPA requires corn-based bioethanol to meet the 20 % GHG emission reduction threshold using advanced efficient technologies, compared to the 2005 gasoline baseline; in contrast, cellulosic-based bioethanols or cellulosic-based diesels must comply with the 60 % GHG emission reduction threshold (Environmental Protection Agency 2014). Hence, going forward from 2013, the governmental mandate requires more than 90 % of the increase in biofuel production to come from the cellulosic biofuels. In fact, conventional biofuel is considered to play a transition role until the technologies for advanced biofuels mature, eventually leading to a decrease in conventional biofuel production level. For advanced biofuels, one important feature is the high transportation and distribution costs. This is mainly due to the bulky volume (or low energy density) of biomass that result in high/frequent traffic coupled with compatibility issues during transportation. Given that the success of the biofuel industry relies heavily on the reliable supply of high-quality biomass at a reasonable cost, designing a sound *biofuel supply chain network* and establishing efficient operational practices are of utmost importance for the success of this nascent industry.

However, there are many challenges associated with biofuel supply chain design and operations. As an emerging industry, the biofuel industry needs to establish the distribution network spanning different stages of the biofuel production process, while at the same time taking into account high levels of logistics cost and uncertainties resulting from the unique features of biomass feedstocks. The imposed competition for agricultural land also needs to be carefully considered as biomass feedstock will directly and indirectly affect food production and environmental quality. Furthermore, governmental policy instruments such as mandates and subsidies affect the economics (such as supply and demand equilibrium) of the biofuel industry and result in various economic, environmental, and social implications. Therefore, a holistic perspective of biofuel supply chain network design and its operational guidelines is in pressing need in order to achieve sustainable development of the biofuel industry.

The objective of this chapter is twofold. First, in Sect. 9.2, we introduce the *background of this nascent industry and establish key features of the biofuel supply chain*. This will provide a starting point for understanding the industry and the main design and operational issues that rise in the biofuel supply chain. Second, in Sect. 9.3, we introduce the *recent relevant modeling literature on biofuel supply chains*. To facilitate the discussion, we present a simple illustrative biofuel supply chain network design model, and explore specific modeling features by discussing the related issues in each subsection. For broader perspectives of biomass production, biofuel industry, and governmental policies beyond the supply chain, please refer to National Research Council of the National Academies (2011) by the National Research Council and the Billion-Ton studies (U.S. Department of Energy 2005, 2011) released by the U.S Department of Energy.

9.2 Biofuel Supply Chain

A biofuel supply chain encompasses all activities from feedstock production, biomass logistics of storage and transportation, biofuel production, and distribution to end consumers. Similar to most other supply chains, a biofuel supply chain involves various distinct stages with different ownership entities such as farmers, biorefineries, distributors, and oil companies, and its performance highly depends on the network design, planning, and operations. Figure 9.2 depicts a schematic overview of an advanced biofuel supply chain network.

Specifics of the intermediate processes and logistics steps (conversion, conditioning, storage, and transportation) may vary depending on the types of biomass feedstocks, conversion technology, and biofuel form. However, the fundamental mechanism and flow of the process are very similar. Therefore, in the remainder of this chapter, we will primarily focus on cellulosic bioethanol as the representative case and discuss further issues and challenges of biofuel supply chain design and operations. For more details on production process and technologies of various types of biofuel, we refer the readers to National Research Council of the National Academies (2011) and Shastri et al. (2014). In what follows, we discuss the core elements of the supply chain: production process, logistics, material supply, and consumption demand.

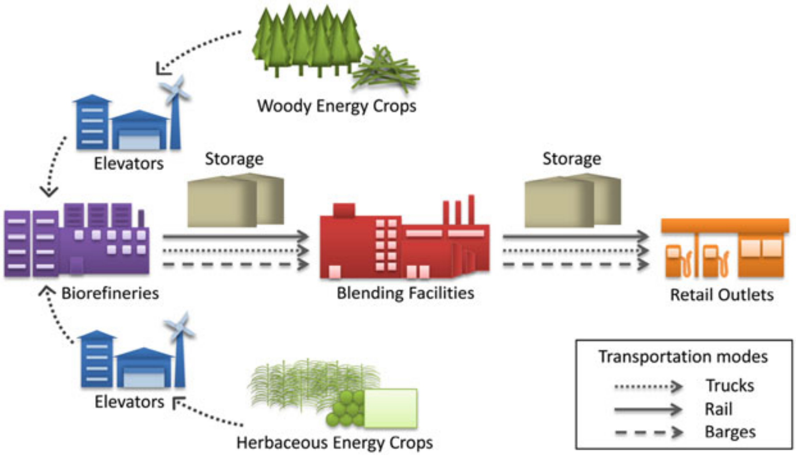

Fig. 9.2 Schematic description of advanced biofuel supply chain network

9.2.1 Stages of Biofuel Supply Chain

Feedstock Production The fundamental source of biofuel is the biomass feedstock, which is made of renewable biological materials. Production of biomass feedstocks include all of the operations required for farmers to generate the feedstock including plant breeding, planting, managing, and harvesting the crops from farmland, field, or forest.

As of 2010, the primary biomass feedstock for biofuel production in the U.S. was corn grain, the majority of which is produced in the Midwest region. However, with the emergence of newer generation crops and the biomass mandate (per RFS2), the sources of feedstock supply are expected to be more diverse and their production regions are expected to expand, e.g., cellulosic feedstocks can be produced on relatively low-quality marginal lands. Feedstock growers are mostly individual farmers who often cooperate closely with local biorefineries through yearly contracts. Although not prevalent yet, long-term contracts are also expected to emerge as demand for cellulosic feedstock (i.e., perennial crops) is anticipated to increase rapidly.

Bioethanol Production The harvested biomass from regional farms is first collected and staged at the nearby shipping terminal or elevators and then subsequently shipped to a nearby biorefinery. At the biorefineries, the biomass conversion occurs through bio-decomposition, fermentation, and distillation, yielding marketplace products such as ethanol and by-products. In essence, this process is analogous to the petroleum refining for the gasoline. The diversity of the biomass resource requires different conversion technologies including biochemical and thermochemical conversions. However, regardless of their sources, ethanol at this stage must satisfy all specific fuel criteria to offer the same performance as a regular fuel.

Constructing biorefineries is costly. In particular, integrated biorefineries that are capable of handling diverse sources of biomass feedstocks requires significant investment so as to achieve economies-of-scale. Currently, many first-generation bioethanol production systems are owned by regional companies or farm cooperatives in the U.S. As for the advanced-generation biorefineries, governmental aids and participation of large oil companies are expected given the high upfront capital investment.

Although not explicitly featured in the above supply chain, residues from the feedstock conversion process such as dried distillers grain with solubles (DDGS) are often marketed as livestock feed. Given the potential economic implications of by-products, the joint-consideration of biofuel and by-product distribution can potentially be another crucial element of a biofuel supply chain design.

Biofuel Production The ethanol from the biorefinery is subsequently transported to blending facilities and blended with gasoline. After this stage, the biofuel is ready to be distributed as a commercial transportation fuel. Most existing vehicles today can run on biofuel blends and roughly half of the gasoline sold in the U.S. includes ethanol. A notable biofuel blend example is E10 which is a blend of 10 % of ethanol and 90 % gasoline. The use of bioethanol helps reduce toxic air pollutant emissions and increase octane components; for example, ethanol used in E10 contains 35 % oxygen allowing a more complete burn in the engine leading to better combustion and fewer emissions (National Research Council of the National Academies 2011). Higher ethanol content blends such as E15, E20 have also been introduced in some states in the U.S. (e.g., E15 is available in many midwestern states) and other countries (e.g., E20 has been used in Brazil since 1970s). E85, a blend of 85 % of ethanol and 15 % gasoline, is another commonly used biofuel that can be used by flexible-fuel vehicles.

Retail Outlets The final stage of a biofuel supply chain is the distribution and sales of fuels to end-consumers. Most of the biofuels in liquid form are shipped to retail outlets through existing fuel distribution systems to the transportation fuel market. These retail market outlets are typically gas stations owned by large oil corporates such as Exxon Mobil and BP, who also often own the biofuel blending facilities. Some biofuels are also used for residential/commercial heating and power generation, and these fuels are shipped directly to these end-user destinations.

9.2.2 Logistics

About 70 % of petroleum products are transported via pipeline in the U.S. However, bioethanol is typically not compatible with existing petroleum pipelines because it is highly corrosive and more soluble in water than petroleum. For this reason, trucking is one of the most common transportation modes for ethanol shipment, especially for relatively short-distance shipment in the upstream supply chain. This includes shipping harvested biomass from the on-farm storage to local elevators and to the nearby biorefineries.

For the downstream side of the supply chain, the shipping between biorefineries and blending terminals (and the retail outlet) could be carried out through several competing modes. In the U.S., ethanol shipments are commonly made by one or more combinations of trains, trucks, and barges depending on the biofuel types and the region. The estimated transportation costs, adapted from Jenkins et al. (2008), are summarized by mode of transportation in Table 9.1. We note that these estimates are based on the optimized supply chain network, and their values may increase considerably otherwise.

Table 9.1 Estimated transportation cost and capacity

Transportation modes	Truck	Rail	Barge
Loading and unloading	\$0.02/gal	\$0.015/gal	\$0.015/gal
*F*ixed or *V*ariable cost	V: \$32/hour/truckload	F: \$8.80/100 gal	F: \$1.40/100 gal
Distance-dependent cost	\$1.3/mile/truckload	\$0.0075/mile/100 gal	\$0.015 mile/100 gal
Capacity	8000 gal	33,000 gal	1,260,000 gal

One of the key challenges in biomass transportation is the handling of its bulky volume. Unprocessed cellulosic biomass materials are typically low on energy-density and aerobically unstable, and hence require special preprocessing (e.g., conditioning and separating grain from the residue) involving significant manual labor. Also, the locations of various feedstock farms are geographically spread out due to land use policy, water availability, soil type, and climate. These characteristics collectively lead to high transportation costs. The transportation cost is estimated to be about 18–28 % of the feedstock cost (Shastri et al. 2014) depending on the type of biomass source.

Another key challenge in biomass feedstock logistics is maintaining a steady rate of supply to biorefineries. Many herbaceous feedstocks are only harvested during a short time window, typically 2–3 months or shorter. For example, corn stover is harvested within a few weeks. Since the biorefineries need to produce fuel all year round, biomass feedstock storage is needed at the refineries so as to ensure steady input. Due to low energy density and monetary value of material, storage infrastructure location and operations that minimize biomass quality losses (e.g., biological degradation during the storage leads to detrimental conversion yield) are actively being addressed in research and practice.

9.2.3 Supply and Demand

There are various sources of cellulosic biomass feedstocks, and their availabilities are location specific. In general, the main determinants of feedstock supply are the feedstock market price and the operating costs which include planting, growing, harvesting, and transporting biomass to elevators. Feedstock supply will also largely depend on the competing options such as the price of agricultural foods or other types of biocrops. Feedstock supply, as any other agricultural product, is subject to yield uncertainty due to weather and disease conditions. Thus, farmers exhibit risk-averse behavior in their land use and crop choice decisions, especially when long-term commitment is required for growing perennial energy crops (Alexander and Moran 2013). A thorough overview of feedstock and its by-product supply in the U.S. is provided in U.S. Department of Energy (2011).

Demand for biofuel and subsequently the demand for biomass feedstock is dependent on many factors, such as the price of other types of biomass feedstock, advancement of technology, and even the price of crude oil. In the long term, the demand is expected to increase as a result of increasing transportation fuel demand as well as limited availability of petroleum oil reserves.

Another critical factor in shaping the supply and demand of biofuel is government policy. To accelerate the development of the biofuel industry, the U.S. government is establishing various policies and imposing necessary instruments. The major legislation promoting biofuel demand is the RFS 1 and 2 that requires 36 billion gallons of biofuels by 2022 (at least about 45 % of which be produced from cellulosic feedstocks). Although oil companies can import bioethanol (e.g., sugarcane ethanol from Brazil), the mandate certainly drives up the need for producing biofuels domestically. A complementary instrument to the mandate for promoting biofuel industry is subsidies provided in the form of direct payment, tax credits, and loans to the farmers and biorefineries. For example, the federal government established the Biomass Crop Assistance Program (BCAP) to incentivize farmers to grow biomass feedstocks (USDA Farm Service Agency 2014a). Also, biorefineries are eligible for guaranteed low-interest loans from the USDA. These subsidies and assistance programs reduce the barriers for feedstock production and infrastructure investment.

9.3 Models of Biofuel Network Design and Operations

The biofuel industry is an emerging business in which the supply of reliable biomass feedstocks is a crucial part of its supply chain. As a result, a sound logistics network lies in the heart of its design.

In what follows, we introduce a generic biofuel supply chain network design problem, which focuses on optimizing its logistics network from farmers to the final retail outlets. Although the baseline model is simplified and stylized for illustrative purposes, it will serve as a baseline model to understand the core trade-offs and essential features of the problem. We will then discuss more advanced features and issues of the problem by reviewing the recent literature.

9.3.1 Logistics Network

One of the most fundamental trade-offs in a biofuel supply chain network is balancing the transportation costs and facility investments in the optimal distribution network. This includes determining the set of biorefinery locations, decisions of biomass transportation origins and destinations, and bioethanol import and distributions. To better understand the mathematical formulation of the distribution network and to quantitatively facilitate the discussion, we introduce the following simple model as an illustrative example.

Inputs

$i \in I =$ set of all biomass farmland regions
$j \in J =$ set of all candidate biorefinery sites
$k \in K =$ set of all blending terminals
$\ell \in L =$ set of all retail outlets
$c \in C =$ set of biorefinery capacity levels
$h \in H =$ set of bioethanol import countries
$t \in [0, 1, \ldots, T] =$ planning horizon from time 0 to T
$s_i^t =$ biomass crop yield at farmland i at t
$d_\ell^t =$ ethanol demand at outlet ℓ at t
$f_j^{c,t} =$ fixed cost of locating a biorefinery j with capacity c at t
$a_j^c =$ capacity of c at biorefinery j
$g_i^t =$ unit production cost of biomass feedstock at farmland i at t
$p_j^t =$ unit processing cost of biorefinery j at t
$b_k^t =$ unit blending cost of terminal k at t
u_{ij}^t, u_{jk}^t, $u_{k\ell}^t =$ unit transportation cost between two nodes at t
$v_{hk}^t =$ unit import cost of bioethanol from country h to terminal k at t
$\alpha =$ conversion rate of biomass to ethanol

Decision Variables

$X_j^{c,t} = 1$ if a biorefinery of capacity c is located at site j at time t; 0 otherwise
Y_{ij}^t, Y_{jk}^t, $Y_{k\ell}^t =$ biomass (or bioethanol) amount shipped from site i to j (j to k, and k to ℓ, respectively) at t
$Z_{hk}^t =$ bioethanol import amount from country h to terminal k at t

We can formulate the problem as the following mixed-integer linear program, where the biorefinery location (and capacity) decision **X** is defined as a binary variable while transportation/distribution decision **Y** and import amount decision **Z** are defined as non-negative variables:

$$\min \left\{ \sum_{j,t,c} f_j^{c,t} X_j^{c,t} + \sum_{i,j,t} (g_i^t + u_{ij}^t) Y_{ij}^t + \sum_{j,k,t} (p_j^t + u_{jk}^t) Y_{jk}^t \right.$$
$$\left. + \sum_{k,\ell,t} (b_k^t + u_{k\ell}^t) Y_{k\ell}^t + \sum_{h,k,t} v_{hk}^t Z_{hk}^t \right\} \tag{9.1}$$

$$\text{s.t.:} \tag{9.2}$$

$$\sum_j Y_{ij}^t \geq s_i^t, \quad \forall i, t \tag{9.3}$$

$$\sum_k Y_{k\ell}^t \leq d_\ell^t, \quad \forall \ell, t \tag{9.4}$$

$$\sum_j Y_{jk}^t \leq a_j^c X_j^{c,t}, \quad \forall i, t \tag{9.5}$$

$$\sum_i \alpha Y_{ij}^t \leq \sum_k Y_{jk}^t \quad \forall j, t \tag{9.6}$$

$$\sum_j Y_{jk}^t + \sum_h Z_{hk}^t \leq \sum_\ell Y_{k\ell}^t \quad \forall k, t \tag{9.7}$$

$$X_j^t \in \{0, 1\}\ \forall j, t, \quad Y_{ij}^t, Y_{jk}^t, Y_{k\ell}^t, Z_{hk}^t \geq 0,\ \forall i, j, k, \ell, h. \tag{9.8}$$

The objective function (9.1) consists of five terms. The first is the fixed cost associated with opening biorefineries. The next three are the relevant processing/operations and transportation costs for the farmers (planting, growing, harvesting biomass feedstocks and shipping them to biorefineries), biorefineries (converting biomass to bioethanol and shipping it to blending facilities), blenders (blending ethanol with gasoline and distributing it to retail outlets), respectively. The last term is the cost associated with bioethanol import from foreign/external sources. Additional considerations can be given to benefits from co-location of different types of facilities as in Xie and Ouyang (2013).

Constraints (9.3) and (9.7) ensure that biomass supply cannot be greater than the crop yield and the amount of bioethanol distributed to a retailer is not greater than its local demand, respectively. As we will discuss in Sect. 9.3.6, the demand constraint presented in this problem is a stylized one, and a set of more sophisticated market equilibrium constraints can be used to reflect the spatial supply-demand-price relationships (see Bai et al. 2012). Constraints (9.7) restrict the ethanol production level at each candidate site to the biorefinery capacity, if a facility is built. Additional constraints such as capacity or minimum/maximum facility utilization in each stage can be easily implemented. Constraints (9.4) and (9.5) are network balance constraints stipulating that the total inflow (biomass and/or biofuel) cannot be greater than the total outflow at each biorefinery and blending terminal. We note that the above problem assumes a centralized decision making setting covering all entities in the supply chain (farmers, biorefineries, blenders, and retail outlets), and the decision maker plans for the entire design and operations of the supply chain. The final constraints (9.8) stipulate binary condition for the location decision and non-negative constraints for the other decision variables. Whereas this problem can be used as a benchmark example, various levels of decentralized settings (e.g., monopolistic, oligopolistic, perfectly competitive) may need to be considered for studying conflicting objectives; this will be discussed further in Sect. 9.3.5.

Most network design models in the literature are formulated in mathematical programs such as the above, aiming to optimize the network design subject to varying objectives and constraints. Various additional features or specific application focus are also addressed in recent years (e.g., Sokhansanj et al. 2006; Huang et al. 2010; Papapostolou et al. 2011; Akgul et al. 2012). For example, Akgul et al. (2012) propose a strategic modeling framework for designing the supply chain during the transitioning from first-generation biomass to the second generation. Kang et al. (2010) incorporate the distribution of DDGS by-products to live stock farms in addition to the biofuel distribution in designing the distribution network. Chen and Önal (2014) present an extensive dynamic model to determine the biorefinery location along with the biomass supply planning to meet the required biofuel production mandate in the U.S. In general, due to large scale and high complexity, these models are usually challenging to solve within a reasonable time frame (most of which are NP-hard problems), and thus heuristic solution methods are often proposed.

A recent overview of biomass supply chain design models is given in Sharma et al. (2013), which also identifies remaining challenges and potential future work.

9.3.2 Transportation and Inventory Management

High transportation cost for bulky cellulosic biomass feedstocks and dispersed farmland sites pose some of the biggest challenges for commercializing the advanced generation biofuels. Since the choice of transportation mode and its travel distances have great impacts on the economic competitiveness of the biofuel industry (Wakeley et al. 2009), optimizing transportation mode choices and managing biomass inventory are critical to biofuel supply chain operations.

Ekşioğlu et al. (2011), Hajibabai and Ouyang (2013), and Xie et al. (2014) proposed network design models that integrate the multi-modal transportation options into the design. They show that optimizing the choice of transportation mode results in significant cost differentials, compared to the case where truck is the sole transportation mode, due to geographical dispersion of demand and supply. The choice of transportation modes can be formulated by augmenting another dimension to the transportation decision variables, for example, in the illustrative example above, by changing Y_{ij}^{t} to $Y_{ij}^{m,t}$, where $m \in M$ represents the set of available transportation modes. The mode-specific transportation costs can then be defined accordingly.

On a related transportation issue, Bai et al. (2011) study the impact on extra traffic congestion that is induced by the emerging biofuel industry, taking into account operational level decisions such as biomass shipment routing and impacts on public mobility. They demonstrate that the transportation cost along with the public congestion experience can be reduced considerably by integrating transportation congestion patterns into designing biofuel distribution networks.

Oftentimes, biomass feedstocks and ethanol fuels need to be staged for economies of scale, e.g., smaller in-bound shipments are held until there is sufficient out-bound shipment volume in order to take advantage of the larger vehicle capacity. In addition, biomass may need to be inventoried on storages near the refineries and blending facilities to ensure constant and timely supply to the station, hedging against time- and weather-sensitive crop yield. Sokhansanj et al. (2006), Rentizelas et al. (2009), and Huang et al. (2014) explicitly consider such storage inventory decisions and jointly optimize the collection, storage, and transportation of biomass and bioethanol.

9.3.3 Uncertainties

Biofuel supply chains are subject to many uncertainties, which include, but are not limited to, seasonality and random yield of biomass, demand and price fluctuations, and production and logistical uncertainty. Other external factors such as unpredictable regulatory policy changes and technological breakthroughs also make biofuel supply chain management challenging. Awudu and Zhang (2012) discusses various sources of uncertainties in a biofuel supply chain along with possible choices of modeling methodologies. Further, they review the sustainability of the biofuel industry from the economic, social, and environmental perspectives.

Many biofuel supply chain network design models primarily focus on the supply side of uncertainties associated with crop yield and seasonality.

Chen and Fan (2012) and Osmani and Zhang (2013) establish models facing feedstock supply and fuel demand uncertainties in two-stage stochastic optimization models. The stochastic optimization approach allows them to evaluate supply chain performance based on different yield scenarios. For example, in a two-stage stochastic optimization formulation, uncertain yield scenarios $\omega \in \Omega$ can be incorporated into the definition of crop yield $s_i^{\omega,t}$. In the first stage, a set of planning decisions (such as location and size of refineries and storages) are made and, in the second stage, the subsequent operational decisions (such as storage and shipping decisions) are made after the realization of the actual yield. Huang et al. (2014) extend the literature by incorporating the seasonality of feedstock supply in addition to yield variability. Whereas introducing seasonality to the model increases the dimension of the problem (i.e., static vs. dynamic) within each stage, an efficient solution method is also proposed to overcome the complexity of the problem. Xie et al. (2014) also consider both the seasonality and variability of biomass supply, focusing particularly on the choice of cost-effective transportation modes for shipping bulky biomass feedstock and liquid biofuel.

One strategy for mitigating biomass feedstock supply uncertainty is crop mixing, which two or more types of crops are planted simultaneously in the same field in the same planting season. This is to hedge against uncertainties due to abnormal weather or pest conditions, which its impact may be type-specific. Crop mix and feedstock supply issues are carefully studied in Khanna et al. (2011) and Zhu and Yao (2011). Also, a related issue regarding feedstock supply is a crop rotation, i.e., different crop types are rotationally planted in the same field over multiple years. Chen and Önal (2012) discusses the crop mix in relation to crop rotation.

Whereas above studies primarily focus on uncertainties from the supply side, Dal-Mas et al. (2011) study the network design and capacity investment planning problem under uncertain price. They propose a stochastic optimization framework to show how the design and profitability of a supply chain are affected by the market condition (prices of ethanol and by-products). Kostin et al. (2012) investigate the production and storage capacity expansion decision under demand uncertainty. Another source of uncertainty may be from the reliability of the infrastructures themselves. Wang et al. (2015b) and Bai et al. (2015) incorporate the risk of biorefinery disruptions (e.g., due to flooding) in planning biofuel supply chain networks.

9.3.4 Land Use Change and Competition

One critical side effect that comes with the rapid development of biofuel industry is direct and indirect land use change. As farmers respond to high biomass prices due to government mandates and subsidies, which will be discussed in the next subsection, more farmland is diverted to biomass feedstock production. Such land use change represents a shift away from food production, and in turn, conversion of more pristine lands such as rainforests and grasslands into farmlands.

The series of direct and indirect land use changes have raised a global concern. First, farmland competition between the food and biomass has led to the so-called "food vs. energy" dilemma. Indeed, accompanying the rapid expansion of biofuel industry, the food price worldwide has increased significantly (Wall Street Journal 2012a,b). For example, corn grain price in the U.S. increased from as low as \$1.5/bushel in 2000 to as high as \$7.1/bushel in 2013 (Dairy Marketing and Risk Management 2014), during the time period in which the corn was one of the main feedstocks to bioethanol production. In addition, land use change can potentially lead to negative environmental and ecological consequences such as increased GHG emissions, intensified soil erosion, and reduced wild animals' habitat. The potential negative impacts have been cautioned by many studies (e.g., Searchinger et al. 2008; Fargione et al. 2008; Inderwildi and King 2009; Lapola et al. 2010), posing controversies over the biofuel industry; for example, Searchinger et al. (2008) suggest that, in contrast to the commonly believed myth, bioethanol may nearly double the GHG emissions as compared to that of gasoline, since the increase in the farmland for biocrops production will accelerate the clearance of wilderness. Lapola et al. (2010) also show that biofuel cultivation in the Amazonian forests can offset the carbon savings from biofuels, resulting in a net loss in the environmental welfare.

In the face of increased land use competition, studies have examined ways to sustainably nurture the biofuel industry while protecting food security and environmental sustainability. To understand the impact of biofuel production to land use, Rathmann et al. (2010) propose a cause-and-effect framework based on the current state of research and arguments on land use competition. Khanna and Crago (2012) review various modeling schemes to measure the impacts of land use changes and discuss the key factors that can influence the assessment. They further discuss the challenges in implementing policies to address the land use change. Focusing specifically on Brazil and the U.S., the two largest ethanol producing countries, Nuñez et al. (2013) examine how land use changes affect the food and biofuel economy. Using an optimization model that endogenizes price, they analyze the impacts of government mandates and commodity trades on domestic and global markets as well as land use in various scenarios.

The farmland use competition in the context of biofuel supply chains is typically captured by formulation into a bi-level optimization problem, or one with equilibrium constraints (e.g., Bai et al. 2012; Wang et al. 2015b). That is, instead of the centralized decision making process in Sect. 9.3.1, the decisions are made by multiple decision makers (simultaneously or sequentially) from upstream to downstream of the supply chain. Hence, for example, farmers sometimes may need to make the land use decision in advance of the biorefineries making the production quantity decision. Using game theoretic models of Stackelberg and/or Nash equilibrium concepts to characterize farmers' land use choice (between growing food and biomass crops) and the resulting feedstock market equilibrium, Bai et al. (2012) and Wang et al. (2013) formulate a biofuel manufacturer's supply chain design model to provide insights on optimal land use strategies and supply chain design. Extended view of farmland competition may also include an "environmental market" in addition to food and biofuel markets. For example, the U.S. Department of Agriculture recommends retiring farmlands from agricultural activities for an extended period of time for environmental preservation and preservation of land quality (USDA Farm Service Agency 2014b). Such an environmental consideration aggravates the land use competition and leads to a farmland use trilemma among food, energy, and environment (Tilman et al. 2009). Wang et al. (2015a) consider this farmland allocation trilemma problem and study the role of governmental policies for stimulating the growth of the emerging biofuel industry and its supply chain in lieu of the incumbent food and environmental markets.

9.3.5 Environmental and Social Impacts

Closely related to the land use change issue are the environmental and social issues accompanied by the biofuel industry development. Such considerations have been integrated into the biofuel supply chain design with the objective of mitigating adverse environmental and social impacts while improving economic efficiency as well as social welfare. This comprehensive approach follows the triple-bottom-line perspective in the sustainable operations management.

One prevalent approach for assessing environmental and societal impacts is via life cycle assessment, which evaluates those impacts over each stage of the supply chain, from its production to distribution to consumption. Using this approach, You et al. (2011) construct a multi-objective optimization model and analyze the trade-offs between three objectives throughout the lifetime of the supply chain: minimizing the sum of supply chain design and operations costs, minimizing GHG emissions, and maximizing accrued local jobs in a regional economy. Such a multi-objective problem can be transformed into one with a single objective by aggregating multiple objectives with proper weights based on the decision maker's utility.

In a similar vein, Giarola et al. (2012) and Gebreslassie et al. (2013) also consider the supply chain design problems with different model features, the former incorporating the carbon trading effect and the latter focusing on a specific feedstock from hybrid poplar (hence, considering some variations in its supply chain). Wang et al. (2015a) define the social welfare as the aggregate of consumer surpluses in food, energy, and environmental markets, and design a tax and subsidy mechanism for each land use purpose to induce the optimal spatial farmland use pattern that maximizes the social welfare.

9.3.6 Governmental Policies

Government plays a critical role in the biofuel industry, as it regulates and incentivizes the industry through various policy instruments. In the U.S., mandates (e.g., RFS) and subsidies (e.g., BCAP) are the two representative instruments in place. While the mandate and subsidies can be easily implemented in the supply chain model formulation (for example, mandate can be simply reflected with a constraint requiring the total influx to blender to exceed the mandate value; subsidy can be reflected by adjusting various costs for the corresponding entity), there are advanced models that incorporate these instruments to derive further implications to the biofuel supply chain. To carefully capture the impact of supply and demand subject to mandate and subsidies, instead of using a stylized demand constraint such as (9.4), the advanced models typically formulate the demand (and price) to be endogenously determined from market equilibrium (e.g., Wang et al. 2013, 2015a; Zhang et al. 2013). This, however, results in mathematical programs with equilibrium constraints (MPEC) which often require efficient solution methods.

A mechanism for enforcing the mandated biofuel production in the U.S. is the Renewable Identification Number (RIN), which requires the biofuel production companies to meet certain volumetric quotas each year. A company's RIN quota can be sold and traded to others, similar to the cap-and-trade mechanism in the emission permits. Incorporating the tradable RIN quotas, Wang et al. (2013) investigates its impact on the biofuel supply chain design. One interesting finding is that a rigid mandate (i.e., flat rate penalty for defaulting the mandates) may lead to a reduction in the total biofuel production, and hence policy makers should be cautioned about the importance of mandate level choices. In Zhang et al. (2013), RIN is considered along with subsidies offered to different entities in the supply chain (farmer, producer, and blender). Wang et al. (2015a) address the coordination issues of mandate and subsidy in the biofuel industry.

Focusing specifically on the environmental policy side, Palak et al. (2014) consider the carbon regulatory mechanisms for reducing GHG emissions. Considering regulatory policies such as carbon cap, tax, and cap-and-trade, they provide insights on the impacts of each potential policy on the biofuel supply chain. Khanna and Crago (2012) and Nuñez et al. (2013) discuss implications for land use policy.

9.4 Conclusion

Biofuel is an alternative energy fuel that is converted from naturally grown renewable resources. With compelling benefits and potential over the economic, environmental, and social dimensions, it is deemed as one of the most promising and ideal alternatives for transportation fuel. To this end, governments around the world, including the U.S., are strongly supporting the development of biofuel production with various policies and regulations including mandate and subsidy programs. In the last decade, from 2003 to 2013, global biofuels production has increased from 14.7 billion tons per year in 2003–65.3 billion in 2013. The increase in the U.S. was even steeper as it grew from 5.2 billion to 28.4 billion during the same time period British Petroleum (2014).

While technological and engineering advancements are key to the success of biofuel industry, providing an efficient and reliable supply chain network design and operations is another critical component to its success. This chapter provides an introduction to the nascent biofuel production industry and key features and issues of its biofuel supply chain. Starting from a basic supply chain design model, we review fundamental trade-offs and the main design and operational issues that rise in a biofuel supply chain and the related economic, social, and environmental contexts. In addition, we provide literature review of recent modeling studies related to the biofuel supply chain design. Finally, we discuss how various operational challenges and policy considerations related to agricultural production, industry manufacturing, market mechanisms, and government regulations are addressed in the recent modeling literature.

References

Akgul O, Shah N, Papageorgiou LG (2012) Economic optimisation of a UK advanced biofuel supply chain. Biomass Bioenerg 41:57–72

Alexander P, Moran D (2013) Impact of perennial energy crops income variability on the crop selection of risk averse farmers. Energ Policy 52:587–596

Awudu I, Zhang J (2012) Uncertainties and sustainability concepts in biofuel supply chain management: a review. Renew Sust Energ Rev 16(2):1359–1368

Bai Y, Hwang T, Kang S, Ouyang Y (2011) Biofuel refinery location and supply chain planning under traffic congestion. Transp Res B Methodol 45(1):162–175

Bai Y, Ouyang Y, Pang JS (2012) Biofuel supply chain design under competitive agricultural land use and feedstock market equilibrium. Energy Econ 34(6):1623–1633

Bai Y, Li X, Peng F, Wang X, Ouyang Y (2015) Effects of disruption risks on biorefinery location design. Energies 8(2):1468–1486

British Petroleum (2014) BP Statistical Review of World Energy (2014). http://www.bp.\penalty0com/content/dam/bp/pdf/Energy-economics/statistical-review-2014/BP-statistical-review-of-world-energy-2014-full-report.pdf

Chen CW, Fan Y (2012) Bioethanol supply chain system planning under supply and demand uncertainties. Transp Res E: Log Transp Rev 48(1):150–164

Chen X, Önal H (2012) Modeling agricultural supply response using mathematical programming and crop mixes. Am J Agric Econ 94(3):674–686

Chen X, Önal H (2014) An economic analysis of the future U.S. biofuel industry, facility location, and supply chain network. Transp Sci 48(4):575–591

Dairy Marketing and Risk Management (2014) Price received for corn grain. Department of Agricultural and Applied Economics, University of Wisconsin. http://future.aae.wisc.edu/\penalty0data/\penalty0annual_values/by_area/2052?tab=feed

Dal-Mas M, Giarola S, Zamboni A, Bezzo F (2011) Strategic design and investment capacity planning of the ethanol supply chain under price uncertainty. Biomass Bioenerg 35(5):2059–2071

Ekşioğlu SD, Li S, Zhang S, Sokhansanj S, Petrolia D (2011) Analyzing impact of intermodal facilities on design and management of biofuel supply chain. Transp Res Rec 2191:144–151

Energy Independence and Security Act (2007) Public Law. 110–140 http://www.gpo.gov/\penalty0fdsys/\penalty0pkg/PLAW-110publ140/html/PLAW-110publ140.htm

Environmental Protection Agency (2014) Renewable fuels: regulations and standards. http://\penalty0www.\penalty0epa.gov/otaq/fuels/renewablefuels/index.htm

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319(5867):1235–1238

Gebreslassie BH, Slivinsky M, Wang B, You F (2013) Life cycle optimization for sustainable design and operations of hydrocarbon biorefinery via fast pyrolysis, hydrotreating and hydrocracking. Comput Chem Eng 50:71–91

Giarola S, Shah N, Bezzo F (2012) A comprehensive approach to the design of ethanol supply chains including carbon trading effects. Bioresour Technol 107:175–185

Hajibabai L, Ouyang Y (2013) Integrated planning of supply chain networks and multimodal transportation infrastructure expansion: model development and application to the biofuel industry. Comput-Aided Civ Infrastruct Eng 28(4):247–259

Huang Y, Chen CW, Fan Y (2010) Multistage optimization of the supply chains of biofuels. Transp Res E: Log Transp Rev 46(6):820–830

Huang Y, Fan Y, Chen CW (2014) An integrated biofuel supply chain to cope with feedstock seasonality and uncertainty. Transp Sci 48(4):540–554

Inderwildi OR, King DA (2009) Quo vadis biofuels? Energy Environ Sci 2:343–346

Jenkins B, Parker N, Tittman P, Hart Q, Cunningham J, Lay M (2008) Strategic development of bioenergy in the western states. Available online. http://www.westgov.org/component/\penalty0docman/\penalty0doc_download/183-strategic-development-of-bioenergy-spatial-analysis?Itemid=

Kang S, Önal H, Ouyang Y, Scheffran J, Tursun D (2010) Optimizing the biofuels infrastructure: transportation networks and biorefinery locations in Illinois. In: Khanna M et al (eds) Natural resource management and policy, vol 33. Springer, Berlin

Khanna M, Crago CL (2012) Measuring indirect land use change with biofuels: implications for policy. Ann Rev Resour Econ 4:161–184

Khanna M, Chen X, Huang H, Önal H (2011) Supply of cellulosic biofuel feedstocks and regional production pattern. Am J Agric Econ 93(2):473–480

Kostin AM, Guillén-Gosálbez G, Mele FD, Bagajewicz MJ, Jiménez L (2012) Design and planning of infrastructures for bioethanol and sugar production under demand uncertainty. Chem Eng Res Des 90(3):359–376

Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, Koelking C, Priess JA (2010) Indirect land-use changes can overcome carbon savings from biofuels in Brazil. Proc Natl Acad Sci USA 107(8):3388–3393

National Research Council of the National Academies (2011) Renewable fuel standard: potential economic and environmental effects of U.S. biofuel policy. National Academies Press, Washington, DC

Nuñez HM, Önal H, Khanna M (2013) Land use and economic effects of alternative biofuel policies in Brazil and the U.S. Agric Econ 44:487–499

Osmani A, Zhang J (2013) Stochastic optimization of a multi-feedstock lignocellulosic-based bioethanol supply chain under multiple uncertainties. Energy 59:157–172

Palak G, Ekşioğlu SD, Geunes J (2014) Analyzing the impact of carbon regulatory mechanisms on supplier and mode selection decision: an application in biofuel supply chain. Int J Prod Econ 154:198–216

Papapostolou C, Kondili E, Kaldellis JK (2011) Development and implementation of an optimisation model for biofuels supply chain. Energy 36(10):6019–6026

Rentizelas AA, Tolis AJ, Tatsiopoulos IP (2009) Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renew Sust Energ Rev 28(4):887–894

Rathmann R, Szklo A, Schaeffer R (2010) Land use competition for production of food and liquid biofuels: an analysis of the arguments in the current debate. Renew Energ 35(1):14–22

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319(5867):1238–1240

Sharma B, Ingalls RG, Jones CL, Khanchi A (2013) Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future. Renew Sust Energ Rev 24:57–72

Shastri Y, Hansen A, Rodriquez L, Ting KC (2014) Engineering and science of biomass feedstock production and provision. Springer, New York

Sokhansanj S, Kumar A, Turhollow AF (2006) Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass Bioenerg 30(10):838–847

Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C, Williams R (2009) Beneficial biofuels – the food, energy, and environment trilemma. Science 325(5938):270–271

U.S. Department of Energy (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge National Laboratory. http://www1.eere.energy.gov/bioenergy/pdfs/final_billionton_vision_report2.pdf

U.S. Department of Energy (2011) U.S. Billion-ton update. Oak Ridge National Laboratory. http://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf

U.S. Energy Information Administration (2014) Data for petroleum and other liquids. http://\penalty0www.\penalty0eia.gov/petroleum/data.cfm

USDA Farm Service Agency (2014a) Biomass Crop Assistance Program. http://www.fsa.usda.gov/\penalty0FSA/\penalty0webapp?area=home&subject=ener&topic=bcap

USDA Farm Service Agency (2014b) Conservation Reserve Program Participant Information: CRP. http://www.fsa.usda.gov/FSA/webapp?area=home&subject=copr&topic=crp

Wakeley HL, Hendrickson CT, Griffin WM, Matthews HS (2009) Economic and environmental transportation effects of large-scale ethanol production and distribution in the United States. Environ Sci Technol 43(7):2228–2233

Wall Street Journal (2012a) The ethanol election delay. http://online.wsj.com/article/SB10001424052970203922804578080950339799518.html

Wall Street Journal (2012b) A mandate to raise food prices. http://online.wsj.com/article/SB10001424127887323713104578133571463805826.html

Wang XL, Ouyang Y, Yang H, Bai Y (2013) Optimal biofuel supply chain design under consumption mandates with renewable identification numbers. Transp Res B Methodol 57:158–171

Wang X, Lim MK, Ouyang Y (2015a) Food, energy, and environment trilemma: sustainable farmland use and biofuel industry development. University of Illinois. Available via SSRN. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2268688

Wang X, Lim MK, Ouyang Y (2015b) Infrastructure deployment under uncertainties and competition: the biofuel industry case. Transp Res Part B 78:1–15

Xie W, Ouyang Y (2013) Dynamic planning of facility locations with benefits from multi-type facility co-location. Computer-Aided Civ Infrastruct Eng 28(9):666–678

Xie F, Huang Y, Ekşioğlu SD (2014) Integrating multimodal transport into cellulosic biofuel supply chain design under feedstock seasonality with a case study based on California. Bioresour Technol 152:15–23

You F, Tao L, Graziano DJ, Snyder SW (2011) Optimal design of sustainable cellulosic biofuel supply chains: multiobjective optimization coupled with life cycle assessment and input-output analysis. AIChE J 58(4):1157–1180

Zhang L, Hu G, Wang L, Chen Y (2013) A bottom-up biofuel market equilibrium model for policy analysis. Ann Oper Res. doi:10.1007/s10479-013-1497-y

Zhu X, Yao Q (2011) Logistics System design for biomass-to-bioenergy industry with multiple types of feedstocks. Bioresour Technol 102(23):10936–10945

Chapter 10
Capacity Investment Decisions in Renewable Energy Technologies

Mark E. Ferguson, Shanshan Hu, Gilvan C. Souza, and Wenbin Wang

Abstract We study an organization's one-time capacity investment in a renewable technology with supply intermittency and net metering compensation. The renewable technology can be coupled with conventional technologies, such as purchasing electricity from the grid, to form a capacity portfolio that is used to meet stochastic demand for energy. Some factors that complicate this decision include the variability in the energy demand, energy prices, compensation for over-production by the energy producing technology and the intermittency of renewable energy producing technologies. We show how to reduce this problem to a single-period decision problem, and how to estimate the joint distribution of the stochastic factors using historical data. We obtain solutions that are simple to compute, intuitive, and provide managers with a framework for evaluating the trade-offs of investing in renewable and conventional technologies. We illustrate our model using a case study for investing in a solar rooftop system for a bank branch.

M.E. Ferguson (✉)
Management Science Department, University of South Carolina, Columbia, SC, USA
e-mail: mark.ferguson@moore.sc.edu

S. Hu • G.C. Souza
Department of Operations and Decision Technologies, Kelley School of Business, Indiana University, Bloomington, IN 47405, USA
e-mail: hushsh@indiana.edu; gsouza@indiana.edu

W. Wang
Department of Operations Management, School of International Business Administration, Shanghai University of Finance and Economics, Shanghai, China
e-mail: wang.wenbin@shufe.edu.cn

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_10

10.1 Introduction

In this chapter we summarize a decision making framework introduced in Hu et al. (2015) for determining the most profitable amount of renewable energy producing capacity to install for a single location of energy consuming (non-power plant) facility such as a bank branch, retail store or office building. While our decision making framework will apply to a large number of applications, the example we use throughout this chapter is an individual bank branch of a large financial services firm such as Wells Fargo. More specifically, we will focus on a Wells Fargo bank branch located in Los Angeles, CA. As discussed in Ovchinnikov and Hvaleva (2013). Wells Fargo is interested in installing solar panels at each of its numerous bank branches located across the United States. While Ovchinnikov and Hvaleva (2013) focus on the timing of when these solar panel investments should be made, our focus, instead, is on the decision that follows once the decision has been made to make a solar energy panel investment—exactly how many panels should be installed on each individual bank branch. There are several aspects to this problem that must be considered.

First, the electricity demand for most properties is highly variable. This variability may be yearly (seasonal patterns related to different heating or cooling needs), weekly, daily and even hourly. In addition, the energy demand may be non-stationary over time, with either an increasing or decreasing trend. Thus, it is not immediately clear what level of energy demand aggregation should be used when determining how much energy producing capacity to procure.

Second, there is also substantial volatility in energy prices. For example, electricity prices in the California market exhibit a clear monthly seasonality as well as a steady upward trend. Future monetary savings of replacing a conventional technology with a renewable one, such as a rooftop solar system to replace buying electricity from the grid, should take these price variabilities into account.

Third, there are often incentives provided by federal and state governments, such as investment rebates and Net Energy Metering (NEM) programs, that are intended to increase the viability of renewable technologies. In a NEM program, a facility that generates renewable energy on site can sell surplus electricity, in excess of demand, back to the grid. Because some states offer NEM while others do not, the presence or absence of NEM causes the optimal capacity decisions for renewable technologies to vary significantly between states. Moreover, with NEM, installers of renewable energy technologies can reduce their energy costs when their energy demand exceeds their supply as well as generate revenue when their supply exceeds their demand. As with energy prices, the actual NEM rates may be variable and non-stationary over time.

Fourth, renewable energy producing technologies such as solar and wind generation present supply intermittency, which has consequences for serving energy demand. As with the energy demand, there is both daily and monthly seasonality in the solar radiation yield and solar radiation does not always peak at the same time periods as the demand for electricity does. Although it is technically possible to store solar energy for later use using batteries, the current energy storage technology is rarely cost effective for small installations such as the rooftop systems used in Wells Fargo bank branches.

In the next section, we start with an intentionally simplistic scenario of a hypothetical investment in a nonrenewable energy producing technology to help build the intuition behind our renewable technology investment model. We include the first three complications in this analysis, as they are also present in nonrenewable technology investments. We then expand our model to include the fourth complication (intermittency of supply) to demonstrate how the problem and solution changes when renewable energy technologies are considered. The investment decision for the nonrenewable technology is not intended to represent a real scenario, but rather to demonstrate the similarities and differences between investment decisions for renewable versus nonrenewable technologies.

10.2 Investment Decision of a Nonrenewable Energy Producing Technology

In many ways, the capacity investment decision for renewable energy is similar to a capacity investment decision of any other technology. We will first focus on these similarities before discussing the major differences. While this is not typically the case for most areas around the world, imagine for a moment a scenario where the cost of buying electric power from the local power plant (or the grid) is more expensive than the cost of supplying electric power from a natural gas generator. In such a hypothetical world (and assuming no other energy producing options), it would be financially prudent to install a natural gas generator outside of every Wells Fargo branch. The initial investment for a natural gas generator depends on the maximum energy production capacity of the generator, i.e. a 1000 kW generator costs more than a 500 kW generator. Once purchased, the generators consume natural gas in order to produce energy, so there is both a fixed and a marginal cost of producing energy through this means. To justify this cost, there must be an accompanying reduction in the cost of purchasing electricity from the grid.

The decision of how much generator capacity should be added would be a relatively straightforward one if the electricity demand from the bank branch was constant each day. For example, suppose the bank branch is open from 8 a.m. to 5 p.m. each day and that there is no electricity demand when the branch is not open. Also assume that the electricity demand throughout the 8 a.m.–5 p.m. day is constant at 10 kWh. Suppose that the price from purchasing electricity from the grid is also constant at \$1/kWh so that the total cost per day is 10 kW × 9 h/day × \$1/kWh = \$90/day. The branch has the opportunity to purchase a natural gas generator that can be used to reduce (or eliminate) the need to purchase electric power from the grid. Suppose the marginal cost of producing power (cost of buying natural gas) for the generator is also constant at \$0.50/kWh. This marginal cost represents the cost of buying natural gas to run the generator; any maintenance and depreciation costs should be added to this figure by amortizing them into an hourly rate. More specifically, suppose a natural gas generator loses \$100 of its value each year due to depreciation and it also requires an additional \$100/year in preventive maintenance in order to operate at its maximum output. It is reasonable to assume that both of these costs vary with the usage of the generator, as a generator that is used more requires more maintenance and depreciates faster than one that is used less. Thus, the combined cost of \$200/year can be amortized over the 9 h/day times 260 days/year that the branch is open, resulting in an additional \$0.086/kWh (200/(9 × 260)). Combining these cost results in a marginal cost of using the generator of \$0.586/kWh. Because we have assumed (for now) that all of these input variables are constant, Wells Fargo faces an easy business decision of how large of a generator to buy for the branch: they should buy a generator that can produce exactly 10 kWh as long as the discounted savings obtained from using the cheaper power provided by the generator provides an acceptable return on investment from the fixed cost of purchasing the generator.

Let's generalize our problem by adding some notation. The model we are building can be thought of as a capacity investment problem with random demands in a T-period planning horizon. The firm decides on the optimal capacity investment level for the technology at the beginning of period $t = 1$ while the planning horizon T corresponds to the the capacity's lifespan. The lifespan of the technology may be determined by its physical lifespan or by an accounting rule. For ease of exposition, we assume that the residual value of the technology is zero at the end of period T but positive residual values can easily be incorporated simply by deducting the discounted expected residual value from the initial investment cost.

To build one unit of capacity of the technology, the firm incurs an initial investment V. In addition, each unit of capacity incurs maintenance costs per period v^{mat} throughout its lifespan T. Let δ represent the discount factor per period and denote $v = V + \sum_{t=1}^{T} \delta^t v^{\mathrm{mat}}$ as the per unit investment cost of capacity, which is equal to the initial investment plus the net present value of future maintenance costs per unit.

Random demand in period t is denoted by X_t. In the Wells Fargo example, X_t is the number of kWh required to meet electricity demand in period t. In addition, denote w as the fuel cost per unit of capacity in period t, which is assumed to be constant. The firm's decision variable is the amount of capacity to purchase, k. With random demand, there may be occasions where the generating capacity of the technology is greater than the demand. In such cases, assume the firm can sell excess energy back to the grid. Such arrangements are common for renewable technologies but the actual rate the utility is required to pay for the excess energy varies by state. Assume for now that there is such an offering for nonrenewable technology as well, through the use of NEM compensation: power generated in excess of demand in a given period t is returned to the grid, and the consumer is credited at a rate of M_t per unit (say, kWh). In reality, NEM compensation is only made available for excess demand produced by renewable energy technology but we are ignoring this detail for this example to help build our intuition. If there is unmet demand in any period, the firm can source energy from the spot market at a random cost P_t. Thus, a firm facing uncertainty in its energy needs and investing in energy-producing technology faces a cost for having too much capacity as well as a cost for not having enough.

Denote by $\mathbf{Y}_t = \{X_t, M_t, P_t\}$ the vector of stochastic processes. Total operating cost to meet demand at period t is

$$C\left(k; \mathbf{Y}_t\right) = wk + P_t\left(X_t - k\right)^+ - M_t\left(k - X_t\right)^+. \tag{10.1}$$

The firm's cost-minimization problem is then:

$$\min \mathscr{C}(k), \quad \text{where} \quad \mathscr{C}(k) = \sum_{t=1}^{T} \delta^{t-1} \cdot \mathsf{E}_{\mathbf{Y}_t}\left[C(k, \mathbf{Y}_t)\right] + vk. \tag{10.2}$$

10.2.1 Conversion to a Single-Period Problem

The multi-period problem described in the section above is a bit inconvenient because solving it requires advanced multi-period optimization techniques such as dynamic programming. To make our problem more amiable to practicing managers, we now transform the multi-period cost function into an equivalent single-period function by appropriately modifying the probability distributions. The main idea is to construct a new random vector $\mathscr{Y}$ by mixing the different random vectors $\{\mathbf{Y}_t\}_{t=1}^{T}$ with so-called "discounting probabilities" for different periods. We present here the main idea, and the details are provided by Hu et al. (2015).

First, we rewrite expression (10.2) as

$$\mathscr{C}(k) = \left(\sum_{m=1}^{T} \delta^{m-1}\right) \cdot \sum_{t=1}^{T} \frac{\delta^{t-1}}{\sum_{m=1}^{T} \delta^{m-1}} \mathsf{E}_{\mathbf{Y}_t}\left[C(k; \mathbf{Y}_t)\right] + vk. \tag{10.3}$$

Next, we define a discrete random variable Γ which takes the value of $t \in \{1, 2, \ldots, T\}$ with $r_t \doteq \delta^{t-1} / \sum_{m=1}^{T} \delta^{m-1} = (1-\delta)\delta^{t-1}/(1-\delta^T)$. Then, we define a mixture of random vectors $\mathscr{Y}$ to be a random sample of $\mathbf{Y}_1, \ldots, \mathbf{Y}_T$, where $\mathbf{Y}_t$ is selected with "probability" r_t. Hu et al. (2015) show that (10.3) can be rewritten as:

$$\mathscr{C}(k) = \frac{1-\delta^T}{1-\delta} \cdot \left(\mathsf{E}_{\mathscr{Y}} \left[C(k; \mathscr{Y}) \right] + \frac{1-\delta}{1-\delta^T} vk \right).$$

Define $a = ((1-\delta)/(1-\delta^T))v$ as the per-period allocation of the investment cost v. We label a as the acquisition cost for the technology. Because $(1-\delta^T)/(1-\delta)$ is simply a scalling factor, the firm decides on k that minimizes its single-period objective function:

$$\mathscr{C}(k) = \mathsf{E}_{\mathscr{Y}} \left[C(k; \mathscr{Y}) \right] + ak. \tag{10.4}$$

We provide an example of how to estimate the joint distribution of $\mathscr{Y}$ in practice using the Wells Fargo application in Sect. 10.2.2. We use the equivalent single-period formulation (10.4), and drop the time indices. Now, for the random variables X, M, and P, the marginal cumulative distribution functions (cdfs) are denoted by $F_X(\cdot)$, $F_M(\cdot)$, and $F_P(\cdot)$, with means μ_x, μ_m, and μ_p, respectively. These marginal distributions can be obtained from the joint distribution of $\mathscr{Y} = (X, M, P)$; we provide more details in the Wells Fargo application in Sect. 10.2.2.

Using (10.1), the objective function (10.4) can now be written as

$$\mathscr{C}(k) = (a+w)\,k + \mathsf{E}\left[P(X-k)^+\right] - \mathsf{E}\left[M(k-X)^+\right]. \tag{10.5}$$

The objective function is convex in k. The optimal capacity decision of the renewable energy technology k^* is given by the unique solution to the equation:

$$\mathsf{E}[M \cdot \mathbf{1}_{\{X<k^*\}}] + \mathsf{E}[P \cdot \mathbf{1}_{\{X \geq k^*\}}] = a + w. \tag{10.6}$$

The optimality condition (10.6) can be viewed as a generalized newsvendor solution with random unit retail price and random salvage value. In the classic newsvendor model, a retailer builds inventory Q to meet stationary but random demand X, with unit retail price π, unit acquisition cost c, and unit salvage value of s. The optimal Q^* satisfies $sF_X(Q^*) + \pi(1 - F_X(Q^*)) = c$, where the left-hand side is the expected marginal revenue of an extra unit of inventory and the right-hand side is the marginal acquisition cost of that unit. Equation (10.6) has a similar interpretation. Note that, when solving Eq. (10.6), a numerical search is necessary as k^* is embedded implicitly on the left-hand side of the equation.

10.2.2 Example Application: Decision of Generator Capacity at a Bank Branch

We illustrate the use of our model to optimize Wells Fargo's investment in a natural gas generator system given the demand shown in Fig. 10.1.

10.2.2.1 Dataset

The planning horizon is 30 years, representing the lifespan of a generator. The operating cost w for a generator is 0.04/kWh. There are three stochastic processes as inputs to the model: Demand $\{X_t\}$, electricity prices $\{P_t\}$ from the grid, and NEM compensation rates $\{M_t\}$. We have obtained electricity demand data for a Wells Fargo branch in Los Angeles, CA, in 15-min intervals, for an entire year. It is expected that electricity demand for this branch will be stationary during the planning horizon. Second, we obtained the monthly retail electricity rates for commercial users in California as shown in Fig. 10.2. Finally, the NEM compensation rate is regulated and relatively stable so we assumed that its ratio to the grid electricity price is maintained at the current value of 0.33 for California (PG&E 2014). Hence, the NEM compensation rates increase annually, along with the annual average electricity prices.

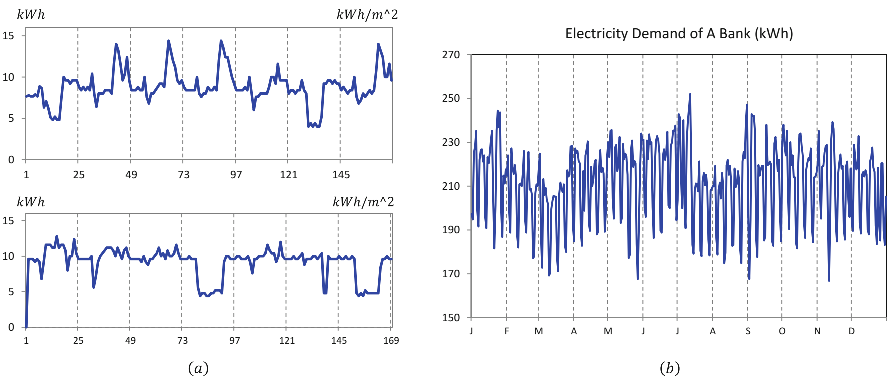

Fig. 10.1 Hourly and daily electricity demand at a Wells Fargo branch in Los Angeles (Note: The *left figure* displays the hourly electricity consumption for a typical winter week on *top* (01/01/2013–01/07/2013) and a typical summer week on *bottom* (07/01/2013–07/07/2013). In the *right figure*, we plot aggregate daily demand.) (**a**) Hourly electricity demand. (**b**) Daily electricity demand

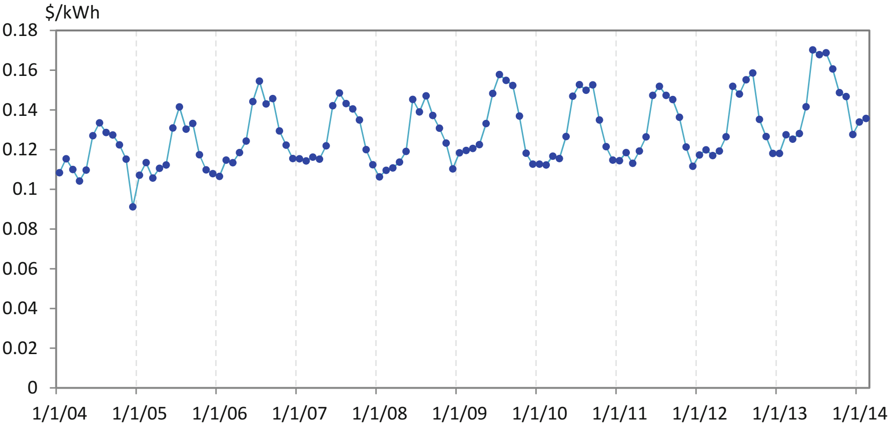

Fig. 10.2 Monthly retail electricity prices for commercial users in California

The annual discount rate for Wells Fargo is 3.5 %, which results in an annual discount factor of $\delta = 0.965$. In our calculations, we discount on a yearly basis so that all costs within the same year are discounted by the same factor.

10.2.2.2 Construction of $\mathscr{Y}$

We next construct the distribution of $\mathscr{Y}$. We first explain how to construct the electricity price process $\{P_t\}$ based on our 10-year historical monthly data. Three independent random variables P_A, P_B, and P_C are constructed to capture the trend, monthly seasonality and random shocks of the electricity prices in the planning horizon. We first estimate the annual trend by regressing the annual averages of historical prices over time (ten observations), and then use the regression equation to project the price trend for the next 30 years. The 30 projected values are used as the possible realizations of P_A, and their probability masses are $\mathbf{r} = \{1/\sum_{t=0}^{29} \delta^t, \delta/\sum_{t=0}^{29} \delta^t, \ldots, \delta^{29}/\sum_{t=0}^{29} \delta^t\}$, corresponding to r_t defined in Eq. (10.3). To construct the monthly seasonality component P_B, we remove the trend from the historical observations so that the residuals only contain monthly seasonality and the random shocks. We estimate the monthly seasonality by averaging all residuals for the same month in the past 10 years. The 12 averages obtained are the realizations of P_B, and each has a probability mass of 1/12. This procedure guarantees that P_C has a mean of zero, and, as as a result, it does not impact the optimal value of k^*, as shown in Hu et al. (2015). The NEM compensation rate is set as $M = 0.33P_A$ as explained before.

For the probability distribution of demand, we build a different empirical distribution for each month (due to the monthly seasonality), with 20 "buckets". The probability of each bucket is simply the proportion of demand observations in that month that fall into that bucket. The joint distribution of $\mathscr{Y} = (P, X, M)$ can now be generated: there are 30 annual indices for trend, 12 monthly indices for seasonality, and, for each month, 20 buckets of demand. This results in $30 \times 12 \times 20$ combinations, with each probability equal to the product of the three corresponding individual probabilities.

The unit investment cost for a generator at this branch is $v = \$450/\text{kW}$. This cost is the sum of upfront investment cost, NPV of lifetime insurance cost, fixed cost for maintenance, and so forth. Multiplying this value by the allocation adjustment ratio $(1-\delta)/(1-\delta^{30})$ results in $a = \$24/\text{kW}$. Solving Eq. (10.6) using Excel Solver, the optimal PV capacity is $k^* = 9.6\,\text{kW}$. Our entire solution approach is implemented in Excel, and available from the authors upon request.

10.3 Investment of Energy-Producing Renewable Technology

In this section, we now consider the setting where the firm plans a one-time capacity investment k in a single renewable energy technology, such as wind or solar power, which is used to serve stochastic energy demand X_t in each period t. This setting applies to the case of Wells Fargo evaluating a PV system to generate electricity for one of its branches. In order to capture the supply intermittency impact of renewable energy producing technology, a typical period length needs to be around 15 min.

The effective capacity in any period is random to account for supply intermittency; denote the yield rate in period t by $\Lambda_t \in [0, 1]$, and so the effective capacity in period t is $\Lambda_t k$. As before, there is a unit operating cost w per period, which could be negligible for renewable energy technology. As before, power generated in excess of demand in a given period t is returned to the grid, and the consumer is credited at a rate of M_t per unit (say, kWh) due to the NEM compensation. As before, if there is unmet demand in any period, the firm can source energy from the spot market at a random cost P_t.

Now $\mathbf{Y}_t = \{X_t, \Lambda_t, M_t, P_t\}$. Total operating cost to meet demand at period t is

$$C\left(k; \mathbf{Y}_t\right) = w\Lambda_t k + P_t\left(X_t - \Lambda_t k\right)^+ - M_t\left(\Lambda_t k - X_t\right)^+. \tag{10.7}$$

The firm's cost-minimization problem is given, as before, by (10.2).

10.3.1 Conversion to a Single-Period Problem

As with the nonrenewable technology capacity decision, we transform the multi-period cost function into an equivalent single-period function by appropriately modifying the probability distributions. As before, we use the equivalent single-period formulation (10.4), and drop the time indices. Now, for the random variables X, Λ, M, and P, the marginal cumulative distribution functions (cdfs) are denoted by $F_X(\cdot)$, $F_\Lambda(\cdot)$, $F_M(\cdot)$, and $F_P(\cdot)$, can be obtained from the joint distribution of $\mathscr{Y} = (X, \Lambda, M, P)$.

Using (10.7), the objective function (10.4) can now be written as

$$\mathscr{C}(k) = (a + w\mathsf{E}[\Lambda])\, k + \mathsf{E}\left[P(X - \Lambda k)^+\right] - \mathsf{E}\left[M(\Lambda k - X)^+\right]. \tag{10.8}$$

Again, the objective function is convex in k. We find that it is optimal to invest in the renewable technology if and only if $\mathsf{E}[P\Lambda] > a + w\mathsf{E}[\Lambda]$. If this condition is satisfied, then the optimal capacity k^* is given by the unique solution to:

$$\mathsf{E}[\Lambda \cdot M \cdot \mathbf{1}_{\{X<\Lambda k^*\}}] + \mathsf{E}[\Lambda \cdot P \cdot \mathbf{1}_{\{X\geq\Lambda k^*\}}] = a + w\mathsf{E}[\Lambda]. \tag{10.9}$$

As in the nonrenewable technology case, when solving Eq. (10.9), a numerical search is necessary.

10.3.2 Application 2: Solar Photovoltaic (PV) System in a Bank Branch

We now illustrate how to use our model to optimize Wells Fargo's investment in a solar PV system given the demand and solar radiation data shown in Fig. 10.1.

10.3.2.1 Dataset

The planning horizon is 30 years, representing the lifespan of a PV system. The operating cost w for a solar PV system is negligible. Demand, electricity price, and NEM compensation data are as as described in Sect. 10.2.2. For solar yield, we obtained minute-by-minute solar radiation data for Los Angeles, available from April 2010 onwards at `http://www.nrel.gov/midc/lmu`.

The effective capacity of a solar panel degrades geometrically over its lifespan at an annual rate of 0.5 %, and so we represent the solar yield rate as $\Lambda = L \cdot G$, where L is the solar radiation rate (with no annual trend), and G has 30 discrete realizations $= [1, 0.9950, 0.9900, 0.9851, \ldots, 0.8647]$, with probabilities proportional to the corresponding discounting factors for 30 years. We next construct the distribution of $\mathscr{Y}$ in a similar fashion as the first example, with two differences.

First, we now have two random variables with an annual trend: The NEM compensation rate $\{M_t\}$, which increases with the price of electricity, and the solar yield $\{\Lambda_t\}$, which decreases due to PV degradation. For the NEM compensation rate, we set $M = 0.33P_A$ as explained before. The annual degradation for solar yield is captured by the random variable G. Note that the three trending elements P_A, M, and G are governed by the probability vector $\mathbf{r}$.

Second, due to their dependence, we construct 12 *joint* distributions of demand and solar radiation L, one for each month. Define the random vectors $\{X_m, L_m\}$ as the random vector for month $m = 1, 2, \ldots, 12$; each with a probability of 1/12. We use January ($m = 1$) as an example to explain the procedure. First, we create 20 value bins for solar radiation, and 20 value bins for demand, resulting in 400 buckets. The proportion of the joint observations that fall into each of the 400 buckets approximates the pmf of $\{X_1, L_1\}$.

We can now generate the joint distribution $\mathscr{Y} = (P_A + P_B, X, L \cdot G, M)$. There are 30 annual indices for trend, 12 monthly indices for seasonality, and, for each month, 400 buckets of demand and solar radiation. This results in the same $30 \times 12 \times 400$ combinations, with each probability equal to the product of the three corresponding individual probabilities.

10.3.2.2 Optimal Solution and Impact of Data Granularity

The unit investment cost for a new PV system at this branch is $v =$ \$3178/kW. This cost is the sum of upfront investment cost, NPV of lifetime insurance cost, and fixed cost for inverter replacement and extensive maintenance, then deducting a tax incentive of 15 % of system cost, tax savings from accelerated depreciation, and the installation cost from the Solar Incentive Program (SIP) in California. The breakdown costs above are from Ovchinnikov and Hvaleva (2013). Multiplying this value by the allocation adjustment ratio $(1-\delta)/(1-\delta^{30})$ results in $a = \$169$/kW. Solving Eq. (10.6) using Excel Solver, the optimal PV capacity is $k^* = 13.6$ kW. Our entire solution approach is implemented in Excel, and available from the authors upon request.

Figure 10.3 plots a possible scenario for the year 2014, where demand and solar radiation repeat the same pattern as in 2013. The solar PV system provides 100 % of the branch's power needs for 22 % of the hours. The two charts on the left of Fig. 10.3 show that during many summer hours (bottom), and in a few winter hours (top), the solar output is higher than demand. This fact is disguised on the right chart of Fig. 10.3, where the solar output never seems to be sufficient to meet the branch's power demand, but this is because the data is aggregated into daily buckets for visualization purposes.

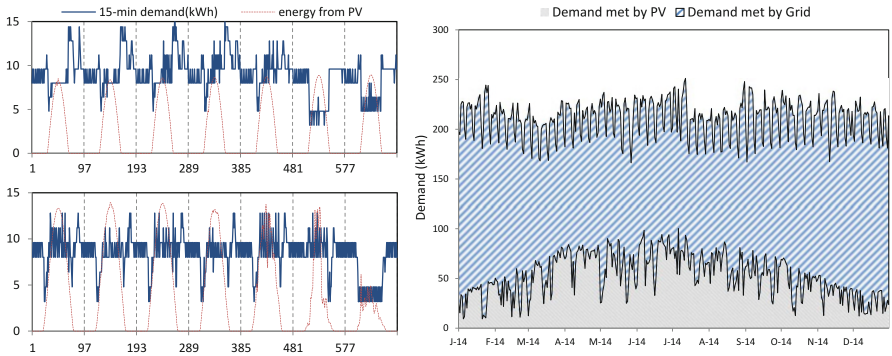

Fig. 10.3 Optimal (15-min granularity) demand fulfillment for Wells Fargo branch in Los Angeles (Note: The *left figure* displays the 15-min electricity consumption and energy generated by the PV under the optimal capacity, for a typical winter (*top*) and summer (*bottom*) weeks. The *right figure* plots aggregate daily demand and aggregate daily solar energy.)

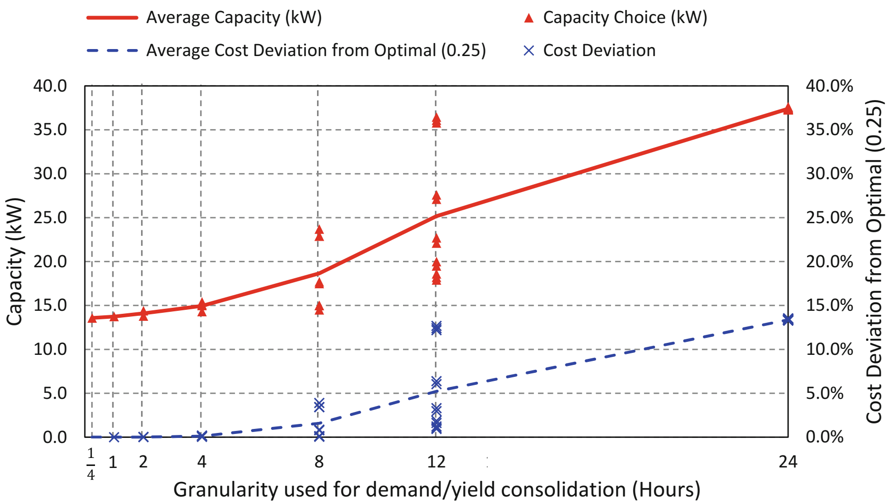

Fig. 10.4 Impact of data granularity for demand and solar yield on optimal solution and cost (Note: There is more than one capacity choice (*filled triangle*) and corresponding percentage cost deviations (*multiplication symbol*) for each granularity level, depending on how aggregation is performed. The *lines* plot their respective averages.)

As discussed in Hu et al. (2015), the level of data granularity used in the renewable energy producing technology can lead to very different solutions. To show this, we computed the optimal solution for different levels of granularity in demand and solar yield, that is, aggregating data in adjacent 15-min intervals into one or more hours. There are different solutions for each granularity level, depending on the "starting time" for aggregation. For example, for a granularity level of 2 h, there are two possibilities for aggregating the data, depending on the starting time: (1) 12 a.m.–2 a.m., 2 a.m.–4 a.m., and so forth; and (2) 1 a.m.–3 a.m., 3 a.m.–5 a.m., and so forth. The results are shown in Fig. 10.4. The optimal solution does not change significantly if one uses 15 min or 1 h for demand-yield data granularity. As the granularity level lowers from 2 to 12 h however, the spread in the possible solutions increases. In general, for a given granularity level, better solutions (i.e., closer to the optimal of 13.6 kW, computed with 15-min granularity) occur when there is a better match between solar supply and demand during the aggregated time intervals.

We also evaluate the total cost $\mathscr{C}(k)$, using the *correct* demand-yield distribution with 15-min granularity, that results from a capacity level computed with less granular data as in Fig. 10.4. We then compare this total cost with the optimal total cost and compute the cost deviation from optimal, which is shown in Fig. 10.4. There is a minimum cost penalty for using a capacity solution computed with granularity levels of up to 4 h. For 8-h (12-h) granularity, the cost penalty averages 1.6 % (5.2 %), but there are significant differences depending on the starting time for aggregation. In all of these cases, the suboptimal solution results in higher savings from the solar power, but a larger increase in the investment cost.

As another benchmark analysis, we compare our solution with a heuristic, used by practitioners, that uses the average yield efficiency to approximate the random yield—this would be equivalent to yearly granularity for random yield. This would result in a capacity level of 43 kW, which is more than three times that of the optimal solution. In addition, such a system would require a roof size of 223 m^2 (2400 sq-ft), which may be infeasible for a bank branch. In terms of total cost, the heuristic would cost Wells Fargo 18 % more than the total lifetime cost of the optimal solution.

10.4 Conclusions

In this chapter, we present a method for determining the amount of renewable energy producing technology to install at a single commercial property that consumes energy but is not responsible for producing it. Thus, our methodology is appropriate for locations such as bank branches, car lots or retail stores but not for power plants or utilities. For such locations, the ability to purchase the maximum energy needs from the grid is always an option. In addition, many commercial properties pay electricity rates, when purchasing from the grid, that vary by the hour of the day. This variation in electricity rates, along with the daily and seasonal variation in energy needs and a possible correlation between these two, makes a capacity decision on how much energy producing technology to install a challenging one. It is rarely optimal for the firm to invest in enough energy producing capacity to meet the maximum peak energy needs of the location. Thus, there are marginal costs associated with purchasing too much capacity as well as too little capacity. In the first part of this chapter, we show how a firm can solve this problem using a variation of the classic Newsvendor model.

When the energy producing technology is renewable, such as solar or wind power, there is an additional complication to the investment problem because the yields of these technologies also have daily and seasonal variability that may also be correlated with the variation in the energy demand and price of purchasing electricity from the grid. In the second part of this chapter, we show how to include this additional complication into our proposed decision making framework. We show that the level of granularity of the data (minutes, hourly, daily, etc.) plays a significant role in the final capacity decision, with lower levels of granularity (such as 15 min intervals) needed for evaluating the renewable energy options. We then demonstrate our methodology by presenting a case study on the amount of solar panel capacity to install at a Wells Fargo bank branch in California. Our results also show the importance of evaluating each location separately, as electricity rates, demand usage, renewable yields and government subsidies for renewable investments vary considerably between regions.

References

Hu S, Souza G, Ferguson M, Wang W (2015) Capacity investment in renewable energy technology with supply intermittency: data granularity matters!, manufacturing and service operations management 17(4):480–494

Ovchinnikov A, Hvaleva A (2013) Wells Fargo: solar energy for Los Angeles branches. Darden business publishing case UVA-QA-0800, University of Virginia, Charlottesville, VA

PG&E (2014) Getting credit for surplus energy. http://www.pge.com/en/mybusiness/save/solar/\penalty0surplus.page. Accessed 23 Sept 2014

Part IV
Regulation-Driven Environmental Responsibility in Supply Chains: Motives and Opportunities

Chapter 11
Owls, Sheep and Dodos: Coping with Environmental Legislation

Atalay Atasu, Luk N. Van Wassenhove, and Douglas Webber

Abstract Environmental legislation affects more and more companies in different industries and is likely to continue to do so. Focusing in particular on the issue of the disposal of waste electrical and electronic equipment (WEEE), this chapter argues that firms are frequently unaware of the threats posed by such legislation, poor at anticipating its provisions and effects, and generally not very skillful at representing their interests in the political process. Contrasting such firms (political "dodos" or "sheep") with a few (political "owls") that have proven themselves to be successful political actors; we proceed to identify the generic ingredients of effective corporate political strategy to cope with environmental legislation.

11.1 Introduction

Most firms live and die—most of the time—in and by the market. But this is not always the case. How well firms fare in the market does not always depend just on how effectively they integrate and deploy their human, research and development, supply chain, marketing, financial and other resources. Numerous scholars have shown how important it is that firms—even

A. Atasu (✉)
Scheller College of Business, Georgia Institute of Technology, 800, West Peachtree Street, Atlanta, GA 30308, USA
e-mail: atalay.atasu@scheller.gatech.edu

L.N. Van Wassenhove • D. Webber
INSEAD, Boulevard de Constance, 77300 Fontainebleau, France
e-mail: luk.van-wassenhove@insead.edu; douglas.webber@insead.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_11

those in sectors in which at first glance the government may not seem to play a central role—be effective *political* actors to promote their interests (see, for example, Baron 2006; Bach and Allan 2010).

The importance of politics or the government to business is something of which some firms, especially those in sectors that have long been exposed to government intervention, are well aware. Thus, if the chemicals industry is regarded as one of the most powerful industrial "lobbies" in the European Union, then this is in large part due to the fact that, over a period of several decades, this sector has been a more frequent target of attempts at government regulation than most others. When, a decade ago, it faced potentially tough new chemicals safety regulations in Europe, it was ultimately fairly successful in shaping these in such a way that they did not pose an existential threat to the industry (Webber 2006a).

Government regulation or other forms of government intervention tend, however, to take most firms and their supply chains by surprise. As important as the impact of such intervention may be on their "bottom line," they are often incapable of organizing themselves as political actors.

Regardless of intermittent trends towards "privatization" or "deregulation," which have been more significant in some countries than others, the economic role of government has not receded during the last few decades (Vogel 1996). As the political after-tremors of the Global Financial Crisis reverberate around the world and the center of gravity in the world economy shifts towards countries in which the state is a key economic actor, this role will more likely expand in the future than recede (Bremmer 2009).

One issue-area in which the role of government regulation seems likely to increase is that of the environment. Since the 1970s, the volume and scope of environmental legislation and regulations has risen sharply across the advanced industrialized world. Whereas initially the U.S. played a vanguard role in this regard, the European Union, under the influence of its "greener" member states in Northern Europe, has meanwhile taken over this function (Vogel 2003). At the federal level in the U.S., political gridlock in the Congress and between the Congress and the presidency has put a brake on the adoption of major new environmental legislation (Kamieniecki and Kraft 2007). However, legislative paralysis in Washington has not prevented environmental protection decisions and regulations being adopted and applied through other channels and at other levels, including that of state and local government (Klyza and Sousa 2008).

Given the likelihood that environment-related problems and issues will grow both in number and in intensity rather than diminish, it is increasingly improbable in the longer term that business opposition will hold, let alone roll, back this tide. Business interests characteristically prevail on technical issues where they enjoy a monopoly or near-monopoly of expertise and which can be settled outside the political limelight (Culpepper 2010). Environmental issues, in contrast, have a higher political salience than many others and they are frequently contested by NGOs that provide a counterweight to business organizations in the policy-making process. At the same time, the effects of environmental legislation and regulations are often cross-sectoral, extending—as we will see below—into sectors in which traditionally government regulation has been limited. Thus, not only are such laws and regulations likely to come in one way or form or another, but they will also often hit firms that have little experience of environmental politics and legislation.

Based in particular on an analysis of the case of electronic waste, this article discusses the growing challenge that environmental legislation and regulations pose to firms and their supply chains and how such proposals tend to take most firms by surprise and find them ill prepared to represent their interests effectively in the political process. Contrasting such firms with a few that, in contrast, have proven to be successful political actors helps us to identify the generic ingredients of effective corporate political action and what politically incompetent or less competent firms might do to raise their political game.

11.2 The Times they are A-Changing: Trends in Environmental and e-Waste Legislation

Since the 1980s, the number of environmental laws has increased exponentially. At the same time, the accelerating speed of technological development has resulted in increased consumption and shortened life cycles. This in turn has led to higher waste generation and the depletion of natural resources. In particular, the exponential increase in the production of electronics during this period has become a serious issue for environmentalists.

Data from Greenpeace[1] highlight the gravity of the problem. Between 1997 and 2005, the average lifespan of computers in developed countries dropped from 6 to 2 years. In 2004, 183 million computers were sold worldwide—an 11.6 % increase on the previous year. By 2009, this number had risen to 281 million units and projections for 2014 anticipated sales of 384 million units.[2] By this time there will be 178 million new computer users in China and 80 million new users in India. If these trends continue, the number of computers disposed of in landfills annually in the U.S. will equal a pile a mile high and the size of a football field.[3] Similarly, worldwide sales of mobile phones, which in developed countries have a lifecycle of less than two years, grew by 30 % to 674 million in the 12 months to 2004. Sales in 2009 were 1.15 billion; a year later they stood at 1.3 billion.[4]

---

1 http://www.greenpeace.org/international/campaigns/toxics/electronics/the-e-waste-problem.

2 http://www.researchandmarkets.com/reports/1138574.

3 http://www.technology-recycling.com/pages/environment_why.html.

4 http://www.theinquirer.net/inquirer/news/1603334/mobile-phone-industry-pulls-recession.

The increased presence of electronics in household waste[5] is the major reason for the recent growth in the volume of e-waste legislation, illustrated in Fig. 11.1. The objective of e-waste legislation is to reduce its environmental impact by ensuring proper collection and recycling, mainly to avoid these waste streams ending up in increasingly scarce land fill capacity.

Clearly, legislators are keen to make producers pay for the costs of proper collection and recycling. Consequently, most e-waste legislation is based on extended producer responsibility, making producers responsible for financing and organizing the operation of e-waste collection and recycling systems. Obviously, the enactment of such laws will result in additional costs for the producers: an e-waste processing cost of up to 3 % of revenues[6] could have a serious impact on the profitability of a typical consumer electronics producer with relatively low profit margins!

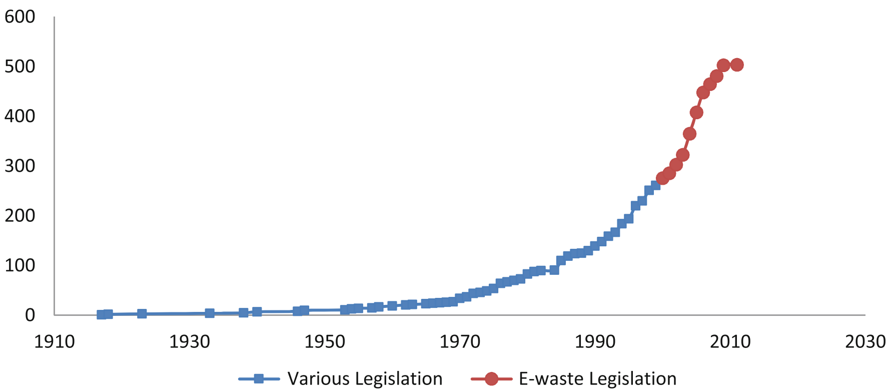

Fig. 11.1 An illustration of the diffusion of international environmental legislation. This graph is based on raw data collected from the Web, not on an exhaustive counting of world-wide legislation

The more numerous and stricter such laws become, the greater will be their impact on costs and profitability, as experienced by the energy industry. By the early 1970s, the energy sector had succeeded in improving costs and efficiency. However, the increased costs associated with the sudden increase in environmental regulations in the next decades left energy companies facing higher costs and plummeting efficiency. If those who fail to acknowledge the past are condemned to repeat it, then clearly companies should take a lesson from the energy industry's experience. Regardless of short-term changes in

[5] Twenty to fifty million metric tons of e-waste are generated worldwide every year, comprising more than 5% of all municipal solid waste. In the U.S. alone, some 14–20 million PCs are thrown out every year. In the EU the volume of e-waste is expected to increase by 3–5 % a year. Developing countries are expected to triple their output of e-waste by 2010 (http://www.electronicstakeback.com/wp-content/uploads/Facts_and_Figures).

[6] www.era.co.uk/news/rfa_feature_07a.asp.

countries' political constellations, the future is likely to bring more rather than less environmental legislation. What matters for companies is to find out when environmental legislation will be enacted/reach the statute books/be passed into law in the countries in which they operate, to what extent and how they may be able to influence it, and how they will be affected by it?

While 26 states in the U.S. have enacted some form of e-waste legislation (mainly focusing on electronics, TVs and monitors), the remaining states are still in the process of discussion or have not yet started working on the issue. Compared to the European Union, the growth of environmental legislation in the U.S. is still limited. In particular, there is no legislation yet at the federal level. Figure 11.2, along with numerous examples of take-back laws for batteries, mercury containing thermostats and auto switches, leftover paint, and fluorescent lamps (Nash and Bosso 2011) suggests, however, that more legislation is likely to come at least at the state level and that if other developed economies such as Europe are the yardsticks it will probably come soon.

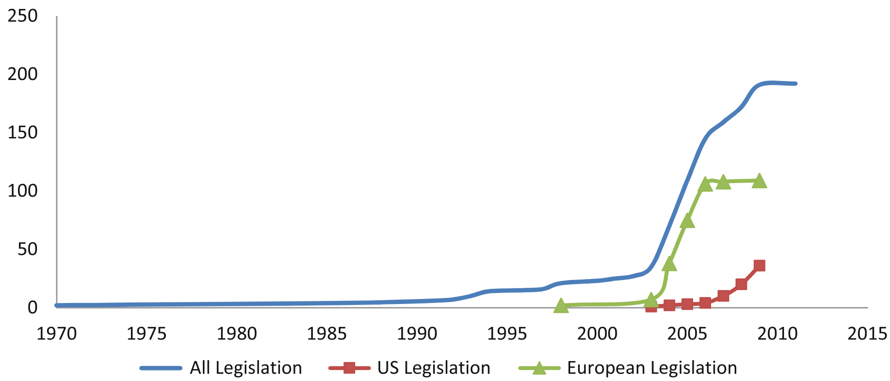

Fig. 11.2 Diffusion of international e-waste legislation

Firms operating in the U.S. and their supply chains would thus be well-advised to start reflecting on how e-waste laws will affect them. What is the right course of action for them to take before facing the threat of environmental regulation? Should certain kinds of companies be more worried than others?

Given their prior experience elsewhere, especially Europe, global companies are likely to be aware of this regulatory threat. Others may be aware of this threat, but not command the experience or resources required to exercise effective political influence. Many of the U.S. firms that we met at a 2008 industry-academic roundtable to discuss business aspects of remanufacturing, for example, anticipated that environmental regulation would grow in the future. One of them explicitly stated that "environmental legislation is coming and we have to be prepared." But neither it nor many of the others knew exactly what they should prepare for—or how they could try to shape forthcoming regulations.

A critical issue in these circumstances is what sectors and firms will be affected by new regulations. Thus, while the current scope of U.S. e-waste laws mainly focuses on TVs and computers, this does not mean that these will not be extended in future to other electrical and electronics manufacturers. Consider the toy manufacturers, whose products frequently contain electronic components. It is quite possible that they will fall within the scope of new e-waste laws in the U.S. Given its earlier experience with material content restrictions in the U.S., Mattel, for instance, had better be prepared. To assess the risk that they will be 'unpleasantly surprised' by falling within the ambit of such laws and how and to what extent these could affect them are two of the first things that firms must consider.

11.3 A Strong Wind or a Perfect Storm? How Exposure to Environmental Legislation Risks Varies

While it is clear that environmental legislation will affect most companies sooner or later, it is also important to understand that some companies will be challenged more than others. Environmental legislation does not affect every company in the same way: rather the devil is in the detail. The ongoing debate in Europe on cost allocation between electronics producers in collective recycling systems provides a perfect example here. The market share heuristic currently used by many EU member states in WEEE directive implementation is widely criticized for distorting competition and favoring certain producers. Using current return share instead of market share to allocate recycling costs would have a completely different effect, i.e., implementation details matter and companies had better be aware of them.

The risk of facing an unpleasant as well as costly surprise due to environmental legislation is driven by two major factors: a company's risk experience and the potential impact.

$$\text{Risk of an Unpleasant Surprise} = \text{Potential Impact}/\text{Risk Experience}$$

The potential impact of environmental laws depends on three major variables: market share, margins, and the environmental attributes of a product. When an environmental law hits a company, the impact is greater if that company's market share is higher, its margins lower and its products characterized by inferior environmental attributes. In our experience of the WEEE Directive in Europe,[7] we observed that companies with higher market shares (such as HP, Braun, Sony, Electrolux and Philips) reacted faster because

[7] www.insead.edu/weee.

these laws had much larger cost implications for them. Industries with razor thin margins were also likely to be more heavily affected. For example, the profits of an electronics producer with 2–4 % profit margins would be significantly affected by an e-waste recycling mandate that entailed a 1–3 % recycling costs. Finally, a company manufacturing a product containing hazardous components would be far more likely to be affected by new environmental legislation. A producer of millions of Cathode Ray Tube TV sets, each containing high amounts of lead, would probably be strongly affected by the cost impact of complying with e-waste laws.

$$\text{Potential Impact} = \text{Market Share} * \text{Environmental Impact}/\text{Profit Margins}$$

Risk experience is driven by two main factors: a company's global presence and the diversity of its product portfolio. Multinational companies are more likely to be affected by environmental legislation in some of the countries where they operate. For example, although no federal e-waste legislation has been enacted in the U.S. to date, companies are required to collect and recycle used products in Europe and in Japan. While a company like HP will already have been affected by such laws, a local U.S. producer will not necessarily be aware of the challenges associated with them.

Diversity of product or business portfolio also increases the potential risk experience. The Dutch multinational Philips, for example, produces a variety of products from TVs to household appliances, from fluorescent lights to healthcare equipment. This variety means that the chances of Philips being affected by an environmental law somewhere in the world before many of its competitors are quite high. Similar arguments could be made for other companies with multiple business units such as GE. Exposure to environmental legislation can provide a cushion to hedge the impact of such risks; companies that have already experienced the effects of the WEEE directive in Europe are likely to be better equipped to reduce the impact on their operations of similar laws when they are enacted in the U.S. or China.

$$\text{Risk Experience} = \text{Global Presence} * \text{Diversity of Portfolio}$$

Companies need to understand their vulnerability to the risk of being affected by some form of legislation as well as its potential impact on them. Local companies with high market shares, limited product portfolios, low profit margins and environmentally harmful products are more likely to be caught unprepared by new environmental laws. If these companies neglect or ignore the presence, or even potential for enactment, of such laws, they will be in for unpleasant (and expensive) surprises—they could be hit by a perfect storm.

$$\begin{aligned}&\text{Risk of an Unpleasant Surprise}\\&\quad= \frac{\text{Market Share} * \text{Environmental Impact}}{\text{Profit Margins} * \text{Global Presence} * \text{Diversity of Portfolio}}\end{aligned}$$

11.4 Owls, Sheep, and Dodos: Some Firms are Politically More Competent than Others

New environmental legislation may not be quite as inevitable as death and having to pay taxes, but there is a high probability that there will be more of it sooner or later—in the U.S. and Europe and elsewhere. So companies should at least be aware of what may be about to happen and whether they should participate actively involved in the processes of environmental policy-making. For the provisions of environmental like other policies are not a given, they are there to be—and can be—shaped. Some policies clearly favor certain companies, while harming others. Companies actively involved in the process of policy making are more likely to reduce the impact of environmental laws on their operations, while others will be left to face potentially unfavorable consequences.

Unfortunately, many firms still prefer to adopt a wait-and-see stance or, worse still, put their heads in the sands like ostriches, refusing to see what is very likely coming.

There are large divergences between companies in terms of their engagement in environmental policy making. We can classify them into three categories (Fig. 11.3).

	Political capabilities	
Awareness	Low	High
Low	DODOS	
High	SHEEP	OWLS

Fig. 11.3 Factors influencing political competency

Dodos are politically inert or "brain-dead" firms. These firms do not wake up to the impending threat of legislation until it has been adopted and implemented. They are neither politically aware nor do they possess much in the way of political resources, let alone any significant capacity to deploy these in such a way as to exert any political influence. In the worst-case scenario, they may face commercial extinction.

Sheep are the firms that are aware, or at least at some point become aware, of the imminence of environmental legislation. However, by the time they actually react to this threat the die has been cast, and their influence on the eventual legislation will be limited or non-existent. Typically, they are at least a step behind the owls. Politically neither knowledgeable nor capable, they are unable to mount an effective political campaign to defeat or shape the terms of the legislation. Sheep are typically reduced to “bleating”—complaining—about it.

Owls are, by contrast, the firms that are aware very early on of the growing, increasingly unstoppable pressures that will/could lead to environmental legislation. They are politically well-informed, knowledgeable and skillful. They can conceive and execute shrewd political strategies that ensure they exert a strong influence on the legislation that is eventually adopted and implemented.

11.4.1 Dodos

As our foregoing analysis indicates, Dodos tend disproportionately to be smaller firms that serve national markets. But big firms too can sometimes display—for themselves—costly political ignorance and inertia. Sony Corporation and Palm Inc. offer two graphic examples of how even giant companies can be politically unwitting.[8] In 2001, Sony suffered a huge financial blow when 1.3 million of its game consoles, the PlayStations, were seized by Dutch customs officials just before Christmas. The problem was the high level of cadmium in the game console’s cables, which failed to comply with the European Union’s environmental protection laws. Sony was forced to replace the cadmium filled cables, which delayed all shipments throughout Europe and cost approximately $90 million. The PlayStation debacle not only opened Sony’s eyes to the impact of such environmental laws, but also those of many other leading electronic manufacturers. The message was loud and clear: environmental directives could no longer be disregarded.

Failing to learn from Sony’s example, Palm had to remove one of its phones, the Treo, from the European market completely in 2006 after it failed to comply with the EU’s Directive on the Restriction of Hazardous Substances (RoHS). Compounding the error that led to its being cut out of the large European market, it then damaged its brand image further by not replacing these non-compliant phones in non-European countries. The financial toll

[8] Sources: http://www.forbes.com/logistics/2006/08/11/rohs-crackdown-hazmat-cx_rm_0814lead.html, http://www.theregister.co.uk/2001/12/05/dutch_officials_seize_cadmiumpacked_playstation/, http://www.macworld.com/article/51643/2006/07/treo.html, http://www.dti.gov.uk/files/file29926.pdf.

that Palm had to pay for its ignorance of EU law and poor political judgment was hefty. Whether environmental restrictions are in place in Europe, Japan, China, or a state in the U.S., the cost of designing a compliant product is usually trivial compared to that incurred by the need for a major recall or the loss of an important market.

The interesting question is what led to two otherwise such savvy companies being caught off-base? The evidence suggests that they fell victim to different forms of environmental concerns or associated regulations, either because they ignored them or because they were simply unaware of them. Given the significant consequences, this seems to be a mistake that other companies should try to avoid.

11.4.2 Sheep

In many cases, firms become politically active only after environmental legislation has been adopted and is being implemented. Sometimes their political mobilization can affect the way in which the issue is ultimately resolved. When, for example, in 2009, New York City passed its law on e-waste recycling, considered to be one of the most stringent and burdensome laws in the country, this prompted a quick reaction by an alliance of electronics producers led by a group of multinationals (including Sony and Samsung), and the Consumer Electronics Association (CEA). This alliance quickly identified problems in the NYC law and launched a lawsuit against it, demanding immediate changes.

Our experiences with the practice of recent e-waste laws reveal that more often firms are incapable of informing the environmental policy-making process, let alone influencing it. There is a widespread "comply and complain" effect, in which companies react only after legislation has been passed, their "bleating" remaining, however, ineffectual. When the WEEE Directive was being considered in Europe, many electronics companies engaged in heated discussions among themselves instead of taking an industry-wide stance and engaging with the policy makers. Driven by environmental concerns among the public and a strong push from NGOs, a directive was passed that not only turned out to be expensive for the industry, but which, when it was implemented in the member states, also distorted competition. The companies that were most heavily penalized by the directive were those that exercised the least influence in the implementation process.

EU directives must be transposed into national legislation in all member states. As general principles are transposed into specific laws with which companies need to comply, points often get lost in political translation; so EU environmental regulations can diverge substantially across member states. In the WEEE case, when companies like HP, Samsung, Electrolux and Sony realized that a number of European countries would enforce collective recycling systems, allocating average recycling costs on a market share basis, they were very discontented. Not surprisingly, companies with environmentally friendly products, i.e. lower recycling costs or lower waste volumes, balked at subsidizing companies with high recycling costs. Consider the following example (Fig. 11.4):

Company	Sales Volume	Waste Volume	Unit Recovery Cost	Total Recovery Cost (Collective)	Total Recovery Cost (Individual)
A	100	50	$2	50	100
B	200	50	$1	100	50

Fig. 11.4 An illustrative example to compare the costs of WEEE compliance under collective and individual systems

Company A has low sales volume, high waste volume and higher recovery costs. Company B has higher sales volume, lower waste volume and lower recovery costs. Under the market share-based collective system mandated by some European countries, Company B subsidized the recovery costs of Company A. To companies like Company B, this system was clearly unfair and it is one of the issues connected with the current WEEE directive. Not only is this an unfair cost allocation method, in no way does it motivate/encourage Company A or B to put more effort into eco-design in order to develop environmentally friendly products. In other words, one of the explicitly stated objectives of the original EU directive got lost in translation.

Most EEE manufacturers did not see this coming. When they realized the practical implications of the WEEE, it was already too late. Many companies have had to comply with market share-based collective systems. Clearly, once countries are locked into a system that was difficult to implement in the first place, the effort to change it becomes substantially more difficult.

Being a political "dodo" or "sheep," in other words, can come at a heavy price.

11.4.3 Owls

Some, typically only a few, "wise" companies are both aware of the potential effects of upcoming environmental laws and of ideas/possible moves in the pipeline and lobby accordingly and—to a disproportionate extent, successfully—for legislation that will benefit them. The following examples from the e-waste legislation context illustrate this strategy:

IBM has been a strong proponent of the Advanced Recycling Fee (ARF) legislation in California.[9] The ARF requires consumers to pay for recycling costs at the time of purchase instead of the manufacturer paying at the end-of-life, i.e., at recycling time. Since IBM has left the PC market, this legislation would effectively exempt it from having to pay for the large quantities of their old computers still in the market when they eventually come in for recycling, i.e., for their "historical waste." Clearly, ARF is a good deal for IBM, since the current producers will have to pick up the bill for these so-called "orphan" products.

Similarly, but in a different way, HP has also been proactive over electronic take-back legislation. From printer ink cartridges to computers, HP has always been at the forefront of recycling (Woellert 2006). Since the early 1990s, HP has implemented cost efficient product take-back initiatives, and also used the returned hardware to sell refurbished products. Consequently, when environmentalists came knocking HP was one of the few computer companies that lobbied to establish a take-back directive for all electronic manufacturers, thereby hoping to turn its experience into a competitive advantage.

Being proactive and lobbying for environmental legislation has significantly benefited both HP and IBM, and other manufacturers would do well to follow their best practices. Unfortunately, many companies struggle when searching for ways to approach environmental legislation. While computer manufacturers, such as HP, are lobbying for universal take-back initiatives, "for television makers … take-back laws are terrifying… [Since] Americans are expected to throw out more than 550 million analog TV sets." (Woellert 2006). However, rather than opposing take-back legislation, television manufacturers would be better advised to propose alternative forms of legislation that would directly benefit their own recycling programs.

In Europe, Philips has long been a supporter of collective producer responsibility implementation of the WEEE Directive. From Philips' perspective, recycling old TV sets is a costly business and achieving cost efficiency is the most important concern. A collective system is the most effective way to achieve this, as it provides scale economies. Philips acted on this conclusion early, making significant lobbying efforts in the Netherlands and the rest of EU. While it is difficult to measure the company's lobbying impact on the eventual directive, it certainly benefited greatly from the dominance of collective systems that emerged.

---

[9] `http://www.electronicsrecycling.org/NCER/UserDocuments/Thompson.doc`.

11.5 What Makes a Firm an Owl?

The impact of environmental legislation on the electronics industry demonstrates the need for companies to be competent political as well as market actors. For any firm facing environmental legislation, the best option is to try to become an owl and mobilize its resources to exert political influence as early as possible.

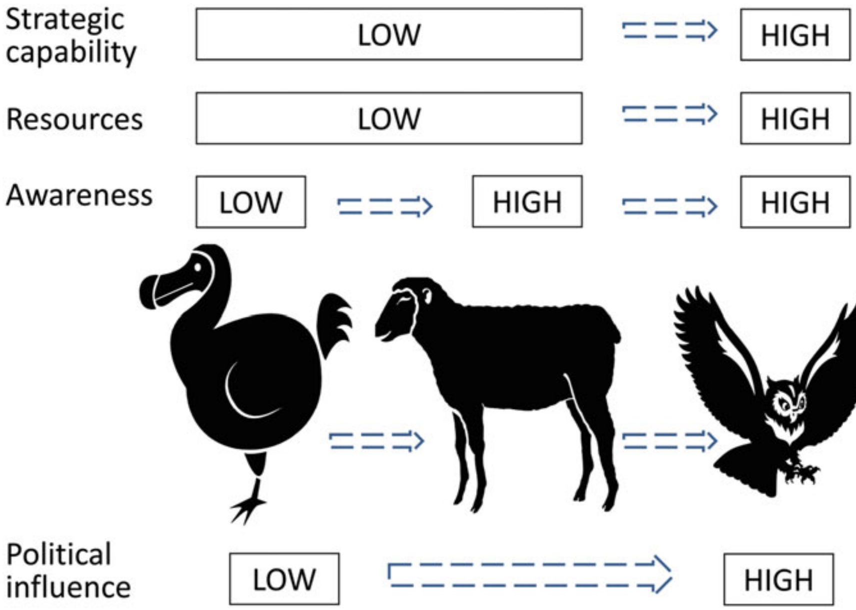

Fig. 11.5 Components of effective political action

Effective political action by firms requires three basic ingredients (as demonstrated by Fig. 11.5):

1. *Awareness*: Firms must be conscious of the impact that environmental concerns, related policies and resulting compliance efforts may have on their activities—both now and in the future. Otherwise they have lost the game before it has even begun.
2. *Resources:* Of course, firms need human resources (depending on the time, place and issue possibly including hired 'lobbyists'), financial resources and—a potentially very useful political asset—reputational resources. But, above all, they need political expertise and knowledge to promote their interests in policy-making circles.
3. *Strategic political capability:* Furthermore, firms must be able to combine and deploy their resources to conceive and execute a strategy (course of action) that will maximize their influence on political decisions affecting them.

Firms must first be aware of threatened or conceivable legislation, understand their position in relation to it and evaluate the risk that it may pose to them, as discussed earlier. Only then can they coordinate, mobilize and deploy the resources required to exert political influence. Large companies are more likely to possess this awareness than firms with low exposure to environmental regulation and a correspondingly high predisposition to be dodos. But a large company with a relatively narrow product portfolio may well be unaware of developments in other industries that could very quickly affect it or lead to the eventual enactment of similar laws for its industry. A toy company, for example, may not easily grasp the serious consequences of the WEEE directive in Europe, simply because it does not consider itself an electrical or electronic equipment manufacturer. Despite the fact that today most toys contain electronics, the WEEE directive still may come as a shock to this sector. Although e-waste laws in the U.S. currently focus mainly on computer screens, monitors and TV sets, the European equivalent of these laws applies to household appliances as well. Therefore, brands like White Westinghouse, a large U.S.-based appliance manufacturer, must take heed of the impact such laws could have on their business.

When it comes to keeping abreast of ongoing developments regarding environmental legislation, small companies are more likely to be dodos or at best, sheep. They are much less likely than large companies to command the political and other resources required to exercise political influence. For such companies, acquiring strategic political capabilities means forming alliances. The IPR working group (an alliance of several companies including HP, Samsung, Electrolux and Sony, see www.insead.edu/weee), which targets a revision of the WEEE Directive on individual producer responsibility is a concrete example of such an alliance, albeit not one of small players.

What kinds of *political* resources do firms require to be capable of effective political action and what kinds of issues and questions must they address in devising and executing a political strategy?

Political knowledge and competence depend on two principal variables. First, firms need a *political network*, one that enables them to gather relevant political information or intelligence as early and as fully as possible. In politics as elsewhere, other things being equal, the early bird catches the worm. In most cases, legislation resembles fairly closely the original draft often written by relatively low-level bureaucrats.

Second, firms must be able to process political information, to assess its meaning and implications, and to store it for potential future use. In other words, they require something like a *collective political memory* so that when a political issue arises, they have some idea, based on historical experience, of how to handle it effectively. Developing this capacity may be harder for firms than for public sector organizations, as rates of personnel turnover in them may be higher.

In developing and executing a political strategy, firms must address six key issues:

What? This is about goals. A firm must decide what it wants to achieve. Should the goals be defensive—to try to defeat proposed legislation—or offensive—to initiate legislation that corresponds to its interests? Should the firm's goals be maximalist, with the heightened risk that it will end up with nothing, or should it concede that legislation is probably inevitable and concentrate its efforts on shaping its provisions in a manner favorable to the firm while building an image as a promoter of widely-accepted societal goals? In the WEEE case, the firms that made the latter choice were clearly the winners. Firms need also to weigh up which trade-offs they can offer political decision-makers, i.e. what concessions can be made to stave off decisions carrying particularly negative repercussions. They must continuously review the "state of play" and be able to react flexibly—i.e. redefine their strategy in the light of what appears to be politically feasible—as political issues unfold over time.

With Whom? This is about coalitions. Firms must decide whether to go it alone or to look for allies to promote their political interests. This presupposes that they can identify their potential supporters *and* opponents. Surprisingly perhaps, firms do not always get this right. In the WEEE conflicts, many firms saw the environmental NGOs as their main opponents. In fact, their real opponents were competing firms—political owls, who, under the cover of a purported concern to protect the environment, succeeded in bringing about the adoption of legislation which suited them while disadvantaging their competitors.

To Whom? This is about targets. Firms must identify who are the decisive actors in the political conflict or issue that affects them. Are they particular ministries or departments or even civil servants in the government bureaucracy? Are they particular members of the legislature or Parliament? Or NGOs, pressure groups or, for that matter, other firms? The answers to these questions will vary across time, place and issue, but firms must reach the critical decision-makers, directly or indirectly, if they want to influence legislation. To do that, they must first know who they are. Again, not all firms get this right.

When? When is about time and timing. Politically influential firms are those that are alert to the dangers posed or opportunities offered by political action *all the time*. Those that are first aware of such dangers and opportunities have an advantage over others, because they can use their informational lead to try to shape the contents of the earliest drafts of proposed legislation. But it is no less important that firms *stay on the alert* as legislation winds its way through the political process. A few years ago, the flagship firms in the European ICT industry had a strong influence on the initial version of a European directive relating to the patenting of computer software. They then "went off to the beach," as some observers of the conflict said, abandoning the field to the lobby of small European software programmers, who won the support of the European Parliament and various parliaments and governments among the EU member states for a version that would have jeopardized the big firms' intellectual property rights (Webber 2006b). In the end, neither side won: the directive failed and the status quo was preserved. But the big ICT firms were taught a powerful lesson about the dangers of complacency and the importance of keeping one's eye on the political ball. This also includes the implementation phase of the political cycle, during which firms that were marginalized early on in the process may have a last chance to shape the way in which the law is implemented and enforced.

How? This is about the communication channels through which firms convey their message. Individual firms do not possess all the means by which pressure groups, social movements, labor unions or even their own collective organizations and trade associations can deploy to promote their political agendas. Individual firms can hardly stage demonstrations, protests, strikes or large-scale campaigns aimed at mobilizing public opinion. They depend more on face-to-face meetings with political decision-makers. Through coalitions with other firms and non-firm organizations or contacts with sympathetic mass media, they may still be able to communicate their position indirectly to key decision-makers. That is why the long-term cultivation of a political network is so critical. Firms lacking a prior relationship with decision-makers on any given political issue put themselves at a huge disadvantage compared with those that can activate longstanding ties and contacts. Eventually they will probably realize that they had lost the political game even before it had really begun.

Why? This is about the content of the message. Political decision-makers often depend on technical expertise that they do not possess themselves, but that firms do. However, unless the companies engaged in a given political conflict take a united stance—a relatively rare phenomenon—political decision-makers will be faced with competing and contradictory expertise. The message—the information and the analysis—conveyed by a firm must therefore be as credible as possible. To achieve this, the message must remain consistent, regardless of the target audience. It must stand up to scrutiny by antagonistic political forces and stand the test of time. Nothing is worse for the credibility—and future political influence—of a firm than a message whose validity or accuracy is disproved by future events, just as a firm's credibility can also be destroyed by failing to live up to commitments made in exchange for any political agreement either not to adopt proposed legislation or to soften its provisions.

We have sketched out above the generic ingredients of effective corporate political action. What constitutes an effective political strategy for a firm may, of course, vary by issue-area and geographic location. Lobbying tactics diverge considerably, for example, between the U.S., on the one hand, and the EU and its member states, on the other. What is legal in one country may be illegal in another. Political decision-making processes—formal and informal—are organized differently, meaning that the appropriate targets of attempts to exercise political influence inevitably also vary by country and region. Lobbying in the U.S. is much more direct and aggressive than in the EU, where the dominant style is more subtle and consensus-oriented as well as more strongly rooted in long-term relationships (Woll 2006). It is precisely their awareness and comprehension of such divergences that separates 'owl' firms from sheep and, still more, dodos.

Equally, a firm's strategic political capabilities are not constant over time and place. Firms can lose or develop and strengthen them. For a long time, Microsoft, for example, ignored politics and the need to develop any political expertise. Only after it became embroiled in big anti-trust disputes in the U.S. did it recognize this need. Even now, whilst its political capabilities in the U.S. are highly rated, it is still learning the hard way how to become an effective political actor in Europe, where it has lost a series of anti-trust conflicts with the European Commission. Philips is a rare case of a firm which, at least in its home base, Europe, appears to have maintained a high level of strategic political capability over a long period. In the 1980s, when it went to Brussels to try to influence European Union policy on consumer electronics trade, "the doors flew open," as one of the participants in the EU trade policy said at the time (Cawson et al. 1990). Arguably, in the recent WEEE conflict, the Dutch-based multinational proved once again that it was still a very wily political operator by exercising a stronger influence on the directive than any other firm.

11.6 Conclusions

Companies like Philips are, however, the exception rather than the rule. In the global economy, firms are faced with the challenge of developing strategic political capabilities in all the increasing number of states where they operate, including some where the political process functions very differently from that in their home base. This applies equally to "non-Western" firms that are expanding rapidly abroad, such as Chinese or Middle East state-owned enterprises. Some have indeed experienced spectacular failures when trying to take over foreign companies. Everything suggests that in the future developing strategic political capabilities is going to become ever more important.

Getting hit by legislation does not necessarily mean a company is a political dummy. But it is clearly dangerous to be a dodo, completely unaware of the adoption and implementation of legislation with profound implications for the company. Other things being equal, firms that move up the 'evolutionary scale' to become at least political sheep stand a better chance of long-term survival and success, even if they tend to try to bolt too late to escape through the paddock gate. Not all firms can or must aspire to become owls gliding masterfully over the (political) landscape, carefully observing what is happening below and diving down to the ground to look after its interests as necessary. Not all may be able to afford to build up the resources required to become effective political actors and not all may have to, given that some sectors may be much less likely to be the target of legislation or regulation than others.

In any case, companies cannot transform themselves from dodos into sheep or owls from one day to the next. Acquiring and developing strategic political capabilities takes time. In terms of environmental legislation, companies also need time to set up systems to enable them to audit their suppliers, check supply chain footprints, and raise company-wide awareness of environmental laws and work, if these seem useful, on partnerships with other companies and NGOs. When Philips restructured its supply chain, for example, it took a strategic decision to develop a portfolio of green suppliers and made a huge amount of investment in people and processes, implemented over years through careful planning. The same approach would be necessary for any firm aiming to manage environmental legislation effectively.

One thing, however, is clear: Any company has to start developing its political awareness, knowledge and capabilities today to be prepared for tomorrow!

References

Bach D, Allan DB (2010) What every CEO needs to know about *non*market strategy. MIT Sloan Manag Rev 51(3, Spring):41–48

Baron DP (2006) Business and its environment, 5th edn. Pearson Prentice Hall, Upper Saddle River, NJ

Bremmer I (2009) State capitalism and the crisis. McKinsey Quart (July): 1–6. http://www.mckinsey.com/industries/public-sector/our-insights/state-capitalism-and-the-crisis

Cawson A, Morgan K, Webber D, Holmes P, Stevens A (1990) Hostile brothers: competition and closure in the European electronics industry. Clarendon, Oxford, p 293

Culpepper PD (2010) Quiet politics and business power: corporate control in Europe and Japan. Cambridge University Press, Cambridge

Kamieniecki S, Kraft ME (eds) (2007) Business and environmental policy: corporate interests in the American political system. MIT, Cambridge, MA/London

Klyza CM, Sousa D (2008) American environmental policy, 1990–2006: beyond gridlock. MIT, Cambridge, MA/London

Nash J, Bosso CJ (2011) Extended producer responsibility in the U.S.: full speed ahead? Harvard Kennedy School Working Paper

Vogel S (1996) Freer market, more rules: regulatory rules in advanced industrial countries. Cornell University Press, Ithaca, NY

Vogel D (2003) The hare and the tortoise revisited: the new politics of consumer and environmental regulation in Europe. Br J Polit Sci 33:557–580

Webber D (2006a) Strong industry, safe and healthy environment? Making chemicals safety policy in the EU. INSEAD Case 11/2006-5362

Webber D (2006b) Lobbying in Brussels: the EU directive on the patentability of computer-implemented inventions (parts A, B, and C). INSEAD Case 11/2006-5375

Woellert L (2006) HP wants your old PCs back. Bus Week (10 April):82. http://www.bloomberg.com/bw/stories/2006-04-09/hp-wants-your-old-pcs-back

Woll C (2006) Lobbying in the European Union: from *sui generis* to a comparative perspective. J Eur Public Policy 13:3(April):456–469

Chapter 12
Ignore, Avoid, Abandon, and Embrace: What Drives Firm Responses to Environmental Regulation?

David F. Drake and Robin L. Just

Abstract A regulator's ability to incentivize environmental improvement among firms is a vital lever in achieving long-term sustainability. However, firms can and do respond to environmental regulation in a variety of ways: complying with its intent; avoiding the regulation by offshoring or by abandoning the market; or ignoring the regulation by continuing with entrenched business practices. The path a profit-maximizing firm will choose depends, in part, on the expected cost of noncompliance, which is a product of the regulator's stated penalty, the likelihood that noncompliant practices are detected, and the likelihood that detected violations are punished. The form of regulatory regime and three important cost thresholds also drive firm response. In this chapter, through examples of regulatory failures and successes, we develop a framework for understanding how these thresholds interact with the type of regulatory regime being considered and the expected cost of noncompliance to determine whether profit-maximizing firms ignore, avoid, or embrace environmental regulation.

12.1 Introduction

In April, 2010, about 40 miles off the Louisiana coast in an area called the Macondo Prospect, the *Deepwater Horizon* drilling rig exploded. The blast claimed the lives of 11 workers and hemorrhaged an estimated 3.2 million barrels of oil into the Gulf of Mexico, causing significant damage to the Gulf's environment and economy (Crooks 2015).

D.F. Drake • R.L. Just
Harvard Business School, Boston, MA 02163, USA
e-mail: ddrake@hbs.edu; rjust@hbs.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_12

The disaster at the *Deepwater Horizon* offshore oil rig is well-documented. What is not as well-known is that 20 years prior to the *Deepwater Horizon* incident, and in response to the *Exxon Valdez* oil spill of 1989, the US Congress passed the Oil Pollution Act of 1990 (OPA) as an amendment to the Clean Water Act, in part to prevent this sort of disaster (US Environmental Protection Agency 2015). The OPA "streamlined and strengthened [the] EPA's ability to prevent and respond to catastrophic oil spills," and increased the penalty for noncompliance (US Environmental Protection Agency 2014a, 2015). In September 2014, a US District Court judge found that BP had acted with gross negligence and willful misconduct prior to the spill, citing an "extreme deviation from the standard of care and conscious disregard of known risks" (United States of America v. BP Exploration & Production, Inc., et al. 2014). In other words, the judge found BP to be in violation of the Clean Water Act. In this instance, it is clear that environmental regulation failed to have its intended effect.

On the other hand, there are numerous examples of regulatory intervention that have been credited with driving environmental improvement. For example, in textiles, the Cotton Dust Standard is credited with improving worker health while achieving compliance significantly faster and at lower cost than had been estimated (Glindmeyer et al. 1991; Occupational Safety and Health Administration 2000); and in power generation, the Acid Rain Program amendment to the Clean Air Act has been credited with reducing sulfur dioxide (SO_2) emissions by roughly two-thirds relative to their baseline levels (Ellerman et al. 2000; Ellerman 2003; Stavins and Schmalensee 2012). This begs the question: what determines whether or not the regulation of firms' production technologies and processes will ultimately be successful in abating environmental harm? To explore that question, one must first understand: (1) the primary characteristics of environmental regulation that influence a profit-maximizing firm's decision-making; and (2) the strategic options that a profit-maximizing firm has when faced with costly environmental regulation. Before turning our attention to these two points, however, it is useful to first understand when and why the regulation of firms' production processes and technologies is necessary.

12.2 Production Technology and Environmental Impact

At the highest level, the environmental impact of a good, or collection of goods, can be viewed through the lens of the well-known "IPAT" equation, which was introduced by Ehrlich and Holdren (1971).

$$\text{(I)mpact} = \text{(P)opulation} \times \text{(A)ffluence} \times \text{(T)echnology} \quad (12.1)$$

Considering the global economy (as Ehrlich and Holdren were), environmental impact is a product of the world's population, "affluence" which is a proxy for per capita consumption, and "technology" which is a measure of per-unit environmental harm. Population and "affluence" co-determine aggregate consumption. As illustrated in Figs. 12.1, 12.2, and 12.3, both population and per capita consumption have grown considerably over the past decades, propelling tremendous growth in aggregate consumption.

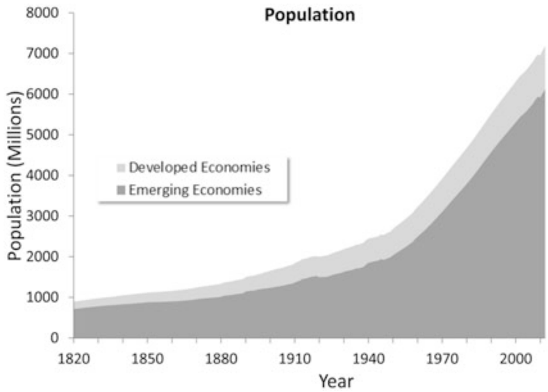

Fig. 12.1 Global population increased to roughly 7 billion by 2011, with 92.3 % of the increase from roughly 4 billion in 1970 occurring in emerging economies (Global Financial Data 2013)

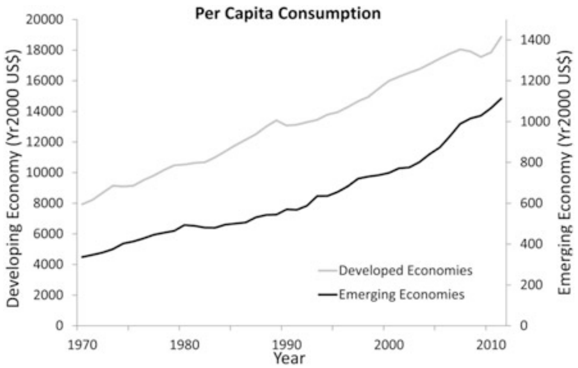

Fig. 12.2 Per capita consumption in the developed world grew to $18,869 by 2011, roughly 2.4 times 1970s levels, and to $1113 in emerging economies, or roughly 3.3 times 1970s levels (World Bank 2013)

As is evident in Fig. 12.2, per capita consumption in emerging economies is only 1/17th the level of per capita consumption in developed economies (World Bank 2013). As Drake and Spinler (2013) note, we should expect continued per capita growth as emerging economies close this consumption gap. Combined with projected population growth through this century (United Nations 2011), this suggests that we should expect continued growth in aggregate consumption for the foreseeable future. In the effort to abate environmental impact, these trends leave "T" as the most promising lever.

While the "T" from the IPAT equation nominally represents "technology", for our purposes, it is better interpreted as the per-unit environmental harm done by a given product or service. This includes the environmental harm or

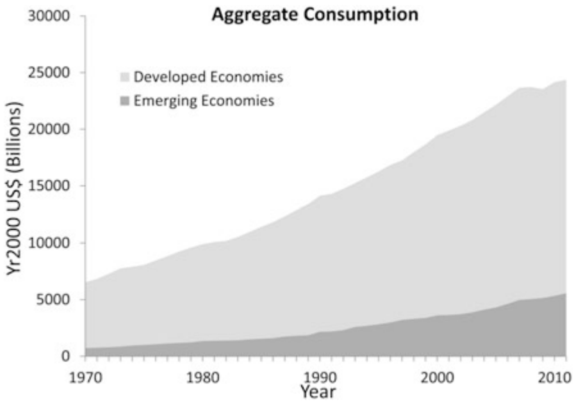

Fig. 12.3 Since 1970, population and per capita consumption trends have driven roughly a 225 % increase in aggregate consumption within developed economies and an astonishing 676 % increase in aggregate consumption within emerging economies (World Bank 2013)

risk related to the given product's or service's material sourcing, production, distribution, use, and disposal.

At times, firms take responsibility for reducing this per unit damage themselves. In its early days, for example, Patagonia phased out the production of a steel piton used for mountaineering when they realized the damage being done to the rock faces of the mountains on which it was used—at the time, the steel piton was Patagonia's top-selling product (Patagonia 2015). Decades later, after learning of damages resulting from fertilizers and pesticides used in conventional cotton farming, the firm voluntarily transitioned to organic cotton for the manufacture of their cotton shirts, even though this roughly doubled their production cost (Bonner 1997). Large, multi-national firms have also demonstrated such stewardship. Unilever, for example, co-founded the Roundtable on Sustainable Palm Oil (RSPO) in 2004 to eliminate deforestation and forest degradation resulting from palm oil sourcing. By 2014, the RSPO included over 2000 members representing over 40 % of all palm oil production worldwide (Unilever 2014). Nike, Dow Chemical, and others have also been lauded recently for their voluntary efforts to reduce the environmental impact of their operations (MarketWatch 2014; Roston 2012).

Despite these examples, however, market forces and/or corporate cultures can be such that regulatory intervention is required to drive environmental improvement. When a product's principal environmental impact derives from sourcing, manufacturing, or distribution, then that regulatory intervention is generally best-directed toward firms' operations. As noted above, at times such regulation succeeds and in other instances it fails. The remainder of this chapter focuses on such regulation, with the aim of developing insight into the factors that determine its outcome.

12.3 Regulatory Dimensions: Expected Cost of Noncompliance and Asymmetry

The expected cost of noncompliance and asymmetry in the stringency of regulation between regions are two of the primary dimensions that determine the effect of regulation on firm decisions (regulatory uncertainty—whether or not regulation will be implemented, or whether and how regulation may be changed—can also play an important role, but is beyond the scope of this chapter). In deciding how to respond to enacted regulation, profit-maximizing firms will weigh the expected cost of compliance against the expected cost of noncompliance. If the product is transportable, then firms will compare these costs across regions, a setting in which regulatory asymmetry becomes an important consideration.

12.3.1 Expected Cost of Noncompliance

In 1272, King Edward I banned the domestic burning of coal due to the smog that it created, ultimately making its use punishable by death. The ban was ignored and the use of coal as a source of heat continued unabated (Urbanito 1994). With such a severe penalty for disobeying the coal ban, how did King Edward's prohibition fail to have its intended effect?

The expected cost for violating enacted regulation is not determined by the stated penalty alone. The expected cost is a product of three drivers: (1) the stated penalty for noncompliance; (2) the likelihood that noncompliance will be detected by the regulator; and (3) the likelihood that detected violations will incur the penalty.

Expected Cost		**Penalty**		**Detection**		**Enforcement**
of noncompliance	=	Magnitude of penalty for noncompliance	×	Probability that noncompliant behavior will be discovered	×	Probability that detected noncompliance will be penalized

For regulation to prove effective, not only must there be a meaningful penalty for noncompliant behavior, there must also be a reasonable chance for the regulator to detect noncompliance and, once detected, a reasonable likelihood that the regulator will enforce the penalty. If any of these three components are insufficient, then regulation is unlikely to alter decision-making.

In the coal example, King Edward's ban did little to change behavior because there was little effort made to detect its use, and thankfully the punishment was not generally enforced when coal use *was* detected (the first citizen found burning coal in violation of the ban was executed, but no others were). King Edward's ban also failed because there was no feasible alternative to turn to; wood was available, but so expensive that few could afford it (Urbanito 1994). In other words, the cost of compliance (switching from coal- to wood-burning for needed heat) was sufficiently steep that it was unachievable for most under King Edward's rule.

While King Edward's coal ban is an extreme and certainly unjust example of environmental regulation, it is illustrative. Implementing regulation with sufficiently meaningful expected penalties to incentivize improvement is not just a matter of the policy's stated penalties. It is also a matter of having appropriate monitoring infrastructure in place, having the will to enforce penalties when detected, and ensuring that feasible alternatives are available and/or discoverable. As we will see in Sect. 12.4, well-intended regulation does not always achieve these ends.

12.3.2 Regulatory Asymmetry

In the early 2000s, amidst electricity market deregulation, rolling blackouts, and a growing population, power needs in California became difficult to meet domestically. To meet demand, US energy companies increased generating capacity across the border in northern Mexico—where relatively lax environmental regulations and a much faster licensing process (in addition to lower construction costs) made for cheaper electricity production—which could be imported via cross-border transmission lines to the US (Carruthers 2007; Weiner 2002; Blackman et al. 2012; California Energy Commission 2012). In 2003 two large power plants, InterGen's La Rosita Power Project and Sempra Energy's Termoeléctrica de Mexicali plant, began operating near Mexicali, Mexico over the objections of environmental and citizens groups on both sides of the border (Carruthers 2007). Opponents said pollution from the plants' operations would not only degrade human health and the environment in Mexico, but would likely cross the border to reduce already impaired air quality in California's Imperial Valley and increase respiratory illnesses among residents (Blackman et al. 2012; Imperial Irrigation District 2010; Government Accountability Office 2005).

In 2010, California passed a bill (California AB-2037) that required Mexican power generators to comply with California air quality regulations in order to sell electricity to California utilities (Blackman et al. 2012). However, this law only applied to new power plants, not existing plants (Bussewitz 2010). In response to the controversy the Mexicali plants eventually installed some pollution control measures, but would still not comply with the stricter environmental standards in the US (Carruthers 2007; Blackman et al. 2012).

12.3.2.1 Regulatory Asymmetry and "Leakage"

In the example above, regulatory asymmetry led to facilities in each region operating to different standards. To that extent, the regulation in place at the time in the US seems to have successfully led to environmental improvement in the operations over which they applied. However, those environmental standards also resulted in a phenomenon known as "leakage"; the relocation of production from the higher-regulatory-standard region to the lower-regulatory-standard region. The cement industry under the European Union Emissions Trading Scheme (EU-ETS) provides another illustration of the risk of such leakage.

Cement possesses a low margin-to-mass ratio, making it relatively expensive to transport. It is also composed primarily of limestone, which is widely available. These two facts have historically made cement (in most cases) infeasible and unnecessary to ship significant distances. As evident in Fig. 12.4, production and capital recovery costs (the black portion of each column) are greater in Europe than in regions in which they could potentially receive imports. However, after accounting for transport costs from those regions to Europe (the white portion of the column for each potential exporting region), European cement manufacturers have traditionally had the distinct cost advantage (Boston Consulting Group 2008b). As a consequence, less than 1.5 % of European cement revenues were generated by imports from extra-EU regions (European Commission 2009). The EU-ETS, however, could dramatically change this competitive balance.

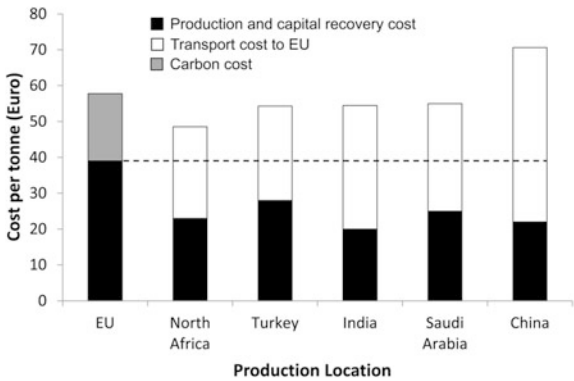

Fig. 12.4 Total landed cost (production and capital recovery cost plus transport cost) is greater outside of Europe than within Europe. However, emissions regulation threatens to put European cement manufacturers at a cost disadvantage, potentially resulting in imports displacing the production of cement in Europe (sources: Boston Consulting Group 2008b; Thomson Reuters 2014)

The EU-ETS applies carbon costs to goods produced within Europe, but not to goods produced outside Europe that are imported into the region. Consequently, as illustrated in Fig. 12.4, carbon costs projected to be incurred by European manufacturers under Phase 4 of the policy (to be implemented in 2020) swing the advantage to potential exporting regions.[1] Due to the regionally-asymmetric nature of carbon regulation, cement manufacturers in North Africa are expected to have a significant cost advantage over European manufacturers, and manufacturers in Turkey, India, and Saudi Arabia are expected to have a slight cost advantage.

Unabated, this setting is likely to lead to leakage, with European production being displaced by production elsewhere. Indeed, Boston Consulting Group (2008a) projects that at an emissions allowance price of €25 per ton of CO_2, all production in Italy, Greece, Poland, and the United Kingdom would be displaced by imports from countries beyond the umbrella of the EU-ETS. When leakage arises, regulation fails to have its intended effect. Rather than abate environmental harm, regulation that leads to leakage simply relocates it. By doing so, the regulation can have adverse effects. In the cement example here, Boston Consulting Group (2008a) estimates that, as a result of the leakage described above, global emissions would *increase* by 7 million tons of CO_2, in part due to the difference in production technologies employed, and in part due to the increased transportation required to ship cement to the EU.

12.4 Examples of Environmental Regulation Outcomes

As is clear from the discussion above, well-intentioned environmental regulation varies considerably in its effect on firm decisions. In some instances, the regulation is ignored by the firms it targets, in others it results in firms exiting the region or abandoning the market entirely, and in many other instances it results in the desired abatement. The expected cost of noncompliance (relative to the expected cost of compliance) and the degree of regional asymmetry in regulatory stringency are two of the most important determinants of firms' responses. Here, we offer examples where firm decisions were driven by each.

12.4.1 Expected Cost of Noncompliance is Too Low

There are many instances where environmental regulation fails to have its desired effect, or any effect at all, on firm abatement efforts. In such cases, an insufficient expected cost for remaining noncompliant with the regulation is often to blame. As noted above, the expected cost of noncompliance might not drive change because the stated penalty itself is insufficient, or because there is inadequate monitoring to detect violations and/or too little enforcement of the regulatory controls.

---

[1] The carbon cost per ton of cement in Fig. 12.4 assumes a cost of €25 per ton of CO_2, roughly in line with Point Carbon's projected average cost of €23 per ton for 2020–2030 (Thomson Reuters 2014).

12.4.1.1 Insufficient Penalty: Leak Detection in Gasoline Storage

One of the most obvious ways in which the expected cost of noncompliance can prove insufficient is if the established penalty for violations is not substantial enough to encourage compliance.[2] In September, 2011, the State of California accused Chevron USA and Chevron Stations of, among other things, tampering with leak detection equipment. At issue was the placement of sensors that are intended to alert operators if underground gasoline storage tanks at the stations were leaking. Such leak detection sensors are only effective when installed within a certain, known, distance from the tanks, and many of Chevron's sensors had been placed out of that range, rendering them useless. Chevron settled with the State a week later, agreeing to pay $24.5 million and submit to a statewide compliance program to correct the violations (State of California Department of Justice, Office of the Attorney General 2011).

Almost a year and a half later, in January 2013, the State sued Phillips 66 and ConocoPhillips (State of California Department of Justice, Office of the Attorney General 2013b), and a month later sued BP and their ARCO gas stations for many of the same violations levied against Chevron (State of California Department of Justice, Office of the Attorney General 2013a). In some cases, the State alleges that BP instructed station owners to improperly install the sensor equipment (CBS San Francisco and Bay City News Service 2013). Presumably these firms were aware of Chevron's settlement and the State's continued detection efforts. Thus, the detection and enforcement of similar violations was likely. Both Phillips 66/ConocoPhillips and BP/ARCO had plenty of time to correctly place any improperly installed sensors, but, ultimately, they were accused of running afoul of the same regulations as Chevron, suggesting that the penalty (signalled through Chevron's settlement) may have been insufficient to catalyze action.

12.4.1.2 Insufficient Detection: The Deepwater Horizon Disaster

The presidential commission responsible for investigating the *Deepwater Horizon* disaster found that the explosion and spill were preventable. They claimed several poor decisions and omissions had contributed to the disaster, including failure to use a sufficient number of centralizers to keep the pipe in the center of the well, poor selection in the type of steel used, and a failure to heed or share test results that indicated that the well seal was subject to failure (Graham et al. 2011). Why, with regulation in place to address offshore oil drilling safety, did BP operate *Deepwater Horizon* horizon drilling this way?[3] Arguably, they deemed it was unlikely that they would be

[2] Penalties can result from administrative, civil, or criminal actions (Stafford 2002).

[3] While multiple companies are being held liable for the accident and spill to different degrees, the burden is mostly BP's. Federal judge Carl Barbier recently ruled that BP is

caught; i.e., the detection of noncompliant operation was insufficient because the monitoring organization was found to be compromised (Graham et al. 2011).

Monitoring the compliance of offshore drilling operations with the Clean Water Act was the responsibility of the then-named Minerals Management Service (MMS). However, in addition to monitoring compliance, the MMS also collected revenue for offshore drilling rights from the same facilities it was tasked to monitor. The presidential commission found that a "culture of revenue maximization" at the MMS had led to poor oversight of offshore drillers in US waters. In fact, every Director of the MMS for the 15 years prior to the *Deepwater Horizon* disaster, has since acknowledged the primacy of royalty collection over regulatory oversight at the agency (Graham et al. 2011).

It was in this compromised regulatory environment that BP ignored the industry's best practices in order to save money and time (Graham et al. 2011). Despite the presence of protective laws on the books, the company chose to ignore them and (absent the disaster that ultimately arose) they could do so with little fear that they would be caught. The expected cost of noncompliance was low because detection efforts were insufficient.

One of the outcomes of the scandal surrounding the MMS's failures to prevent the BP disaster was a total reorganization of the agency into three new agencies in order to separate the collection of oil and gas royalties from regulatory oversight: the Bureau of Ocean Energy Management; the Bureau of Safety and Environmental Enforcement; and the Office of Natural Resources Revenue (Bureau of Ocean Energy Management, Regulation and Enforcement 2015; Salazar 2010). In direct response to the *Deepwater Horizon* disaster, the Department of Interior also recently proposed new regulations to "improve equipment reliability" and reform rules "in well design, well control, casing, cementing, real-time well monitoring and subsea containment" (US Department of Interior 2015).

12.4.1.3 Insufficient Enforcement: New Mexico's Dairy Industry

Dairy farming has been part of life in the US Southwest since Spanish colonization. However, nitrate, a by-product of dairy farming, can contaminate sources of drinking water in the absence of adequate containment (Doremus 2003). This is of particular concern in the arid state of New Mexico where 90 % of drinking water is sourced from aquifers (South Central Climate Science Center 2015; US Environmental Protection Agency 2011), some of which are relics of the last ice age (Plummer et al. 2004).

Nitrate enters groundwater through porous soil if dairy farmers dump waste from their cows into unlined or inadequately lined retention lagoons,

67 % responsible, Transocean 30 %, and Halliburton 3 % (United States of America v. BP Exploration & Production, Inc., et al. 2014).

among other avenues (Doremus 2003). Once nitrate contaminates the water, it's expensive and difficult to remove. Consuming contaminated water is especially dangerous to infants, potentially causing "blue baby syndrome" (low blood oxygen in babies), and death (US Environmental Protection Agency 2014b). To prevent such contamination, New Mexico has set limits on several contaminants, including nitrate, allowed in its groundwater (Olson 2015). To monitor compliance, all dairies are required to have permits, and all permits require monitoring wells, with sampling results submitted to the Ground Water Quality Bureau (McGrath 2010). By 2010, nearly all permitted dairies in New Mexico had monitoring wells installed (McGrath 2010).

Despite the near-universal monitoring, and the existence of technology to prevent contamination (in this case, the installation of synthetic liners), most New Mexico dairy farmers operate out of compliance. Many opt not to line their wastewater storage lagoons, or to line them with clay, manure, or compacted earth, which do little to prevent contamination. As a result, nitrate groundwater contamination has been discovered at 60 % of the state's dairies, with nitrate levels at 20 times the allowable limits in some cases (McGrath 2010).

In this case, the issue is one of insufficient enforcement. The agency responsible for overseeing compliance—the Ground Water Quality Bureau—has experienced high turnover of key staff (Keller 2013; Paskus 2013), is chronically understaffed,[4] and is currently awaiting the outcome of administrative hearings to determine whether the permitting process will remain in place or become less rigorous in terms of groundwater protection, which the industry is pushing for (Keller 2013; New Mexico Environment Department 2014; Olson 2015). As a consequence, they have been unable to enforce compliance in the manner intended, and dairy farmers can operate out of compliance with little risk of punishment. In fact, if this scenario were to change and enforcement were made more likely, some operators have expressed an intent to take their business elsewhere: "we will go to Texas, or we will go to Oklahoma, or we will go to Colorado" (Ogburn 2011).

12.4.2 Expected Cost of Noncompliance is Too High

As suggested by the threat above to take dairy business to states other than New Mexico if groundwater controls there were fully enforced, the expected cost of complying with regulation can cause firms to offshore or abandon

[4] Based on the authors' personal experience and the Ground Water Quality Bureau's organizational chart (New Mexico Environment Department, Ground Water Quality Bureau 2014).

a market altogether. Examples from lead smelting demonstrate this risk of offshoring and market abandonment.

12.4.2.1 Offshoring: Secondary Lead Smelting in the US

Spent (i.e., depleted) lead-acid batteries (SLABs) provide raw material for secondary lead smelters (defined as smelters that use sources other than raw lead ore), with these SLAB smelters responsible for 90 % of US lead production. Further, approximately 90 % of the lead consumed in the US is in the form of lead-acid batteries (Guberman 2014). Lead production in the US therefore has many characteristics of a closed loop supply chain—lead-acid battery recovery enables production that serves lead-acid battery demand—except there is a hitch.

There is an extremely high recycling rate for SLABs in the US, on the order of 98 % recovery (The Battery Council International 2013). However, many hazardous materials can be emitted in the recycling process, including lead, so the process is strictly controlled by US environmental regulations, which drives significant compliance costs (US Environmental Protection Agency 2014c). To prevent *leakage*—the relocation of production from the regulated region to less-regulated regions—it has been made illegal in the US to send unauthorized batteries to be recycled in other countries (US Environmental Protection Agency 2012). Nevertheless, due to regional variation in compliance costs, significant volumes of the SLABs recovered in the US are exported to regions with lower regulatory standards, including Mexico, with roughly a 500 % increase in known SLAB exports from the US to Mexico between 2004 and 2011.[5] By 2012, US exports supplied up to 60 % of the SLABs recycled in Mexico (Lloyd 2012).

Rather than the regulation succeeding in abating the targeted toxic emissions, leakage results in their relocation and potential exacerbation. In the case of Mexican SLAB recycling, for example, the standards for worker exposure and environmental contamination are much lower in authorized Mexican facilities than in US facilities, and nonexistent in unauthorized facilities, of which there are many (Lloyd 2012). As a result, contamination poses a significant problem—Mexican workers in one recycling plant were found to have blood lead levels five times higher than workers in a US plant (Occupational Knowledge International and Fronteras Comunes 2011), and soil sampled by the New York Times at an elementary school playground outside of another Mexican plant had lead levels five times higher than considered safe by the US EPA (Rosenthal 2011).

[5] The US ambient air standards for lead became even more restrictive in 2008, which to led a surge in lead battery exports (Lloyd 2012).

12.4.2.2 Abandonment: Primary Lead Smelting in the US

Until recently, the US was home to both secondary and primary lead smelting. However, the last primary lead smelter—located in Herculaneum, MO, and operated by the Doe Run Company—closed in late 2013. The company made an agreement with the EPA to shut down rather than upgrade the plant with new technology that would reduce SO_2 and lead emissions at a cost of around \$100 million (The Doe Run Company 2013; Jones 2013). In the words of Doe Run Company's general manager Gary Hughes:

> We are aware of no primary lead smelting process that will meet the standard for ambient air at the Herculaneum site. We believe the only existing technology that can meet today's standards in Herculaneum, as well as potential future standards, is the new electrowinning lead metal process we announced in 2010. We hoped to be building such a plant by now, however constructing a full-scale plant given other regulatory compliance spending requirements puts our company at financial risk (The Doe Run Company 2013).

In this case, rather than reducing the environmental intensity of primary lead smelting, regulation forced the smelters to shutter their business. Whether or not this would be beneficial or harmful to the environment depends on how the demand that had been served by primary smelters is satisfied post-abandonment. If consumption decreases or demand is served by less environmentally-intensive producers as a result of abandonment, then the environmental performance would improve as a consequence of abandonment. However, if the production in the regulated region is simply displaced by less-regulated production outside the region (i.e., *leakage* results from abandonment), then abandonment can increase environmental intensity due to the use of more toxic processes and technologies and the additional transport required to deliver the goods to the regulated market.

12.4.3 Expected Cost of Noncompliance is On-Target

Environmental regulation will incentivize firms to invest in abatement effort when: (1) the expected penalties for noncompliance exceed the cost of compliance; and (2) the cost of compliance are more favorable than offshoring production or exiting the market. In such settings, not only do the odds of a firm embracing regulatory requirements through the adoption of proven technologies increase, but innovation related to abatement efforts can be catalyzed as well, as the following examples from the textile and power generation sectors illustrate.

12.4.3.1 Adoption: The Cotton Dust Standard

Cotton dust, a waste by-product emitted during yarn manufacturing and automated knitting and weaving, was known to cause byssinosis ("brown-lung disease"), which is a respiratory illness resulting in wheezing, shortness of breath, and sometimes death among the exposed (Sutcliffe 2000). The Occupational Safety and Health Administration (OSHA) passed the Cotton Dust Standard to keep cotton dust emissions within levels deemed safe for worker health. Producers fiercely fought the regulation, claiming that it would cause them to bear an economic burden that would undermine their ability to compete in the global market (The Wall Street Journal 1981). In 1981, the US Supreme Court upheld the Standard, deciding that OSHA was not obligated to consider the cost-benefit of regulation when protecting worker health (Viscusi 1985). Producers ultimately complied with the Standard, with actual compliance costs coming in more than an order of magnitude *under* industry projections (The Wall Street Journal 1981; Occupational Safety and Health Administration 2000).

Contrary to the sector's protestations, compliance with the Cotton Dust Standard was credited with improving the global competitiveness of US textile manufacturing. At the time, *The Economist* reported that US textile exports increased 45 % year-over-year due to the regulation catalyzing a technological advantage, stating that "tighter dust control rules for cotton plants caused firms to throw out tonnes of old, inefficient machinery and to replace it with the latest available—to produce better quality and higher output speeds of fabrics" (1980).

Industry compliance with the regulation occurred faster than required, more cheaply than predicted, and was successful in protecting worker health by greatly reducing the incidence of brown lung disease among textile workers (Glindmeyer et al. 1991; Occupational Safety and Health Administration 2000). The Cotton Dust Standard proved successful because alternative, compliant technology existed, and the cost of compliance was significantly less than the penalties firms would have incurred had they failed to comply—in fact, by *The Economist*'s account (1980), the cost of compliance was negative in this case, improving firm profitability. The US textile industry was behind the times, technology-wise, and the Cotton Dust Standard provided the incentive to update its core technologies, boosting productivity even as the operators came into compliance with the new standards. Regulation spurred widespread adoption of an available technology. As we will see through the example below, well-designed regulation can also catalyze innovation to enable the adoption of new technologies.

12.4.3.2 Innovation: The Acid Rain Program

The Acid Rain Program (ARP) provisions of the 1990 Clean Air Act Amendments were implemented to address concerns over air pollution and the effects of acid rain caused by SO_2 and nitrogen oxide (NO_x) emissions from coal-fired power generation. The ARP is a classic cap and trade regime wherein the EPA determines the total number of SO_2 allowances to issue each year (i.e., they set the "cap"), and then coal-fired power generators buy and sell allowances from that fixed pool (i.e., they "trade"). If they over-comply relative to the number of allowances that they own, firms can sell their excess. If a firm emits more SO_2 than they have allowances for, they can purchase more allowances from the issued allowance-currency. This trading sets the allowance market price. To reduce the amount of SO_2 emitted, the EPA lowers the cap (i.e., total allowance currency) over time.[6]

The targeted reduction of SO_2, which was significantly more expensive to control than NO_x (Smock 1991), was set at 10 million tons below 1980 levels annually, representing roughly a 60 % reduction (Ellerman et al. 2000; Ellerman 2003; Stavins and Schmalensee 2012). Compliance with the SO_2 program was largely achieved by power generators switching to lower-sulfur coal and the use of flue-gas desulfurization systems; i.e., "scrubbers" (Ellerman 2003). The benefits have been substantial, with up to a 50-1 benefit-to-cost ratio, based largely on positive human health effects—reductions of respiratory disease and mercury toxicity—rather than acid rain reduction itself (Chestnut and Mills 2005; Stavins and Schmalensee 2012).

Unlike compliance with the Cotton Dust Standard, technological innovation (as opposed to the adoption of proven technologies) played a central role in the effectiveness of the ARP. In order to reduce their SO_2 emissions, coal-fired power generators learned how to mix various kinds of coal to create lower sulfur blends and how to develop financially feasible "scrubber" systems (Stavins and Schmalensee 2012, citing Bellas and Lange 2011; Ellerman et al. 2000; Frey 2008; Popp 2003). The ARP also led many companies to adopt new internal processes to account for allowance price uncertainty and risk when making operational decisions (Kruger 2005).

The regulatory landscape for power generators is politically loaded these days, but there was relatively little pushback when operators were faced with the ARP. Operators had a hand in designing the program, and the cap-and-trade design of the regulation provided the flexibility for improvements to be made where they were most cost efficient (while allowing others to "pay to pollute" through the purchase of allowances).

[6] If a reduction of SO_2 emissions does not arise when the cap is lowered, then the allowance price increases through standard demand and supply economics. As the cap is reduced further, this results in a cost trade-off that eventually favors improved abatement effort.

12.5 Decision Framework: Ignore, Avoid, Abandon, and Embrace

As discussed above, firms' responses to environmental regulation can run the gamut from ignoring the regulation, to implementing the intended improvements, to closing down or offshoring their business. Which path a profit-maximizing firm would take is determined, in part, by the expected cost of noncompliance p and the cost that they would incur to offshore F. Two other factors help determine a firm's response to environmental regulation: (1) the class of environmental regulation the firm faces; and (2) relative expected cost of noncompliance thresholds.

There are two broad classes of environmental regulation that a firm may face: a command-and-control/compliance-based regime, or a "pay-to-pollute"/market-based regime. Under compliance-based regulation—such as the New Mexico "Dairy Rule", the ambient air quality standards of the Clean Air Act amendments, and the Cotton Dust Standard—firms are either in compliance or out of compliance. Under a compliance-based regime, if the firm operates within the established standard it faces no penalty. They are only at risk of being penalized if they operate outside the standard (i.e., if they are noncompliant). Under a "pay-to-pollute" regime—such as the Acid Rain Program of the Clean Air Act Amendments and carbon emissions regulation under European Union Emissions Trading Scheme—there is no set standard per se. Under such a regime, each and every unit of the regulated pollutant that the firm emits is costly (i.e., causes them to consume a permit).

There are three expected cost of noncompliance thresholds that affect a profit-maximizing firm's decision-making in this context. First is the expected cost of noncompliance at which the firm is (economically) indifferent to compliance and noncompliance, p_c. Under compliance-based regulation, this is the break-even expected penalty for compliance. Under "pay-to-pollute" regulation, this can be viewed as the break-even expected penalty for clean technology adoption—i.e., it is the expected penalty at which the firm earns equal expected profits with a clean and dirty technology. Second is the expected noncompliance cost break-even for domestic and offshore production, $p_o(F)$, which increases as the cost to offshore increases (the profit-maximizing firm is willing to operate in the regulated domestic region at greater expected noncompliance costs if the cost to offshore is greater). And third is the expected cost of noncompliance threshold at which out-of-compliance production becomes unprofitable in the regulated region, p_e. These thresholds are summarized in Table 12.1.

The relative magnitudes of these thresholds determine a profit-maximizing firm's response to environmental regulation under both compliance-based and "pay-to-pollute" regimes.

Table 12.1 Expected cost of noncompliance thresholds

p_c	Expected noncompliance cost break-even for compliance/clean-tech adoption
$p_o(F)$	Expected noncompliance cost break-even for domestic and offshore production
p_e	Expected noncompliance cost beyond which domestic production is unprofitable

12.5.1 Decisions Under Compliance-Based Regulation[7]

A profit-maximizing firm's potential responses to compliance-based environmental regulation depend on whether: (1) the compliance threshold is less than the offshoring threshold for any fixed offshoring cost, $p_c \leq p_o(0)$; (2) the compliance threshold is greater than the offshoring threshold at some offshoring cost, but less than the exit threshold, $p_o(0) < p_c \leq p_e$; or (3) the compliance threshold is greater than the exit threshold, $p_e < p_c$.

If the break-even for compliance is less than the break-even between domestic and offshore profit at any offshoring cost, $p_c \leq p_o(0)$, then the firm will either ignore or embrace the regulation (as illustrated in Fig. 12.5a). If the expected cost of *non*-compliance, p, is greater than the expected cost of compliance, p_c, then the firm adheres to the regulation. Otherwise, the profit-maximizing firm ignores the regulation and continues operating as it had (e.g., *Deepwater Horizon* and the compromised monitoring of the MMS due to conflicts of interest).

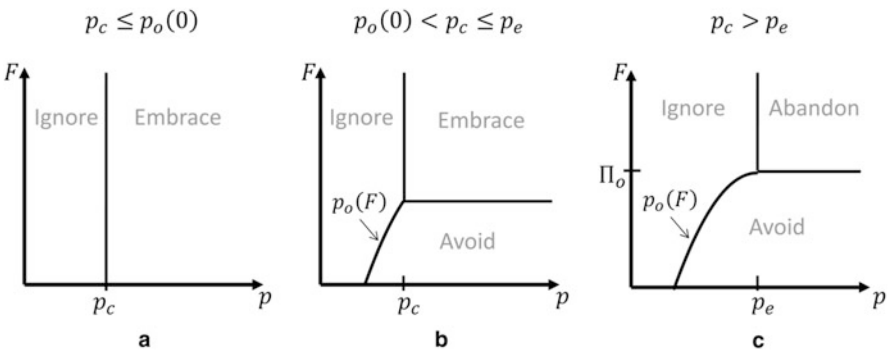

Fig. 12.5 Ignore, embrace, avoid, and abandon decisions under compliance-based regulation when: (**a**) the compliance threshold is less than the offshoring threshold, $p_c \leq p_o(0)$; (**b**) the compliance threshold is between the offshoring threshold and exit threshold, $p_o(0) < p_c \leq p_e$; and (**c**) the compliance threshold is greater than the exit threshold, $p_c > p_e$

[7] This section draws from logic developed in Drake (2015).

Figure 12.5b illustrates the case where $p_o(0) < p_c \leq p_e$; i.e., the expected cost of compliance is greater than the break-even between domestic and offshore profit at some fixed offshoring cost and it is less than the cost at which domestic production becomes unprofitable. In such a setting, the regulator can only induce compliance if the expected cost of noncompliance *and* offshoring costs, F, are sufficiently great. If the cost a firm incurs when offshoring is small enough, then (because $p_o(0) < p_c$) a profit-maximizing firm would relocate their operations at a sufficiently great expected noncompliance cost rather than comply. Secondary lead smelting (discussed in Sect. 12.4 above), with its 500 % increase in SLAB exports to Mexico for processing there rather than in the US, provides one such example in which relocation was deemed a more attractive option to firms than compliance.

Lastly, the case where the expected cost of compliance exceeds the expected cost of noncompliance at which domestic production becomes unprofitable, $p_c > p_e$, is illustrated in Fig. 12.5c. In this setting, the regulator cannot induce a profit-maximizing firm to adopt more stringent standards at any expected cost of noncompliance. At sufficiently great noncompliance costs, firms will either avoid the regulation by offshoring production (if the cost to offshore is sufficiently small), or they will abandon the market if offshoring costs exceed the profit that they could earn by relocating, Π_o. Primary lead smelting in the US provides an example of this context, where increasingly stringent air quality standards contributed to the Doe Run Company closing the last primary lead smelter in the country. If the demand that the abandoning firm had served is satisfied by less environmentally impactful providers, then abandonment by the worst performers can be a beneficial outcome. However, if market abandonment results in the abandoning firm's market share falling to more environmentally harmful producers (as can often be the case when demand shifts to less regulated regions due to abandonment), then the regulatory standards that drove abandonment would have an adverse effect on environmental performance.

12.5.2 Decisions Under "Pay-to-Pollute" Regulation

As with compliance-based regulation, firms' response to a "pay-to-pollute" regime depend on the relative magnitude of the clean technology adoption, offshoring, and exit thresholds, p_c, $p_o(0)$, and p_e, respectively. The key difference between compliance-based and "pay-to-pollute" regulation is that, under the latter, firms incur environmental costs regardless of the technology they operate (unless they fully eliminate the regulated pollutant), while the firm avoids further environmental cost under a compliance-based regulation so long as they meet the specified standard. As a consequence, it is possible for "pay-to-pollute" regulation to "overshoot", leading to offshoring or market abandonment rather than clean technology adoption.

The potential to overshoot is evident in the case where the clean technology adoption threshold is less than the offshoring threshold, $p_c \le p_o(0)$, illustrated in Fig. 12.6a. If the penalty for each unit of pollutant emitted, p, is sufficiently greater than the clean technology adoption threshold, regulation can result in offshoring or abandonment (depending on whether offshoring costs, F, are sufficiently small), which sharply contrasts the compliance-based setting illustrated in Fig. 12.5a. Similarly, overshooting is possible when the clean technology adoption threshold is greater than the offshoring threshold, but less than the exit threshold, i.e., $p_o(0) < p_c \le p_e$, as illustrated in Fig. 12.6b.

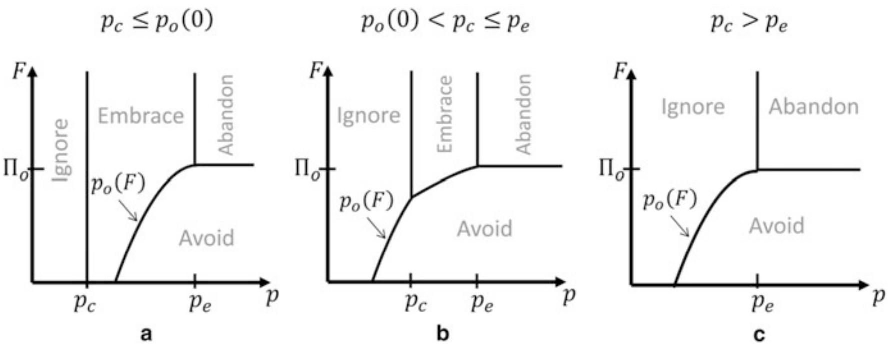

Fig. 12.6 Ignore, embrace, avoid, and abandon decisions under "pay-to-pollute" regulation when: (**a**) the clean technology adoption threshold is less than the offshoring threshold, $p_c \le p_o(0)$; (**b**) the adoption threshold is between the offshoring threshold and exit threshold, $p_o(0) < p_c \le p_e$; and (**c**) the adoption threshold is greater than the exit threshold, $p_c > p_e$

If the clean technology adoption threshold exceeds the exit threshold, $p_c > p_e$, then overshooting is not a concern because, as in the case with compliance-based regulation, there is no region in which the regulator can induce environmental improvement (as illustrated in Fig. 12.6c). This appears to be the setting with carbon capture and storage in cement under the EU-ETS as described in Sect. 12.3.2.1, where the emission price that would incentivize the adoption of carbon capture and storage technology (European Cement Research Academy 2009) is greater than the emissions price at which cement production would offshore or abandon the market (Boston Consulting Group 2008a).

12.6 Conclusion

A regulator's ability to incentivize environmental improvement among firms is vital in achieving long-term sustainability, particularly with continued growth in aggregate consumption projected. However, firms can and do respond to environmental regulation in a variety of ways: complying with its intent; avoiding the regulation by offshoring or by abandoning the market; or ignoring the regulation by continuing with entrenched business practices.

The path a profit-maximizing firm will choose depends, in part, on the expected cost of noncompliance, which is a product of the regulator's stated penalty, the likelihood that noncompliant practices are detected, and the likelihood that detected violations are punished. However, the type of regulatory regime—compliance-based or "pay-to-pollute"—and three cost thresholds also drive firm response: (1) the compliance or clean technology adoption threshold; (2) the offshoring threshold; and (3) the exit threshold. Understanding how these thresholds interact with the type of regulatory regime being considered and the expected cost of noncompliance to determine whether firms ignore, avoid, or embrace the regulation is a vital first step in the design of efficacious environmental policy.

References

Bellas AS, Lange I (2011) Evidence of innovation and diffusion under tradable permit programs. Int Rev Environ Resour Econ 5(1):1–22

Blackman A, Chandru S, Mendoza-Dominguez A, Russell AG (2012) Health impacts of power-exporting plants in northern Mexico. Resour Future. Available at http://www.rff.org/research/publications/health-impacts-power-exporting-plants-northern-mexico-0. Accessed 11 Mar 2015

Bonner S (1997) Patagonia: a green endeavor. Appar Ind Mag 58(2):46–48

Boston Consulting Group (2008a) Assessment of the impact of the 2013–2020 ETS proposal on the European cement industry

Boston Consulting Group (2008b) Assessment of the impact of the 2013–2020 ETS proposal on the European cement industry: methods and assumptions

Bureau of Ocean Energy Management, Regulation and Enforcement (2015) Reorganization of the Bureau of Ocean Energy Management, Regulation and Enforcement. Available at http://www.boemre.gov/. Accessed 30 Jan 2015

Bussewitz C (2010) Calif-bill would block out-of-state power deals. Associated Press, Sacramento, CA

California Energy Commission (2012) California electricity demand: historic noncoincident peak demand (in megawatts). Available at http://energyalmanac.ca.gov/electricity/historic_peak_demand.html. Accessed 11 Mar 2015

Carruthers DV (2007) Environmental justice and the politics of energy on the US-Mexico border. Environ Polit 16(3):394–413

CBS San Francisco and Bay City News Service (2013) State sues BP, Arco over alleged environmental violations at stations. Available at http://sanfrancisco.cbslocal.com/2013/02/04/state-sues-bp-arco-over-alleged-environmental-violations-at-gas-stations/. Accessed 28 Oct 2014

Chestnut LG, Mills DM (2005) A fresh look at the benefits and costs of the US Acid Rain Program. J Environ Manag 77(3):252–266

Crooks E (2015) BP 'gulf spill' civil trial enters final phase. Financial Times (online edition). Available at http://www.ft.com/intl/cms/s/0/5a143052-9cd7-11e4-adf3-00144feabdc0.html#axzz3jGy6gIO7. Accessed 20 Jan 2015

Doremus D (2003) Environmental regulation of New Mexico's dairy industry. In: Proceedings of the decision-makers field conference 2002, the Lower Pecos Region. Available at https://www.env.nm.gov/gwb/New_Pages/docs_policy/DoremusDecisionMakers.pdf. Accessed 29 Jan 2015

Drake DF (2015) Carbon tariffs: Effects in settings with technology choice and foreign production cost advantage. Harvard Business School Working paper

Drake DF, Spinler S (2013) Sustainable operations management: an enduring stream or a passing fancy? Manuf Serv Oper Manag 15(4):689–700

Ehrlich PR, Holdren JP (1971) Impact of population growth. Science 171(3977):1212–1217

Ellerman AD (2003) Lessons from phase 2 compliance with the US Acid Rain Program

Ellerman AD, Joskow PL, Schmalensee R, Montero J, Bailey EM (2000) Markets for clean air: the US Acid Rain Program. Cambridge University Press, Cambridge/ New York, NY, iD: HVD_ALEPH008478406; includes bibliographical references (p. 343–352) and index

European Cement Research Academy (2009) Technology paper number 31: post combustion capture using absorption technologies. Cem Sustain Initiat. http://www.wbcsdcement.org/pdf/technology/Technology%20papers.pdf. Accessed Jan 2014

European Commission (2009) Glass, ceramic, clay and cement production statistics—NACE Rev. 1.1 (Tables 1 and 4). Available at http://ec.europa.eu/eurostat/statistics-explained/index.php/Archive:Glass,_ceramic,_clay_and_cement_production_statistics_-_NACE_Rev._1.1. Accessed 21 Mar 2014

Frey E (2008) Technology diffusion and environmental regulation: the adoption of scrubbers by coal-fired power plants. NCEE working paper series, working paper #08-04

Glindmeyer HW, Lefante JJ, Jones RN, Rando R, Kader H, Weill H (1991) Exposure-related declines in the lung function of cotton textile workers. Am Rev Respir Dis 144(3):675–683

Global Financial Data (2013) GFDatabase: development database. Available at https://www.globalfinancialdata.com/databases/developmentdatabase.html. Accessed 13 Feb 2013

Government Accountability Office (2005) Air pollution; estimated emissions from two new Mexicali power plants are low, but health impacts are unknown. Available at http://www.gao.gov/new.items/d05823.pdf. Accessed 11 Mar 2015

Graham B, Reilly WK, Beinecke F, Boesch DF, Garcia TD, Murray CA, Ulmer F (2011) National commission on the BP Deepwater Horizon oil spill and offshore drilling; the gulf oil disaster and the future of offshore drilling. Report to the President [of the USA]

Guberman DE (2014) Lead fact sheet. USGS.gov. Available at http://minerals.usgs.gov/minerals/pubs/commodity/lead/mcs-2014-lead.pdf.

Imperial Irrigation District (2010) Resolution 9–2010 in support of AB-2037 Electricity: Air Pollution. Available at http://www.iid.com/home/showdocument?id=1140.

Jones T (2013) Last US lead smelter to shutter in ore-rich Missouri. Bloomberg.com (December 23). Available at http://www.bloomberg.com/news/articles/2013-12-23/last-u-s-lead-smelter-to-shutter-in-ore-rich-missouri. Accessed 28 Oct 2014

Keller SJ (2013) New Mexico's groundwater protections may take a hit. HCN.org (October 24). Available at http://www.hcn.org/issues/45.17/new-mexicos-groundwater-protections-may-take-a-hit. Accessed 28 Jan 2015

Kruger J (2005) Discussion paper: companies and regulators in emissions trading programs. RFF.org. Available at http://www.rff.org/Documents/RFF-DP-05-03.pdf. Accessed 28 Jan 2015

Lloyd E (2012) Hazardous trade? An examination of US-generated spent lead-acid battery exports and secondary lead recycling in Mexico, the United States and Canada. CEC.org. Available at http://www3.cec.org/islandora/en/item/11220-hazardous-trade-examination-us-generated-spent-lead-acid-battery-exports-and. Accessed 28 Jan 2015

MarketWatch (2014) Nike's sustainability report shows company reducing environmental impact while continuing to grow. Available at http://www.marketwatch.com/story/nikes-sustainability-report-shows-company-reducing-environmental-impact-while-continuing-to-grow-2014-05-07. Accessed 16 Jan 2015

McGrath S (2010) Testimony before the Water Quality Control Commission in the matter of: proposed amendment to 20.6.25 NMAC (Dairy Rules). Available at https://www.env.nm.gov/gwb/documents/DairyRegs/NOIAttachment2-SarahMcGrath Testimony03-07-10.pdf. Accessed 20 Jan 2015

New Mexico Environment Department (2014) State supreme court affirms Roswell as location for upcoming Dairy Rule hearings. Available at http://www.grantcountybeat.com/news/non-local-news-releases/19158-state-supreme-court-affirms-decision-to-hold-dairy-rule-hearings-in-roswell. Accessed 2 Feb 2015

New Mexico Environment Department, Ground Water Quality Bureau (2014) Ground Water Quality Bureau organizational chart, October 2014. Available at https://www.env.nm.gov/gwb/NMED-GWQB-OrganizationChart.htm. Accessed 28 Jan 2015

Occupational Knowledge International and Fronteras Comunes (2011) Exporting hazards: US shipments of used lead batteries to Mexico take advantage of lax environmental and worker health regulations. Available at http://www.okinternational.org/docs/Exporting%20Hazards_Study_100611v5.pdf . Accessed 22 Oct 2014

Occupational Safety and Health Administration (2000) Regulatory review of OSHA's Cotton Dust Standard [29 CFR 1910.1043]. Available at https://www.osha.gov/dea/lookback/cottondust_final2000.pdf. Accessed 10 Feb 2015

Ogburn SP (2011) A citizen activist forces New Mexico's dairies to clean up their act. HCN.org (December 5). Available at http://www.hcn.org/issues/43.20/a-citizen-activist-forces-new-mexicos-dairies-to-clean-up-their-act. Accessed 30 Jan 2015

Olson WC (2015) Personal communication (30 January 2015)

Paskus L (2013) The canary in the copper mine (is dead). Santa Fe Reporter SFReporter.com (May 14). Available at http://www.sfreporter.com/santafe/article-7423-the-canary-in-the-copper-mine-%28is-dead%29.html. Accessed 10 Feb 2015

Patagonia (2015) Company history. Available at http://www.patagonia.com/us/patagonia.go?assetid=3351. Accessed 16 Feb 2015

Plummer LN, Bexfield LM, Anderholm SK, Sanford WE, Busenberg E (2004) Geochemical characterization of ground-water flow in the Santa Fe group aquifer system, Middle Rio Grande basin, New Mexico Available at http://pubs.usgs.gov/wri/wri034131/pdf/wrir03-4131.pdf. Accessed 10 Feb 2015

Popp D (2003) Pollution control innovations and the Clean Air Act of 1990. J Policy Anal Manag 22(4):641–660

Rosenthal E (2011) Lead from old US batteries sent to Mexico raises risks. NYTimes.com (December 9). Available at http://www.nytimes.com/2011/12/09/science/earth/recycled-battery-lead-puts-mexicans-in-danger.html?pagewanted=all&_r=0. Accessed 28 Oct 2015

Roston E (2012) Stained by past, Dow Chemical wins new image embracing trees Bloomberg.com (June 26). Available at http://www.bloomberg.com/news/2012-06-26/stained-by-past-dow-chemical-wins-new-image-embracing-trees.html. Accessed 20 Jan 2015

Salazar K (2010) Order no. 3299. the establishment of the Bureau of Ocean Energy Management, the Bureau of Safety and Environmental Enforcement, and the Office of Natural Resources Revenue. Available at http://www.doi.gov/deepwaterhorizon/loader.cfm?csModule=security/getfile&PageID=32475. Accessed 10 Feb 2015

Smock R (1991) Utilities struggle with acid rain control compliance decisions. Power Eng 95(8):17–22

South Central Climate Science Center (2015) New Mexico drought histories. Available at http://www.southcentralclimate.org/index.php/pages/resources/category/new_mexico_drought_histories. Accessed 10 Feb 2015

Stafford S (2002) The effect of punishment on firm compliance with hazardous waste regulations. J Environ Econ Manag 44:290–308

State of California Department of Justice, Office of the Attorney General (2011) Attorney General Kamala D. Harris announces proposed $24.5 million settlement with Chevron gas station and tank owners. Available at http://oag.ca.gov/news/press-releases/attorney-general-kamala-d-harris-announces-proposed-245-million-settlement. Accessed 22 Dec 2014

State of California Department of Justice, Office of the Attorney General (2013a) Attorney General Kamala D. Harris sues BP and ARCO over environmental violations at gas stations. Available at https://oag.ca.gov/news/press-releases/attorney-general-kamala-d-harris-sues-bp-and-arco-over-environmental-violations. Accessed 22 Dec 2014

State of California Department of Justice, Office of the Attorney General (2013b) Attorney General Kamala D. Harris sues Phillips 66 and ConocoPhillips over environmental violations at gas stations. Available at https://oag.ca.gov/news/press-releases/attorney-general-kamala-d-harris-sues-phillips-66-and-conocophillips-over. Accessed 22 Dec 2014

Stavins RN, Schmalensee R (2012) The SO2 allowance trading system: the ironic history of a grand policy experiment. J Econ Perspect 27(1):103–122

Sutcliffe V (2000) OSHA amends Cotton dust standard. EHSToday.com. Available at http://ehstoday.com/news/ehs_imp_33930. Accessed 18 Feb 2015

The Battery Council International (2013) Battery recycling. Available at http://batterycouncil.org/?page=battery_recycling. Accessed 23 Jan 2015

The Doe Run Company (2013) The Doe Run Company provides update on closure of last primary lead smelter in US/press release, December 14, 2013. Available at http://www.doerun.com/media-center/news-releases/article/articletype/ar ticleview/articleid/107/the-doe-run-company-provides-update-on-closure-of-last-primary-lead-smelter-in-us. Accessed 28 Oct 2014

The Economist (1980) Textiles reel off the ropes. Economist 277(6 December):82–83

The Wall Street Journal (1981) Labor aide attacks OSHA stand on cost-benefit analysis. Wall Street J (March 30)

Thomson Reuters (2014) EU carbon price to average €23/t between 2021 and 2030: Thomson Reuters assess the future. Thomson Reuters (online) (August 28). Available at http://blog.financial.thomsonreuters.com/eu-carbon-price-average-e23t-2021-2030-thomson-reuters-assess-future/. Accessed 22 Jan 2015

Unilever (2014) Roundtable on Sustainable Palm Oil. Available at http://www.rspo.org/. Accessed 12 Jan 2015.

United Nations (2011) World population prospects: the 2010 revision, Volume 1: comprehensive tables. ST/ESA/SER.A/313. Department of Economic and Social Affairs, Population Division, United Nations, Geneva

United States of America v BP Exploration & Production, Inc., et al. (2014) In re. Oil Spill by the Rig “Deepwater Horizon” in the Gulf of Mexico, 844 F. Supp. 2d 746, 2012 US Dist. LEXIS 21795 (E.D. La., 2012) MDL 2179 SECTION J:LEXIS 123,245

Urbanito D (1994) London’s historic “pea-soupers”. Available at http://www2.epa.gov/aboutepa/londons-historic-pea-soupers. Accessed 16 Jan 2015

US Department of Interior (2015) Interior department releases proposed well control regulations to ensure safe and responsible offshore oil and gas development. Available at http://www.doi.gov/news/pressreleases/interior-department-releases-proposed-well-control-regulations-to-ensure-safe-and-responsible-offshore-oil-and-gas-development.cfm. Accessed 15 Apr 2015

US Environmental Protection Agency (2011) Ground water cleanup at superfund sites. Available at http://www.epa.gov/superfund/health/conmedia/gwdocs/brochure.htm. Accessed 29 Jan 2015

US Environmental Protection Agency (2012) Implementation resources for spent lead-acid battery exporters. Available at http://www.epa.gov/epawaste/hazard/international/oecd-res.htm. Accessed 25 Feb 2015

US Environmental Protection Agency (2014a) Summary of Oil Pollution Act. Available at http://www2.epa.gov/laws-regulations/summary-oil-pollution-act. Accessed 15 Jan 2015

US Environmental Protection Agency (2014b) Basic information about nitrate in drinking water. Available at http://water.epa.gov/drink/contaminants/basicinformation/nitrate.cfm. Accessed 29 Jan 2015

US Environmental Protection Agency (2014c) Fact sheet: proposed decision, national ambient air quality standards for lead. Available at http://www.epa.gov/oaqps001/lead/pdfs/20141219fs.pdf. Accessed 23 Jan 2015

US Environmental Protection Agency (2015) Oil Pollution Act overview. Available at http://www.epa.gov/oem/content/lawsregs/opaover.htm. Accessed 15 Jan 2015

Viscusi WK (1985) Cotton dust regulation: an OSHA success story? J Policy Anal Manag 4(3):325–343

Weiner T (2002) US will get power, and pollution, from Mexico. N Y Times NYTimes.com. Available at http://www.nytimes.com/2002/09/17/international/americas/17MEXI.html. Accessed 11 Mar 2015

World Bank (2013) World development Indicators database. Available at http://data.worldbank.org/data-catalog/world-development-indicators. Accessed 4 Feb 2013

Chapter 13
Strategic Disclosure of Social and Environmental Impacts in a Supply Chain

Basak Kalkanci, Erjie Ang, and Erica L. Plambeck

Abstract Governments are beginning to mandate that firms disclose what they learn about their social and environmental impacts in their supply chains (e.g., regarding use of conflict minerals and generation of greenhouse gases). This chapter shows that such a mandate will deter firms from measuring (and thus improving) those impacts, for two reasons. First, as demonstrated by consumer choice experiments, voluntary disclosure of these impacts can boost a firm's market share. Mandating disclosure, in contrast, reduces a firm's expected gain in market share from learning about these impacts and disclosing this information. Second, investors' valuation of a firm drops upon disclosure that impacts are high. Therefore, to the extent that managers are concerned about that valuation, a mandate for disclosure will discourage managers from seeking information about these impacts, lest they be forced to disclose that the impacts are high.

> *I don't want to touch it [IPE database of environmental violations by factories in China] or I would not be able to say "sorry, I don't know."*
>
> – Sourcing manager for a major brand, speaking to Ma Jun, director of the Institute for Public Economics

B. Kalkanci (✉)
Scheller College of Business, Georgia Institute of Technology, Atlanta, GA, USA
e-mail: Basak.Kalkanci@scheller.gatech.edu

E. Ang • E.L. Plambeck
Stanford Graduate School of Business, Stanford University, Stanford, CA, USA
e-mail: erjieang@stanford.edu; plambeck_erica@gsb.stanford.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_13

13.1 Introduction

Governments around the world are beginning to mandate that firms disclose information about social and environmental impacts in their supply chains. But does requiring greater transparency on such issues as conflict minerals and greenhouse gas emissions actually encourage firms to improve how they source inputs? The insights presented in this chapter [which are developed in Kalkanci et al. (2013) and Kalkanci and Plambeck (2015)] show that mandatory disclosure requirements may instead lead to higher social and environmental impacts.

A relatively small number of global firms actively try to monitor environmental and social impacts in their supply chains; most firms typically know only their first-tier suppliers. Learning about the social and environmental impacts associated with a final end product can be both difficult and costly, requiring close scrutiny of the extended supply chain from mining of raw materials, through multiple stages of manufacturing, to final use and disposal. Monitoring greenhouse gas emissions throughout the supply chain, for example, means going back to look at the energy used to produce basic materials like chemicals, metals, minerals, paper and petroleum products—this energy accounts for approximately 85 % of all industrial energy use and associated CO_2 emissions (IPCC 2007). Tracking the use of “conflict minerals” (gold, tantalum, tin, and tungsten that are mined and, directly or indirectly, help finance armed groups in the Democratic Republic of Congo and nearby areas) also proves difficult, as these inputs enter far upstream in the complex supply chains for a wide variety of end products, including consumer electronics and automobiles (Kearney 2012).

Despite the inherent difficulties in obtaining accurate information about suppliers, a firm that makes the effort to learn about social and environmental impacts in its supply chain is likely to find a number of ways to reduce those impacts, in some cases with little or no additional cost. At Wal-Mart, for example, reducing pollution in the supply chain made sense for improving overall productivity. One manager observed that “We had to look at the entire value chain. If we had focused on just our own operations, we would have limited ourselves to 10 % of our effect on the environment and, quite frankly, eliminated 90 % of the opportunity that’s out there.”

Making the effort to find this information also makes sense in a broader business analysis. Any firm is likely to face the possibility that, in the future, it may incur costs associated with its supply chain social and environmental impacts. Such costs might arise due to future climate change policy, for example, or negative publicity regarding suppliers’ social or environmental impacts. Indeed, among the firms surveyed by Lee et al. (2012), risk of brand damage is the primary motivation for measuring and addressing supply chain social and environmental impacts.

In valuing a firm, strategic investors try to account for potential future costs associated with the firm’s supply chain social and environmental impacts (Institutional Investors Group on Climate Change 2010; Griffin et al. 2014; Ioannou and Serafeim 2015). Managers often make decisions that increase the investors' current valuation of a firm at the expense of the firm's long-run profitability (Graham et al. 2005) in part because stock options constitute a large component of executive compensation (Frydman and Saks 2005). Thus, in deciding whether or not to learn about and disclose impacts, a manager considers both the long-term profit of the firm as well as its valuation by investors.

13.2 The Rationale for Mandatory Disclosure

Governments are beginning to mandate disclosure of social and environmental impacts. As a government cannot compel a firm to know all the social and environmental impacts of its supply chain, any mandate is limited to requiring that a firm disclose whatever it does know. For example, the U.S. Dodd-Frank Wall Street Reform and Consumer Protection Act mandates that firms must disclose any known use of conflict minerals. Following complaints from the National Association of Manufacturers and others regarding the costs and difficulties of learning about conflict minerals in complex supply chains, the Securities and Exchange Commission has granted that a firm may state that whether or not its product contains conflict minerals is "undeterminable" (SEC 2012).

In France, a new law grants consumers the right to information about the environmental impact of consumer products. In 2012, a subset of firms began labeling consumer products with their supply chain greenhouse gas emissions as part of a national experiment. The French government is currently collecting feedback from the participating companies, NGOs, and other actors to determine whether to mandate such labels on all consumer products (Ernst and Young 2013). Under a mandate, a firm that has not measured the supply chain emissions associated with its product will nevertheless be required to label the product with its best estimate of emissions, likely based on an industry average (French Ministry of Ecology, Sustainable Development and Energy 2012). Legal scholars Fung et al. (2007) warn that such policies, which require a firm to disclose what it knows, may fail to motivate the firm to take action. China, Denmark, Malaysia, and South Africa also are among the countries that have enacted regulations on mandatory disclosure.

In this chapter, we analyze the effect of mandatory disclosure on a firm's social and environmental impacts in its supply chain compared to voluntary disclosure. We use an analytical model to capture the firm's interaction with its investors and consumers. We use consumer choice experiments to inform our model about how disclosure of social and environmental impacts affects a firm's market share, depending on whether the disclosed information is positive or negative, and on whether the disclosure is voluntary or mandatory.

Below, we highlight key contributions of this work and how they relate to earlier literature. Extensive empirical literature (much of it based on U.S. Toxic Release Inventory data) suggests that requiring a firm to disclose its emissions will motivate the firm to reduce those emissions; Doshi et al. (2013) provide an excellent survey. Yet these papers address a requirement for a firm to disclose information about its own emissions, which presumably it knows or can easily learn, while our primary focus in this chapter is on supply chain impacts—wherein the issue of learning this information is more difficult.

The model-based literature (surveyed in Verrecchia 2001) suggests that mandatory disclosure requirements may be unnecessary to elicit full information disclosure by firms. In some analyses (Grossman 1981; Milgrom 1981), a seller with private information about the quality of its product always voluntarily discloses that information to customers, because lack of disclosure would be interpreted as a signal of poor quality. Subsequent works, however, show that a firm might choose not to voluntarily disclose information because doing so would be costly, or because customers or investors are uncertain about what the firm knows (Verrecchia 2001). Our results suggest that full information disclosure can be achieved voluntarily, to the extent that the consumers value a firm's leadership in the voluntary disclosure of negative social and environmental impacts.

A stream of model-based literature shows that mandatory disclosure can, paradoxically, increase social welfare by preventing firms from learning and disclosing information. If product quality testing is free, mandating disclosure prevents a seller from testing and (if income and quality are complements) strictly increases expected customer utility and the seller's profit (Matthews and Postlewaite 1985). In Shavell (1994), a seller has private information about the cost it must incur to learn about the quality of its product. Based on whatever information the seller discloses about product quality, a customer undertakes a complementary investment, which ideally would increase with the quality of the product. Without a disclosure requirement, the seller spends more to learn about quality than would be socially optimal, and then withholds negative information, which is inefficient. A mandatory disclosure requirement reduces learning and strictly increases welfare. Our model is similar to Shavell (1994) in that a firm has private information about the cost it must incur to learn about the social and environmental impacts of its supply chain. Unlike that of Shavell, our model incorporates the responses of investors and of consumers to impact information, two different mechanisms by which a mandate for impact disclosure reduces the firm's incentive to learn about these impacts.

An ecolabel can boost a firm's market share, though it typically does not enable a firm to charge a higher price (RESOLVE 2012; Nielsen 2011; Haanaes et al. 2012; Laroche et al. 2001). Our experimental results show that voluntary disclosure of even negative social and environmental impact information might increase a firm's market share. This observation is consistent with the consumer reaction to Patagonia's disclosures about its impacts in recent years: Patagonia posted descriptions on its website of the poor working conditions in suppliers' factories and, in a full-page advertisement in the New York Times, stated that "the environmental cost of everything we make is astonishing" and disclosed CO_2, water, and waste impacts of its best-selling jacket. Patagonia's sales rose 30 % after that advertisement appeared (Keown 2012). In other contexts, voluntary disclosure of negative information has been shown to increase trust (Hoffman-Graff 1977; Peters et al. 1997), which potentially leads to increased market share (Chaudhuri and Holbrook 2001).

13.3 Model Formulation

We now formulate a model to analyze the effect of mandatory disclosure on a firm's social and environmental impacts in its supply chain. Consider managers of two competing consumer-goods firms (say Firms 1 and 2), who face uncertainty regarding the magnitude of social and environmental impacts in their respective supply chains and simultaneously decide whether to learn about those impacts. To model their decisions, we assume the following: learning about the social and environmental impacts is costly because many impacts occur upstream in the supply chain. The learning cost is random; each manager observes her firm's learning cost, but knows only the distribution of the other firm's learning cost. Fortunately, a manager that learns the impacts immediately finds opportunities to reduce them with no additional cost.

Each firm expects to bear costs associated with its social and environmental impacts over the long-run. These costs can be due to future policy or negative publicity by an NGO. Therefore, each firm's long-term expected profit is equal to the firm's expected revenue from the consumer market minus the expected costs associated with social and environmental impacts.

The manager of each firm seeks to maximize a weighted average of the long-term expected profit and short-term valuation of the firm by investors. Investors update their valuation based on whether or not and what the firm discloses regarding impacts. Investors assign a higher valuation to a firm with relatively low expected social and environmental impacts, because they anticipate that the firm's social and environmental impact cost in the near future will be low.

Given these model assumptions, we consider two possible scenarios for disclosure: a "mandatory disclosure" scenario, in which each manager must reveal whatever information is uncovered, and a "voluntary disclosure" scenario in which, after learning about the impact of their supply chains, managers simultaneously decide whether or not to reveal what they have learned. We assume that a firm that learns that its impact is high has a lower long-term profit than a firm that does not learn this same information. In the voluntary disclosure scenario, if the manager does not disclose, investors only know that either the firm did not learn, or it learned but did not disclose.

Also, note that we will use the results of a series of consumer choice experiments to formulate the revenue from the consumer market in our model. As such, in the voluntary disclosure scenario, when Firm 1 discloses a low impact and Firm 2 does not disclose, Firm 1 gains market share. In contrast, when Firm 1 discloses a high impact and Firm 2 does not disclose, Firm 1 gains market share in the voluntary disclosure scenario but loses market share in the mandatory disclosure scenario. When Firm 1 discloses a low impact and Firm 2 discloses a high impact, Firm 1 gains market share in both scenarios.

Note that our model can be relevant for firms with industrial customers as well. Wal-Mart, for example, considers transparency and environmental performance in allocating its business between competing suppliers; it prefers to purchase more units, rather than pay a higher price per unit, to motivate a supplier to measure, improve, and disclose environmental performance. This approach is consistent with what the model suggests: a firm may gain market share, but not a higher price, by disclosing impact information to a customer.

13.4 Experimental Results

To gauge consumer reaction to disclosure, two sets of consumer choice experiments were designed based on our modeling assumptions. These experiments were performed online, with participants drawn from the U.S. national pool administered by Survey Sampling International. In this experiment, each participant viewed the pictures, prices, and technical specifications for a laptop from HP (Firm 1) and a similar one from Dell (Firm 2) (a sample survey is provided in the Appendix). For different participants, we presented different scenarios regarding the firms' disclosures of environmental or social impacts. We then asked each participant to choose the laptop that he or she would prefer to purchase and to rate how much he or she trusts each firm.

13.4.1 Greenhouse Gas Emissions

We used six scenarios with disclosure of greenhouse gas (GHG) emissions, plus a control scenario without disclosure. Survey participants were informed that the level of emissions associated with a firm's laptop could be "high" (1263 lbs of CO_2 equivalent) or "low" (754 lbs of CO_2 equivalent); in all but the control scenario, we informed participants that the industry average life-cycle GHG emissions for a laptop computer is approximately 903.9 lbs of CO_2 equivalent. In a voluntary disclosure scenario, a firm could choose not to disclose emissions information. In a mandatory disclosure scenario, participants were told that a new U.S. law required each firm to disclose its best estimate of the total lifecycle GHG emissions associated with its product. In this scenario, a firm that did not learn actual GHG emissions reported only the industry average of 903.9 lbs of CO_2 equivalent.

The survey results were quite clear in the GHG scenarios (Fig. 13.1): When one firm disclosed positive impact information—a low level of emissions—it won greater market share than in the control scenario without disclosure by either firm (regardless of whether disclosure was voluntary or mandatory and regardless of whether the competitor disclosed a high level of emissions or no emissions information for its product). When one firm voluntarily disclosed negative impact information—a high level of emissions—and the competitor did not disclose, the disclosing firm still won greater market share than in the control scenario without disclosure. In contrast, in the mandatory scenario, when one firm disclosed a high level of emissions it lost market share.

Those results may be explained in part by participants' relative levels of trust in the two firms (Table 13.1 in the Appendix). Without disclosure by either firm, the two firms were statistically indistinguishable in participants' ratings of trust. When one firm disclosed positive impact information—a low level of emissions—it received statistically higher ratings for trust than did the other firm (regardless of whether disclosure was voluntary or mandatory and regardless of whether the competitor disclosed a high level of emissions or no emissions information for its product). When one firm voluntarily disclosed negative impact information regarding a high level of emissions, it received statistically higher ratings for trust than did a competitor that failed to disclose impact information. In contrast, in the mandatory scenario, when one firm disclosed a high level of emissions, it did not receive statistically higher ratings for trust than its competitor. These findings support a general business belief that higher consumer trust and confidence in a firm will lead to higher market share. For some consumers, the opposite may also hold true: a firm that is not perceived to be trustworthy may lose market share.

13.4.2 Conflict Materials

We used six scenarios with disclosure regarding conflict minerals, plus the control scenario without disclosure. Survey participants were told that a firm disclosed that its product contained conflict minerals, or that a firm disclosed that its product was free of conflict minerals. In a voluntary disclosure scenario, a firm could choose not to disclose information about conflict minerals. In a mandatory disclosure scenario, participants were informed that a new U.S. law mandates that each firm must disclose any known use of conflict minerals. No disclosure here indicates that a firm has not yet been able to determine that its product is free of conflict minerals.

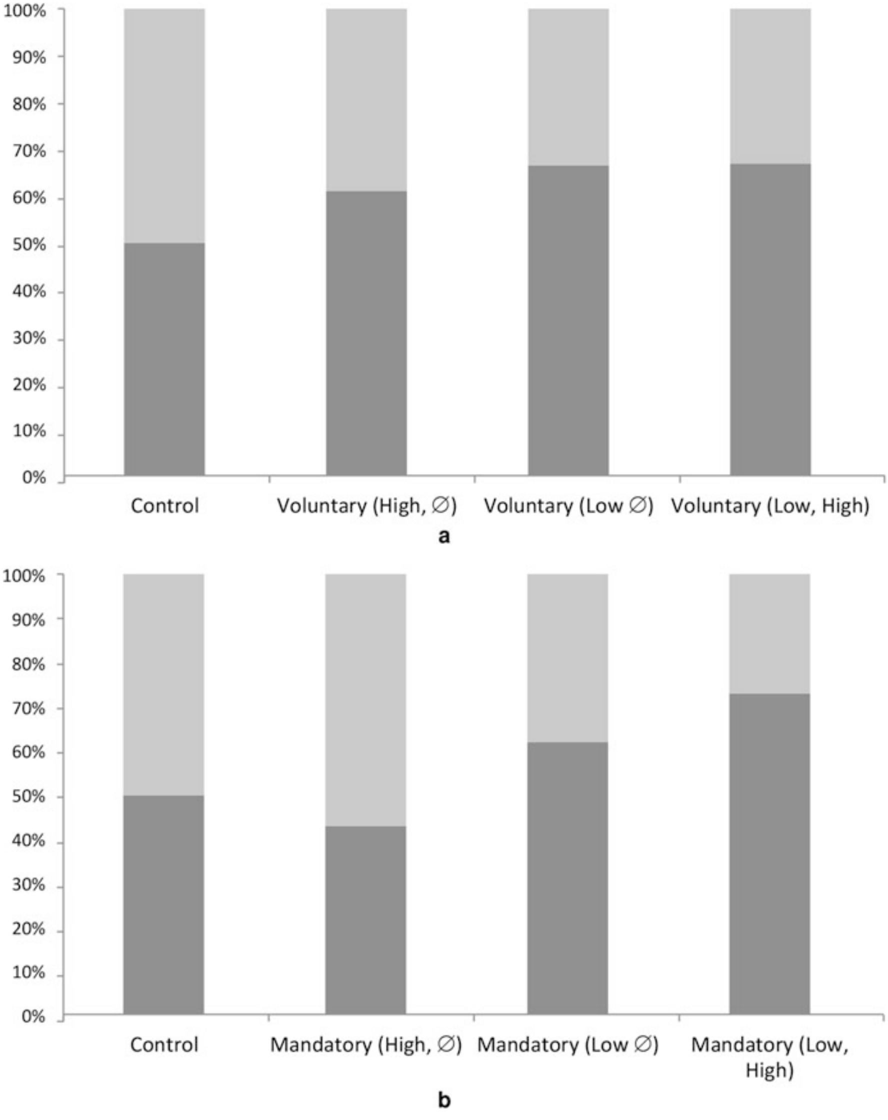

Fig. 13.1 Scenarios regarding disclosure of GHG emissions and the resulting choice of laptop. (**a**) Market shares under voluntary disclosure (vs. control), (**b**) Market shares under mandatory disclosure (vs. control). (Note: Firm 1 and Firm 2's market shares are displayed in dark and light gray, respectively. Market shares under different disclosure scenarios are significantly different from the control)

The results of these scenarios were largely the same as the results reported for the greenhouse gas emissions scenarios, with a single exception (Fig. 13.2): When one firm voluntarily disclosed negative impact information—that its product contains conflict minerals—and the competitor did not disclose impact information, the disclosing firm did not have a statistically significant change in market share relative to the control. However, an additional proportion test shows that firm disclosing voluntarily did have statistically higher market share than if its disclosure had been mandated. This might suggest, for example, that mandatory disclosure regulations for conflict minerals puts the disclosing firm at a disadvantage.

It is interesting to note that the results for how survey participants viewed the trustworthiness of the two firms were qualitatively the same as for the greenhouse gas emissions scenarios (Table 13.2 in the Appendix). When one firm voluntarily disclosed negative impact information—that its product was produced with inputs containing conflict minerals—it received statistically higher ratings for trust than did a competitor that failed to disclose impact information. This would again support general marketing principles that consumer trust has a significant impact on market share.

13.5 Analytical Results

Below, we highlight the insights from our theoretical model described in the Model Formulation Section by leveraging the experimental results described above [we refer the reader to Kalkanci et al. (2013) and Kalkanci and Plambeck (2015) for the full development of the theoretical results].

First, our results suggest that a mandate may not be necessary to elicit full information disclosure. A manager who learns that impacts are low will voluntarily disclose that information, because it will boost both sales and investors' valuation of the firm. A manager who learns that impacts are high might also voluntarily disclose that information because the firm will likely gain market share from disclosing a high impact if the competitor does not disclose impact information. The trade-off is that the firm may lose market share from disclosing a high impact if the competitor discloses a low impact, and disclosing a high impact will reduce investors' valuation of the firm. Hence a manager discloses high impact only if she places little weight on that valuation. This result is consistent with the example of voluntary disclosure by Patagonia, a firm with a single owner/founder who remains involved in management.

Our main result is that mandating disclosure has the opposite effect of the one intended by policy makers. In fact, mandating that firms disclose the social and environmental impact information of their supply chains actually

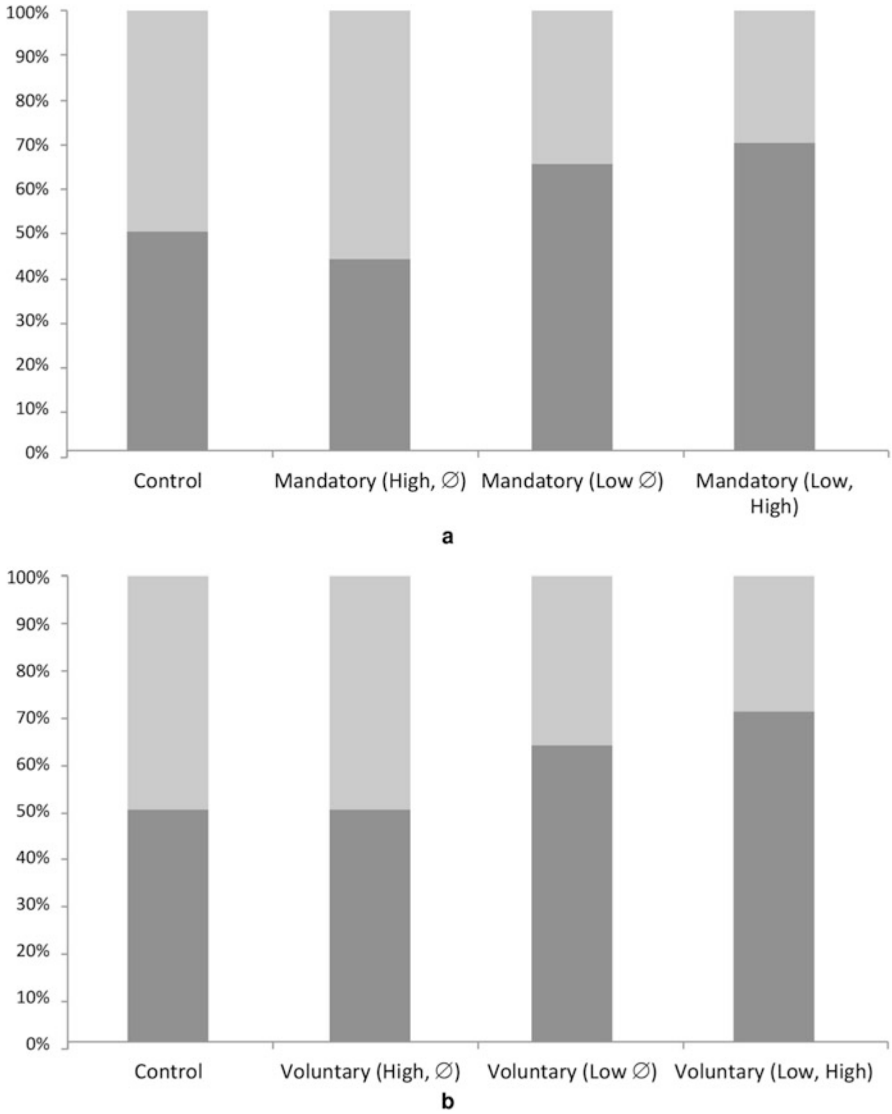

Fig. 13.2 Scenarios regarding disclosure of conflict minerals and the resulting choice of laptop. (**a**) Market shares under voluntary disclosure (vs. control), (**b**) Market shares under mandatory disclosure (vs. control). (Note: Firm 1 and Firm 2's market shares are displayed in *dark* and *light gray*, respectively. Firm 1 does not lose market share from being the only firm to disclose high impact compared to control. Market shares under other disclosure scenarios are significantly different from the control)

increases those impacts. The rationale is that the mandate deters managers from learning about and, thus, reducing impacts in their supply chains. The loss of learning occurs for two different reasons. The first is customer choice. Mandating disclosure strictly reduces a firm's expected increase in market share from learning about its supply chain impacts, regardless of whether the firm's impact is high or low, and regardless of whether or not the firm's manager would voluntarily disclose a high impact. The second reason arises if the manager would not voluntarily disclose a high impact, because doing so would reduce the firm's expected market share and/or valuation by investors. In this case, a mandate for disclosure discourages a manager from learning to avoid being forced to disclose that impacts are high.

The manager will not disclose high impacts if there is reason to be concerned with the investor valuation following voluntary disclosure. The investors infer that the manager either does not know the firm's impacts or the manager is hiding them (when the impacts are not disclosed) and they reduce their valuation of the company. This, however, motivates the manager even more to learn and disclose low impacts. Therefore, we predict that voluntary disclosure will be even more effective than a mandate as the manager becomes more concerned with the investors' valuation.

The results collectively imply the following. First, a manager facing a very high cost of learning about social and environmental impacts should lobby for mandatory disclosure. This is because a manager with a high cost of learning will not invest in learning, and therefore stands to lose market share in the event that a competitor learns and discloses impact information. The mandate for disclosure will mitigate the firm's expected loss in market share. In addition, a mandate for disclosure increases investors' valuation of a firm that does not disclose. The mandate for disclosure enables investors to infer that the firm has a high cost of learning that prevented it from learning. Without the mandate, investors think that the firm may have chosen not to disclose because its impacts are high, and increase their expectation of the firm's impacts and associated future costs, accordingly.

Second, regardless of whether disclosure is mandatory or voluntary, when a firm anticipates a higher cost associated with social and environmental impacts, the manager is likely to invest more in learning and thus in reducing those impacts. Pressure to penalize about the supply chain impacts can come from both governments and NGOs. More surprisingly, in the scenario with mandatory disclosure, an increase in the impact cost can benefit the firms. This would tend to counteract the problem of a manager who underinvests in learning to avoid being forced to reveal to investors that the company's supply chain impacts are high.

Finally, consider how a large buyer, like Wal-Mart, should motivate its suppliers to learn and to disclose their social and environmental impacts when buyers are considering how to allocate business between suppliers based on the information they disclose. We consider two possibilities for business allocation as an extension to our analysis: the buyer can allocate more business to a supplier with lower impact when both suppliers disclose their impacts, and/or allocate more business to a supplier that discloses its impacts when the other supplier is not forthcoming about its impacts. Our results show that allocating business by comparing the disclosed impacts backfires and deters the suppliers from learning their impacts. Rewarding the supplier that discloses information, however, always motivates the suppliers to learn (regardless of voluntary or mandatory disclosure). Therefore, the buyers should, at least initially, put more emphasis on the suppliers' transparency than their disclosed impacts when they reward business to their suppliers.

13.6 Conclusion

Suppose that a firm invests in learning and finds out that impacts are worse than it anticipated. Should it nevertheless disclose them? Our experimental results suggest the answer is "yes" in the case of GHG emissions, but "no" in the case of conflict minerals. For GHG emissions, the results from our analysis show a firm that voluntarily discloses a very high level of GHG emissions gains market share if competitors do not disclose information about GHG emissions. If its competitors were to subsequently respond by disclosing a similarly high level of emissions, the firm would be no worse off. Additional experiments suggest that if the competitor were to subsequently respond by disclosing a low level of emissions, the firm could prevent a loss of market share by reminding consumers of its leadership in disclosure and providing detailed information about its emissions and reduction efforts. The marketing literature on "brand loyalty" and "usage dominance" implies that an initial gain in market share (for a firm that is first to disclose) will generate a persistent market share advantage (Guadagni and Little 1983; Deighton et al. 1994; Villas-Boas 2004). We therefore recommend that a firm should voluntarily disclose even a high level of greenhouse gas emissions.

Regarding conflict minerals, we observed that a firm that voluntarily discloses that its product contains conflict minerals neither gains nor loses market share, if competition does not disclose information about conflict minerals. However, it loses market share if competition discloses that its product is free of conflict minerals. We therefore recommend that a firm should not voluntarily disclose that its product contains conflict minerals.

Policy makers should recognize and act upon the fundamental tenet of operations management that *measurement leads to improvement*. Some governments are starting to require firms to disclose what they know regarding greenhouse gas emissions or conflict minerals in their supply chains. Our findings, however, suggest that such a requirement will deter measurement. To promote measurement, policy makers could potentially require firms to measure their supply chain impacts in a specific manner, and obtain third party certification that they are doing so; indeed, activists have called for such requirements regarding conflict minerals (Dunnebacke 2012). However, firms have sought to convince the regulatory authorities that specific learning requirements and third party verification thereof would be prohibitively costly and difficult to implement, because they have numerous suppliers spanning several tiers that are constantly being changed (National Association of Manufacturers 2012; SEC 2012). As an alternative approach to promote measurement, policy makers could facilitate firms' efforts to measure their suppliers' impacts. Commonly, in emerging economies suppliers bribe auditors and local officials, falsify documents, and coach employees in how to corroborate those false documents, in order to "pass" audits. To the extent that government authorities penalize such corruption and deception, buyers will undertake more auditing, auditing will be more effective in measuring impacts, and suppliers will exert more effort to reduce their impacts (Plambeck and Taylor 2015).

In lieu of government mandates, our model suggests three ways in which NGOs can spur firms to measure and reduce their supply chain impacts. First, NGOs can reduce a firm's cost of doing so. By working in partnership with environmental NGOs to learn about the environmental impacts of its supply chain, Wal-Mart observed various opportunities to profitably reduce those impacts, as described in Plambeck and Denend (2007, 2010). The Institute for Public Economics (IPE) maintains an internet database of environmental violations by factories in China, which enables a firm to easily identify violations by its suppliers. Second, NGOs can expose and publicly shame firms for abuses in their supply chains. For example, the IPE assiduously collects evidence that prominent multinational firms are sourcing from offending factories in its database. Only by threatening widespread publicity about such abuses can IPE motivate many firms to use its database and demand improvement from suppliers (Ma 2012). Third, NGOs and educators can sensitize people to issues like conflict minerals and climate change, which may magnify a firm's gain in market share from voluntarily disclosing its impacts, magnify a firm's loss in market share in the event that abuses in its supply chain are exposed, and thus spur firms to measurement and improvement.

Appendix

Firms' Consumer Trust Ratings Under Different Scenarios

Table 13.1 Scenarios regarding disclosure of GHG emissions and the resulting trust ratings

Scenario			Trust rating		Which firm is more trustworthy?
Disclosure	GHG emissions				
	Firm 1	Firm 2	Firm 1	Firm 2	
Control			6.993 (1.823)	6.807 (1.933)	No difference
Voluntary	High	∅	6.798 (1.921)	6.327 (2.082)	Firm 1
	Low	∅	6.886 (1.875)	6.446 (1.909)	Firm 1
	Low	High	6.926 (1.828)	6.431 (2.007)	Firm 1
Mandatory	High	∅	6.662 (1.889)	6.673 (1.894)	No difference
	Low	∅	7.145 (1.788)	6.691 (2.091)	Firm 1
	Low	High	6.994 (1.724)	6.283 (1.993)	Firm 1

Table 13.2 Scenarios regarding disclosure of conflict minerals and resulting rating of trust

Scenario			Trust rating		Which firm is more trustworthy?
Disclosure	Conflict minerals				
	Firm 1	Firm 2	Firm 1	Firm 2	
Control			6.993 (1.823)	6.807 (1.933)	No difference
Voluntary	Yes	∅	6.552 (1.776)	6.218 (1.956)	Firm 1
	No	∅	6.846 (1.904)	6.195 (1.972)	Firm 1
	No	Yes	6.898 (1.804)	6.410 (1.896)	Firm 1
Mandatory	Yes	∅	6.778 (1.760)	6.584 (1.817)	No difference
	No	∅	6.839 (1.821)	6.362 (2.013)	Firm 1
	No	Yes	6.844 (1.871)	6.306 (1.934)	Firm 1

Surveys for GHG Emissions and Conflict Minerals

Below, we provide a sample of the survey information provided to the participants.

Product Choice and Evaluation Scenario

Imagine that you have $400 and you are shopping for a new laptop. After evaluating your needs, desires, and constraints regarding important issues (portability, battery life, being able to run software required for work, your budget, etc.) you have narrowed your decision down to TWO OPTIONS:

HP Pavilion G6t

Dell Vostro 1540

We present product information about each of these purchasing options, in order to help you make your decision.

Display:
—*HP Pavilion G6t:* 15.6 Inches LED.
—*Dell Vostro 1540:* 15.6 Inches LED.

Technical Specifications:
—*HP Pavilion G6t:* Intel i3ŋ2350M Processor (2.3 GHz), 4GB DDR3 RAM, 500 GB Hard Drive, SuperMulti DVD+/ŋR/RW, WLAN 802.11 b/g/n, Bluetooth (R), 5.5 h of battery life.
—*Dell Vostro 1540:* Intel i3ŋ370M Processor (2.27 GHz), 4 GB DDR3 RAM, 500 GB Hard Drive, Optiarc ADŋ881H SATA DVDRW, WLAN 802.11 b/g/n, Bluetooth 3.0, 5.7 h of battery life.

Price:
—*HP Pavilion G6t:* $396.98.
—*Dell Vostro 1540:* $396.78.

Greenhouse Gas Emissions Information:
—*HP Pavilion G6t:* HP has voluntarily disclosed the following estimate of the lifecycle greenhouse gas emissions associated with the Pavilion G6t as 1.263 lbs of CO_2-equivalent.
—*Dell Vostro 1540:* Dell has NOT disclosed any environmental impact information.

References

Chaudhuri A, Holbrook MB (2001) The chain of effects from brand trust and brand affect to brand performance: the role of brand loyalty. J Mark 65(2):81–93

Deighton J, Henderson CM, Neslin SA (1994) The effects of advertising on brand switching and repeat purchasing. J Mark Res 31(1):28–43

Doshi A, Dowell G, Toffel MW (2013) How firms respond to mandatory information disclosure. Strateg Manag J 34(10):1209–1231

Dunnebacke A (2012) Anti-corruption views—global witness comments on SEC conflict minerals rule. http://www.trust.org/trustlaw/blogs/anti-corruption-views/global-witness-comments-on-sec-conflict-minerals-rule/. Accessed 10 Nov 2012

Ernst & Young (2013) Report on company feedback from the French national environmental labeling pilot. http://www.developpement-durable.gouv.fr/IMG/pdf/synthserapportEYV2_EN_3.pdf. Accessed 11 Feb 2015

Frydman C, Saks RE (2005) Executive compensation: a new view from a long-term perspective, 1936–2005. Rev Finan Stud 23(5):2109–2138

Fung A, Graham M, Weil D (2007) Full disclosure: the perils and promise of transparency. Cambridge University Press, New York. p 48–49

Graham JR, Harvey CR, Rajgopal S (2005) The economic implications of corporate financial reporting. J Account Econ 40(1):3–73

Griffin PA, Lont DH, Sun Y (2014) Supply chain sustainability: evidence on conflict minerals. Pac Account Rev 26(1/2):28–53

Grossman SJ (1981) The role of warranties and private disclosure about product quality. J Law Econ 24(3):461–483

Guadagni PM, Little J (1983) A logit model of brand choice calibrated on scanner data. Mark Sci 2(3):203–238

Haanaes K, Reeves M, von Streng Velken I, Audretsch M, Kiron D, Kruschwitz N (2012) Sustainability nears a tipping point. MIT Sloan Manag Rev 52(2):69–74

Hoffman-Graff MA (1977) Interviewer use of positive and negative self-disclosure and interviewer-subject sex pairing. J Couns Psych 24(3):184–190

Institutional Investors Group on Climate Change (2010) Global investor survey on climate change: annual report on actions and progress 2010. http://www.ceres.org/resources/reports/2010-global-investor-survey-on-climate-change-1

Ioannou I, Serafeim G (2015) The impact of corporate social responsibility on investment recommendations: analysts' perceptions and shifting institutional logics. Strateg Manag J 36(7):1053–1081

IPCC (2007) In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge/New York

Kalkanci B, Plambeck E (2015) Supply chain social and environmental impacts: Measurement, reduction and disclosure. Working paper. Georgia Institute of Technology, Atlanta, GA

Kalkanci B, Ang E, Plambeck E (2013) Measuring and improving supplier responsibility under voluntary vs. mandatory disclosure. Working paper. Georgia Institute of Technology, Atlanta, GA

Kearney AT (2012) Conflict minerals: yet another supply chain challenge. http://www.atkearney.com. Accessed 12 Oct 2012

Keown J (2012) Boosts sales by saying 'don't buy.' In: Stuff.co.nz. http://www.stuff.co.nz/business/industries/6656053/Boosts-sales-by-saying-don-t-buy. Accessed 2 Aug 2012

Laroche M, Bergeron J, Barbaro-Forleo G (2001) Targeting consumers who are willing to pay more for environmentally friendly products. J Consum Mark 18(6):503–520

Lee HL, O'Marah K, John G (2012) The Chief Supply Chain Officer Report 2012. SCM World

Ma J (2012) Author's interview of Ma Jun, Director of the Institute for Public Economics (October 12)

Matthews S, Postlewaite A (1985) Quality testing and disclosure. RAND J Econ 16(3): 328–340

Milgrom P (1981) Good news and bad news: representation theorems and applications. Bell J Econ 12(2):380–391

Ministry of Ecology, Sust. Dev. and Energy (France) (2012) Product environmental footprint. http://www.developpement-durable.gouv.fr/Product-Environmental-Footprint.html. Accessed 2 Aug 2012

National Association of Manufacturers (2012) Testimony of Franklin Vargo before the House Committee on Financial Services Subcommittee on International Monetary Policy and Trade, p 7

Nielsen (2011) Sustainability survey: global warming cools off as top concern. http://www.nielsen.com/us/en/insights/press-room/2011/global-warming-cools-off-as-top-concern.html. Accessed Oct 2012

Peters RG, Covello VT, McCallum DB (1997) The determinants of trust and credibility in environmental risk communication: an empirical study. Risk Anal 17(1):43–54

Plambeck EL, Denend L (2007) The greening of Wal-Mart's supply chain. Supply Chain Manag Rev 11(5):18–25

Plambeck EL, Denend L (2010) Wal-Mart's sustainability strategy A and B: 2010 update. Stanford Graduate School of Business Case Study

Plambeck EL, Taylor T (2015) Supplier evasion of a buyer's audit: Implications for motivating supplier social and environmental responsibility. Manuf Serv Oper Manag. Published online: September 9, 2015. doi:10.1287/msom.2015.0550

RESOLVE (2012) Toward sustainability: the roles and limitations of certification. RESOLVE, Inc., Washington, DC

Shavell SM (1994) Acquisition and disclosure of information prior to sale. RAND J Econ 25(1):20–36

Securities and Exchange Commission (2012) SEC adopts rule for disclosing use of conflict minerals. http://www.sec.gov/news/press/2012/2012-163.htm. Accessed 25 Aug 2012

Villas-Boas JM (2004) Consumer learning, brand loyalty and competition. Mark Sci 23(1):134–145

Verrecchia RE (2001) Essays on disclosure. J Account Econ 32(1–3):97–180

Chapter 14
The Effect of EPR on the Markets for Waste

Gökçe Esenduran and Atalay Atasu

Abstract Extended Producer Responsibility (EPR), a widely used policy tool, requires producers to assume financial and/or operational responsibility for ensuring their end-of-life products are properly collected and treated. EPR implementation in today's economy, however, poses a change as some basic, underlying assumptions do not hold. Today's economy challenges assumptions that (1) waste is costly to recover, (2) waste consists only of end-of-life products, and (3) waste is homogenous with respect to its geographic location, design, or condition. In this chapter, we discuss the impact of EPR on waste markets when these assumptions are challenged.

14.1 Introduction

A growing world population combined with accelerating economic development, faster new-product introductions, and increased consumption has placed significant burden on the world's resources. According to the World Wide Fund for Nature, humans' environmental footprint exceeded the Earth's biocapacity by 50 % in 2007. A primary cause of this overburden is the amount of waste generated in industrialized nations. According to recent studies, waste production in the past century has risen tenfold and will double again by 2025 (Hoornweg et al. 2013). In the U.S., for example, containers and

G. Esenduran (✉)
Fisher College of Business, The Ohio State University, Columbus, OH, USA
e-mail: esenduran.1@osu.edu

A. Atasu
Scheller College of Business, Georgia Institute of Technology, Atlanta, GA, USA
e-mail: Atalay.Atasu@scheller.gatech.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_14

packaging constitute 30 % of total municipal solid waste, while durable goods (such as furniture, appliances, and electronics) and non-durable goods (such as paper and clothing) constitute another 20 % each (EPA 2012). Some waste products, such as plastic bottles, remain in nature for almost 450 years (U.S. National Park Service 2014) if dumped in landfills or left untreated. Others, such as electronics, contain hazardous substances such as lead, cadmium, mercury, that may leak and pose health and environmental hazards. To abate these negative externalities, governments worldwide have been passing various forms of environmental regulation, a widely used example of which is "Extended Producer Responsibility" (EPR). This requires producers to assume financial or operational responsibility for ensuring their end-of-life products are properly collected and treated (Lifset 1993; Lindhqvist 2000). The Organization for Economic Cooperation and Development (OECD) defines EPR as (OECD 2001)

> "an environmental policy approach in which a producer's responsibility for a product is extended to the post-consumer stage of a product's life cycle."

EPR first appeared in the early 1980s in a few European member states targeting packaging waste and since then has progressively been adopted around the world. Today, several developing countries in Asia, Africa, and South America are in the process of introducing EPR-type policies for managing discarded products, following in the footsteps of developed economies such as the U.S. and EU. A recent OECD study identified 384 EPR policies across industries and regions (Kaffine and O'Reilly 2013). The EU, for example, has EPR-aligned directives on four waste streams: packaging, batteries, End-of-Life Vehicles (ELVs) and Waste Electrical and Electronic Equipment (WEEE). Several member states have additional state-level EPR policies for other products such as tires, graphic paper, oil, and medical waste. The U.S. has no federal EPR policy, but statewide regulations exist for products such as electronic waste (e-waste), mercury lights, carpets, packaging, paint, and pharmaceuticals (Nash and Bosso 2013). In Canada, provincial governments implement EPR schemes, which are harmonized through a country-wide action plan for several products, including cars, electronics, packaging, and pharmaceuticals (Canada 2014).

An EPR policy has two main objectives: (1) diverting waste from landfills by increasing customers' collection and proper recovery of discarded products and (2) moving end-of-life product management responsibility (physical, financial, or both) from municipalities to producers, thereby incentivizing producers to design products that are easier to recover and recycle (OECD 2001). A popular way of translating EPR policy into law has been "product take-back regulation," introducing specific collection and recovery objectives. In a market regulated with targets, producers typically must achieve them at minimum levels and ensure collected items are treated in an environmentally friendly way (e.g., through recycling or reuse). The first version of the WEEE Directive, for example, mandated collection requirements at a minimum target of 4 kg of e-waste per inhabitant. Although some member states—Cyprus, Greece, Latvia, Malta, Hungary, Romania, Slovakia and Poland—failed to meet this target individually, statistics show the EU did so by 2010 (Eurostat 2013). A recent European Commission's revision of the WEEE Directive imposes a more ambitious collection target: 45 % of the items put on the market in the last 3 years, which increases to 65 % by 2019 (Europa-Environment 2012).

Though reasonably sound on paper, product take-back and recovery regulation is complicated because its implications depend on market conditions and the validity of foundational EPR assumptions. A key one is that waste is costly to recover and, unless regulated, will end up in landfills. Evolving product designs and recycling technology along with new market conditions, however, are challenging that. Electronics, once classified as waste and often subject to take-back regulation, have gained value. In this vein, EPR principles also assume customers discard products because they have no remaining useful life, an indication that these regulations over-emphasize recycling when many products could be suitable for reuse. Finally, EPR policies tend to overlook the heterogeneity of waste with respect to its geographical location, design, or condition. In this chapter, defining "waste" as products discarded by customers with or without recoverable value, our aim is to identify and discuss the impact of EPR-type policies on waste markets, especially when assumptions behind these principles are challenged.

The rest of this chapter is organized as follows: In Sect. 14.2, we discuss recent significant changes in the value of waste. In Sect. 14.3, we identify the players in waste markets regulated by EPR-type policies, and interactions among them. In Sect. 14.4, we identify three challenges in EPR implementations and discuss literature's contribution to solve them. We conclude in Sect. 14.5.

14.2 Waste Markets Dynamics

Although material intensity (i.e., the amount of materials required per unit of GDP) has declined over time as technology advances, material use per capita has increased from 4.6 to 10.3 t/cap/yr. in the period after WWII. In 2007, the total volume of material resources exploited worldwide reached 60 billion metric tons, eight times higher than a century ago (Krausmann et al. 2009). This demonstrates waste levels are growing along with resource exploitation, which drives up commodity prices. The price of gold, for example, has risen from about 300 Euro/kg in 2004 to 1400 Euro/kg in 2013 (Gold 2013). Raw-material scarcity also is becoming a serious issue (KPMG 2012); combined with higher commodity prices, it causes the value of waste to increase. Metals, paper, cardboard, compost, and plastics constitute nearly two-thirds of the total waste stream in Europe (ZeroWasteEurope 2014) and more than three-quarters in the U.S. (EPA 2012). If recovered properly, these can be used instead of raw materials facing future scarcity. Therefore, demand and interest for recycling metals, e-waste, paper, and glass is growing.

Waste is Becoming a Valuable Commodity Consider e-waste, specifically a used cell phone, which we use as the core example throughout this chapter. Various metals, including copper, tin, cobalt, and precious metals such as gold, silver, and palladium, make up 23 % of a used cell phone (by weight) (UNEP 2009). Although especially precious metals are present in each individual phone in trace amounts (e.g., only 250 mg of silver in each phone), one combined ton of phones contains 3.5 kg of recoverable silver, 340 g of gold, 140 g of palladium, and 130 kg copper. Accordingly, e-waste is becoming one of the more economical sources of certain rare earth metals, with 10–50 times higher copper content than copper ore and 5–10 times higher gold content than gold ore (Kukday 2007; Hunt 2013).

Furthermore, the electronics sector is an end market for eight of the 14 critical raw materials the EU recently specified (Thompson and Hollins 2013). E-waste, therefore, actually can be a valuable commodity with almost no shortage. Indeed, the UNEP found 20–50 million metric tons of e-waste are generated worldwide every year.

It is Easier to Recover the Value The material content of new technology products has been changing over time. Certain electronics (computers, LCD monitors, or cell phones) now contain fewer toxic chemicals such as cadmium and mercury. This is partly because of regulations such as the Restriction of Hazardous Substances Directive (RoHS), which bans the use of certain hazardous substances, and partly because of increasing customer demand for products with non-toxic materials. Indeed, a recent analysis shows that every cell phone classified under a high environmental concern category was released before 2010. Because these new products contain fewer toxic materials, they also are easier and safer to recycle. Recycling and waste management technologies, meanwhile, are improving as well. A recent study found that patent activity in e-waste recycling more than doubled in 2010 compared to the previous year (WIPO 2014).

All these recent market developments show that EPR's recycling net-cost assumption no longer holds for certain electronics. Some e-waste categories (used computers, LCD monitors, cell phones) can be recycled at a net profit. In the EU, an estimated 70 %-plus of e-waste is valuable, holding a market value of 350–600 million Euros (ERP 2013). Some of these items may even be eligible for reuse, especially those that suffer from rapid obsolescence, such as laptops and cell phones (Gui et al. 2013). Many electronic products customers replace are indeed in working condition or can easily be refurbished.

Waste is Heterogenous Although waste is becoming a valuable commodity, the quantities and types of materials used in electronic products vary greatly, making waste highly heterogeneous within and between devices

(Zhang 2011; Cui and Roven 2011; CDTSC 2013). Furthermore, waste is widely dispersed geographically and its recoverable value depends significantly on the ease of waste collection. This creates heterogeneity in waste's economic attractiveness based on geographical location, product design, and condition.

In sum, while recovery of some products, such as cathode-ray tube (CRT) screens, may have a net cost, waste recovery for recycling or reuse of others may be profitable. In this case, several different market entities vie to collect this fraction of e-waste in addition to those mandated to do so by EPR-type policies. This makes it very important to understand how markets for valuable waste operate, which we investigate next.

14.3 Waste Markets

Although EPR's main objective is to shift the responsibility of managing end-of-life products from municipalities to producers[1] several other parties are involved in and affected by policy implementation, some officially and others unofficially.

Most take-back regulation implementations allow producers to comply collectively through Producer Responsibility Organizations (PROs), which collect and recover discarded products on members' behalf. The European Recycling Platform (ERP), set up by Braun, Sony, Electrolux, and HP in 2002 is an example. In addition to PROs officially representing producer members in the waste market, municipalities may remain in charge of some aspects of discarded product handling, running municipal collection centers, for example. Municipalities in Germany handle e-waste collection of e-waste, whereas producers have full responsibility for other products such as packaging, batteries, and ELVs. Because of the recoverable value in certain types of waste, unofficial entities[2] engage in collecting and recovering these items. These can be legal but unlicensed third parties in the waste markets or informal/illegal actors (including some exporters) that producers or policymakers cannot easily identify and track.

[1] For example, under the WEEE Directive, "producer" is defined as "any person who, irrespective of the selling technique used (1) manufactures and sells EEE under his own brand, (2) resells under his own brand equipment produced by other suppliers, (3) imports or exports EEE on a professional basis into a Member State."

[2] We call these "unofficial" because they are not registered under a regulatory body and the amount of waste they handle does not count toward meeting regulatory targets.

The relationship between these official and unofficial entities collecting, trading, and recycling may be complicated and would depend on the type of waste, region of interest, and market dynamics/structure. As an illustrative example[3] we present the flow of e-waste in Fig. 14.1.

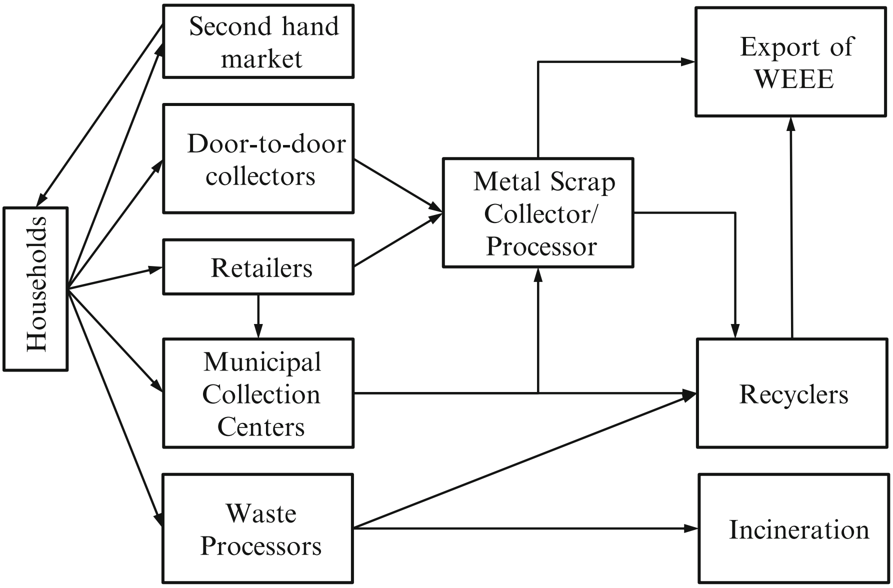

Fig. 14.1 A simplified representation of e-waste flow (compiled from Huisman et al. 2012; Ademe 2013)

Waste-holders (or households) can discard waste at municipal collection points, give it to scrap processors or door-to-door collectors, or return it to a retailer as part of "old for new." Here, e-waste either goes to compliance schemes (PROs or individual producers), or is sold (as-is or after being dismantled) to metal scrap processors. While policymakers may assume the former always occurs, municipalities may have an incentive to sell such waste to scrap processors who pay a comparably higher return. For example, 70–90 % of large domestic appliances and 50–80 % of IT and telecom equipment municipalities collect are sold to these processors in Europe (EPA 2012). Items collected at retailers also may end up outside the reach of compliance schemes if retailers opt for scrap metal processors, while scavengers' door-to-door collection creates yet another venue for waste to go untracked. Finally,

[3] Figure 14.1 is only representative and not comprehensive. In reality, many other loops may exist between entities involved in this reverse chain and some relationships we show may not exist under certain circumstances. Furthermore, the figure only shows the flow of e-waste from B2C; it is argued that almost all e-waste originating from B2B customers ends up in the hands of unofficial entities (Huisman et al. 2012).

a small fraction of e-waste, usually small household equipment may end up in incineration. As illustrated, a significant share of waste ends up in alternative unofficial routes, legal or illegal, and is not captured by compliance schemes or recorded under regulations, which we call "waste leakage." For example, data from 2008 show that each inhabitant of the Netherlands generates an average 18.5 kg of e-waste annually, of which 14.8 kg (80 %) is recycled. However, producer-funded e-waste compliance schemes compose only 5.7 kg (31 %) of this amount; unofficial entities handle the majority of e-waste (DigitalEurope 2011). More recent figures show that 85 % of e-waste in the EU may be separately collected, but only 33 % is officially reported and 40 % is not treated in line with legal requirements.

While the treatment of more e-waste than reported appears like good news, this creates several problems. First, unofficial entities do not have to comply with any regulatory requirement that compliance schemes (producers or PROs) must meet, therefore they can operate at relatively low cost and offer better pricing than registered and formal entities. This creates an unfair competition environment and, at worst, could lead to these unofficial entities adopting recycling techniques and methods that pose environmental risk and/or lead to the loss of valuable materials. Complicating matters, due to the heterogeneity in e-waste (as we discussed in Sect. 14.2), we observe a "cherry-picking" problem within this industry where entities are interested in collecting items that are valuable and easy to recover. Not having to comply with regulations, these unofficial entities have no incentive to properly treat discarded products of lesser value. Furthermore, some materials (e.g. copper, steel and aluminum) are relatively easily extracted from many discarded products, whereas scarce and more valuable materials (e.g., rare earth metals) are more difficult to extract unless properly treated and with the right technology. When illegal entities handle discarded items, the latter typically are not recovered. For these reasons, the existence of unofficial collection and recycling entities may complicate waste market dynamics and make it difficult to predict potential implications of EPR regulations.

14.4 Challenges in EPR Implementations

New challenges clearly are emerging in the waste market. When waste producers should collect according to EPR policies ends up in the hands of unofficial entities, this interference challenges the functioning of compliance schemes and affects EPR policy outcomes. In this section, we discuss how waste leakage, profitable recovery, and competition against independent third-parties effects EPR's efficiency.

14.4.1 Competition Against Local Recyclers

The way EPR is implemented may significantly affect competition for valuable-waste collection. For example, when producers face collection and recovery targets, they have no choice but to compete with unofficial entities. Although the revised WEEE Directive imposes collection targets on European member states, member states likely will shift this burden to producers when translating the directive into national law. One of the most popular alternatives the UK considers for transposition is imposing a collection target on producers based on a proportion of the member state target and producers' market shares (BIS 2013). By this case, in order to meet the 65 % collection target by 2019, e-waste collection must double compared with 2008 levels (Huisman 2010). Unsurprisingly, companies such as HP have raised concerns about the revised directive (HP 2013):

> "The WEEE Directive was created as part of the concept of producer responsibility. However, producer responsibility was based on waste being a cost. In this new era when waste has a value, policy should instead focus on ensuring all waste is properly treated and reported, that producers pay for waste where there is a cost."

Based on this quote, electronics producers believe that when waste has value, regulations such as the WEEE Directive may unnecessarily impose a burden on them. Recent reports by Digital Europe, European CE, and IT Trade Association (DigitalEurope) also confirm Europe's IT industry shares HP's concerns. Producers there argue that stringent collection targets amid an active market for e-waste recycling is a questionable practice. In particular, they claim that the overall economic and environmental benefits of increased collection targets in such markets would be debatable, given they must compete with unofficial recycling entities to access e-waste.

We observe a similar situation in some U.S. states. Currently, seven (Minnesota, Connecticut, Illinois, Indiana, New Jersey, New York, and Wisconsin) of the 23 with EPR-based e-waste take-back laws have imposed specific collection targets directly on producers (ETC 2015). For example, in Minnesota the collection target is 60 % in the first year, then increases to 80 % in subsequent years (Revisor of Statutes 2007). In states with no specific collection targets, producers are responsible for the amount that comes back through collection channels, but several states with e-waste laws have signaled intentions to impose targets after observing initial return rates. In the near future, therefore, producers in the U.S. may face similar challenges.

In this new environment where waste is valuable and collected by both official and unofficial entities, what are the implications of imposing stringent recovery targets on producers? Esenduran et al. (2015a) answer this question, specifically aiming to understand how imposing recovery targets only on producers affects: landfill diversion levels, producers' design incentives to facilitate product recovery, as well as the economics of the waste market (producer profits, third-party profits, and waste-holder welfare). To this end, they build an economic model of the waste-collection competition between producers (or PROs) facing take-back regulation and the informal, unregulated recycling sector. They do this using a Hotelling framework and consider a case where the producer and recycler simultaneously announce recovery prices and offer them to holders of valuable waste. The regulator, on the other hand, chooses a recovery target to maximize the total welfare, which is the sum of producer and recycler profits, waste-holder surplus, and environmental benefits.

The results show the following: When there is no competition for waste, regulating the market results in larger waste market coverage (thus a higher environmental benefit in terms of landfill diversion). Incentive to design environmentally superior products also exists. On the other hand, imposing stringent targets on producers in the presence of competition for waste has several drawbacks. Although recovery targets ensure the producer's larger waste-market coverage, the total landfill diversion achieved by the producer and the recycler (thus the related environmental benefit) might decrease. The reason behind this unexpected result is as follows: Stringent recovery targets imposed on producers lead them to act more aggressively against competitors in the waste market by increasing recovery prices. Recyclers may not respond the same way, therefore the amount these entities collect may decline, along with total landfill diversion.

Furthermore, conventional wisdom may suggest that producers under stringent recovery targets would have stronger incentives to make costly design changes that facilitate product recovery. However, Esenduran et al. (2015a) find this is not always true. When producers make design changes, recyclers also may benefit from these changes in the form of lower recovery cost and become better positioned to compete with producers. When design changes lead to stronger competition, producers' incentives for making changes that may exist absent regulation could diminish under stringent recovery targets. To summarize, EPR-based regulation might distort the waste market significantly and have unintended consequences in the presence of competition for waste collection.

These results have important implications for policymakers. When waste has value, there are two ways to avoid the unintended consequences of take-back regulation on the market. First, if possible to track and trace unofficial actors in the waste market, these entities should be registered under the scope of EPR regulation, which would count their recovered waste toward meeting regulatory targets. Encouragingly, current regulatory practice seems to be moving in this direction. The Netherlands, for example, recently published a draft for WEEE Directive implementation where all recyclers (even if they not associated with the producers) must report their recycling volume to be counted toward achieving the targets (DigitalEurope 2014). For this approach to be successful, however, the same environmental standards should be applied to e-waste recycling, regardless of who handles recycling operations (i.e., producers or unofficial recyclers). There exist several e-waste recycling standards, such as WEEELABEX, R2, and e-Stewards, that ensure the proper treatment of e-waste. Furthermore, the European Committee for Electrotechnical Standardization (CENELEC) is in the process of developing a European standard for member state adoption (CENELEC 2013). However, when not possible to identify and track unofficial entities in the waste market, policymakers should consider reducing recovery targets imposed on producers. This can help prevent the informal recycling sector from reducing collection efforts to avoid competition with the producers.

We note another way in which imposing collection targets only on producers distorts waste market dynamics: When producers (or PROs) must prove they paid for collection and treatment of a certain amount of e-waste but cannot meet the requirements through their own collection channels, some regulations allow producers to buy "evidence" from other operators. This serves to prove producers paid for a sufficient amount of e-waste recovery to meet obligations and creates an opportunity for independent (and unofficial) entities. As discussed above, municipalities collect a significant amount of discarded products and may prefer selling these to unofficial entities. It is estimated, for example, that up to 80 % of the e-waste European municipalities collect is sold to independent (and unofficial) entities outside the scope of the WEEE Directive (ERP 2013). This practice allows these unofficial entities to profit by selling easily recoverable valuable contents in the commodity market and by selling "evidence" to producers (or PROs) at inflated prices, or "profiteering." This practice results in excessive compliance costs for the producers and has been seen in the UK, where unofficial entities have tremendously increased the price of *recycling certificates* sold to producers or PROs and ultimately inflated costs tied to the WEEE Directive by up to 50 %.

Another issue that exacerbates the waste-availability problem is the way collection targets are set. For example, under the WEEE Directive, collection targets are defined as a percentage of products placed on the market in the preceding 3 years. Although consumers have purchased more electrical and electronic equipment in recent years, they will not necessarily discard these products at the same rate. If consumers keep these items for a longer time, it will not be possible to find a sufficient number of used products to meet targets, only intensifying competition for e-waste. Defining collection targets based on recent sales, therefore, may result in a target that is unattainable in the market. One solution could be defining a collection target as a fraction of the total amount of waste generated instead of products put on the market.

14.4.2 Global Competition for Waste

The flow of waste in the market gets more complicated with significant trafficking from developed to developing countries lacking the proper infrastructure to manage them. When a substantial amount of waste leakage occurs, especially with (legally or illegally) exported products containing recoverable value, this affects the functioning and success of EPR-based policies. Exporting waste long has been a global issue and led to many developing and developed countries adopting *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal* in 1989. The Basel Convention requires that, prior to sending abroad, all hazardous waste, including hazardous e-waste (e.g., waste containing lead, mercury, cadmium, CRT screens, PCBs, etc.), first must receive consent from the recipient country.

In practice, Basel Convention adoption does not necessarily imply the country will not export any hazardous waste. Under the WEEE Directive, for example, minimum requirements (such as evidence of evaluation or functionality testing, business-to-business agreement for take-back) set for shipments prove that used electrical or electronic products do not count as *waste*. These efforts alone, however, do not eliminate illegal activities. The difficulty in classifying such used products as second-hand products versus hazardous waste remains a complicating issue. Recent figures show a significant amount of used electrical or electronic products are exported to Africa and other non-OECD countries, with an estimated 30–80 % of these items not functioning (i.e., should be classified as *waste*).

Although the U.S. signed the Basel Convention, it has not ratified it. Generally, e-waste generated in the U.S. is preprocessed domestically and sent overseas for end processing, including recovering precious and special metals. A few big U.S. recycling companies dismantle e-waste manually or with automated shredders to recover these items' aluminum, steel and plastic content before shipping to smelters overseas the circuit boards, where most high-value metals reside. The U.S. does not yet have integrated smelting capacity, therefore it does not completely process any of its e-waste. This may change because a new "urban mining" refinery dedicated to recovering valuable metals such as gold, silver, and palladium from e-waste is opening in Arkansas (Noyes 2014).

It is estimated that 50–80 % of e-waste collected in the U.S. is exported to developing countries such as China, India and Pakistan due to low-cost labor and less-stringent environmental regulations (Greenpeace 2009). The U.S., however, introduced the Responsible Electronics Recycling Act (RERA) in 2013, prohibiting the export of certain e-waste (such as computers, TVs, cell phones) with listed toxics (such as mercury, lead, cadmium) to countries that are not members of the OECD or the EU (U.S. Congress 2013). This legislation seeks to prohibit exporting untested and nonfunctional electronics to developing nations, while exporting used and functioning items are allowed. The rationale behind this approach is that used items with remaining useful lives could provide access to technology with reasonable prices for people in developing countries.

Indeed, e-waste plays a significant role in developing countries' recycling sectors even though it is not generated locally. In these countries, scavengers in the informal sector predominantly handle waste that is mostly illegally imported. For example, informal recycling entities handle 95 % of e-waste in

India. Usually, economically challenged groups of society who are not educated about the potential health and environmental hazards of mishandling of e-waste and unsafe backyard recycling operations work in this sector. These informal entities commonly extract gold from circuit boards by drenching them in cyanide or hand-picking over open fires despite risks to soils, water, and human health. Similarly, CRT screens, coolants, gases used in refrigerators, if not treated properly, can pose serious environmental and health risks.

In this context, it is important to identify the interactions between the EPR requirements and export bans. Alev et al. (2015) studies this issue through a durable goods manufacturer. The authors develop and analyze a stylized model where a durable goods manufacturer operating under EPR obligations chooses the quantity of new products to sell, what used products to recover from the secondary market, what end-of-life products to recover, and what products to export to the developing country for recycling. Considering a producer who can choose to fulfill its EPR obligations by collecting used products with remaining lives or collecting end-of-life products, they analyze how a partial exports ban (such as the approach proposed in the U.S.) compares with a full exports ban (such as the Basel Convention) in environmental performance measures. Partial export restrictions, they find, may have unintended consequences, causing the producer to interfere with a secondary market more. This reduces reuse, seen as more environmentally friendly than recycling. Furthermore, partial export bans may result in an increase in production (thus consumption) and higher export volume in the developed country.

14.4.3 Competition Against Third-Parties and Secondary Markets

When products consumers discard have high residual value, a producer may have incentive to collect these products even in the absence of EPR regulations for several reasons. First, some producers find it profitable to collect and remanufacture these used products. Second, some producers who are not interested in selling remanufactured product counterparts may prefer collecting used products in order to interfere with secondary markets. Some independent third parties also may have an interest in collecting and remanufacturing these used products, which may cannibalize new-product sales. When EPR is introduced in a market where some used-item collection is ongoing, it is unclear how the total amount of used product collection will change.

Esenduran et al. (2015c) considers a monopolist that collects used products for remanufacturing in the absence of EPR regulation and studies whether EPR regulation with collection targets promotes or hinders remanufacturing. Under the WEEE Directive, producers who put a product on the market for the first time are subject to collection targets. Based on this definition, Gray and Charter (2007) argue that a remanufactured and resold product in the market where it was introduced should be exempt from collection targets. Once the product reaches a collection center, however, it may be difficult to identify if the product already has been remanufactured. The authors show that if the collection target is sufficiently high but remanufactured products are exempt, legislation would increase remanufacturing. However, if the collection target applies to remanufactured products as well, remanufacturing and collection may decrease. This occurs because imposing stringent collection targets on remanufactured products effectively increases the cost of remanufacturing. Although EPR policies generally encourage reuse, this might hurt the existing remanufacturing levels if regulation does not hold remanufactured products exempt from collection targets.

Although product reuse is usually perceived as an environmentally superior alternative to recycling, separate reuse targets so far have not been implemented in practice. However, environmental organizations such as RREUSE and Computer Aid strongly advocate for them and European policymakers continue to discuss their inclusion in the WEEE Directive (Computer Aid 2010; RREUSE 2012).

Indeed, the European Commission proposed that separate reuse targets of 5 % be incorporated in a recent WEEE Directive revision. Although it did not specify such targets, reuse targets will be reconsidered in 2016. Esenduran et al. (2015b) in a follow-up work study how EPR regulations with collection and additional reuse targets affect the remanufacturing industry. In practice, remanufacturing is carried out either by independent remanufacturers (IRs) (e.g., Nokia is not involved in the remanufacturing but IRs do sell remanufactured Nokia units), original equipment manufacturers (OEMs) (e.g., Nikon and Canon remanufacture their own units, and remanufactured units of these brands sold by other parties are labeled as OEM-refurbished), or both (e.g., both Apple and Gazelle sell refurbished iPhones). Considering all these possible market structures, Esenduran et al. investigate how regulation affects remanufacturing levels and OEM-IR competition. Even while not implementing reuse targets, several e-waste laws (e.g., those in New York State and Illinois) state that reuse should be preferred over recycling while imposing collection and proper recovery obligations. Some argue that regulation may promote remanufacturing (Willis 2010) because, under regulation with collection targets, OEMs are required to collect more used products than they would have collected otherwise. To offset the cost of collection and disposal, then, OEMs might consider remanufacturing collected cores. Esenduran et al. show this is not always true. Imposing regulations with high collection targets on the OEM may hurt remanufacturing levels because it reduces new product manufacturing, which in turn would reduce the amount of collection as well as remanufacturing as available cores decrease. Similarly, a stringent reuse target also may reduce the level of remanufacturing. The authors also consider whether regulation would make OEM-IR competition more or less likely. If the OEM is the only party who remanufactures in the absence of regulation, their results show that, after the regulation is imposed, the IR never would enter the remanufacturing market. In other words, IRs in markets where only OEMs remanufacture see remanufacturing as even less attractive than it was in the absence of regulation. However, in markets where only the IR remanufactures in the absence of regulation, the OEM may enter the remanufacturing market as regulation is introduced, sparking competition. The impact of regulation on competition, therefore, depends on who remanufactures in the first place.

Finally, a durable goods manufacturer may interfere with the secondary market even when not involved in remanufacturing business. In this case, manufacturers could interfere to moderate competition against the secondary market by reducing the cannibalization of new product sales and driving up new-product prices by increasing the resale value of used products. In this context, Alev et al. (2015) study whether EPR regulation would create additional incentives for a monopolist producer to collect and recycle used products with remaining useful lives instead of end-of-life products not eligible for reuse. Results suggest that, when collection targets are not sufficiently high, this would be the case. This result implies that, in a durable goods setting, EPR regulation may have unintended consequences by reducing product reuse.

14.5 Conclusions

The EPR principle is built on certain assumptions including that (1) recovering waste has a net cost, (2) products discarded by customers have no useful life left, and (3) waste is homogenous with respect to its geographical location, design or condition. As these assumptions are being challenged in today's waste markets, it is important to identify the implications of EPR regulation on waste markets. Having a closer look at the waste markets (see Sect. 14.3), we understand there are several entities (official and unofficial) involved in waste recovery. EPR regulations affect all players in the waste market (regardless of them being official or unofficial), and their reactions in turn affect the success of such regulation.

Literature so far has discussed competition waste collection under EPR regulation, interactions of export bans and EPR regulations, and the effect of EPR regulations on product reuse (secondary markets) and the remanufacturing industry. One common takeaway emerges: Ignoring today's challenges to EPR's foundational assumptions would result in unintended consequences, decreasing landfill diversion, diminishing product design incentives, or lowering product reuse. When implementing the EPR principle in the form of a regulation, policymakers should pay attention to market conditions and product characteristics to avoid these.

References

Ademe (2013) Study on the quantification of waste of electrical and electronic equipment (WEEE) in France. Available at http://www.ademe.fr/sites/default/files/assets/documents/91257_report-weee-arising-france.pdf. Accessed Jan 2015

Alev I, Agrawal V, Atasu A (2015) Extended producer responsibility, secondary markets and export restrictions. Working paper, Georgia Institute of Technology, Atlanta

BIS (2013) Implementation of the WEEE recast Directive 2012/19/EU and changes to the UK waste electrical and electronic equipment (WEEE) system: consultation department for business innovation and skills. Available at www.gov.uk/government/uploads/system/uploads/attachment_data/file/190207/bis-13-762-implementation-of-weee-recast-directive-and-changes-to-the-uk-weee-system-consultation.pdf. Accessed Aug 2015

Canada (2014) Available at http://www.ec.gc.ca/gdd-mw/default.asp?lang=En&n=FB8E9973-1. Accessed Aug 2015

CDTSC (2013) E-waste report: determination of regulated elements in seven types of discarded consumer electronic products. Available at: https://www.dtsc.ca.gov/HazardousWaste/EWaste/upload/Consumer_Electronic_Products.pdf. Accessed Aug 2015

CENELEC (2013) WEEE recycling standards – general technical requirements for treatment of WEEE. Available at www.cenelec.eu/dyn/www/f?p=104:110:1758419883472534::::FSP_PROJECT,FSP_LANG_ID:23677,25. Accessed Feb 2015

Computer Aid (2010) Why reuse is better than recycling. Available at http://www.computeraid.org/uploads/ICTs-and-the-Environment---Special-Report-1---Reuse-%28Aug10%29.pdf. Accessed May 2015

Cui J, Roven H (2011) Electronic waste. In: Letcher T, Vallero D (eds) Waste: a handbook for management. Academic Press, New York

DigitalEurope (2011) WEEE collection rate: measuring all WEEE flows. Available at http://www.digitaleurope.org/DesktopModules/Bring2mind/DMX/Download.aspx?Command=Core_Download&EntryId=490&PortalId=0&TabId=353. Accessed Aug 2015

DigitalEurope (2014) An example of best practice in implementing WEEE II. Available at http://www.digitaleurope.org/DocumentDownload.aspx?Command=Core_Download&EntryId=669. Accessed Oct 2014

EPA (2012) Municipal solid waste (MSW) in the United States: facts and figures. Available at http://www.epa.gov/epawaste/nonhaz/municipal/msw99.htm. Accessed Jan 2015

ERP (2013) Assessment and proposals for the revision of the WEEE Directive based on the European Recycling Platform's 4 years of operations. Available at https://www.erp-recycling.pt/CMS_BackOffice/ResourceLink.aspx?ResourceName=A%2Bbetter%2BWEEE%2BDirective-ERP%2Bwhitepaper.pdf. Accessed Feb 2015

Esenduran G, Atasu A, Van Wassenhove L (2015a) Valuable e-waste: implications for extended producer responsibility. Working paper, The Ohio State University, Fisher College of Business

Esenduran G, Kemahlioglu-Ziya E, Swaminathan JM (2015b) Impact of take-back regulation on the remanufacturing industry. Working paper, The Ohio State University, Fisher College of Business

Esenduran, G., Kemahlioğlu-Ziya, E. and Swaminathan, J. M. (2015), Take-back legislation: consequences for remanufacturing and environment. Decis Sci. doi: 10.1111/deci.12174

ETC (2015) Electronics takeback coalition. Available at http://www.electronicstakeback.com/wp-content/uploads/Lessons-Learned-from-State-E-waste-laws.pdf. Accessed Feb 2015

Europa-Environment (2012) Directive 2012/19/EU of the European Parliament. Available at http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:EN:PDF. Accessed Jan 2015

Eurostat (2013) Waste statistics – electrical and electronic equipment. Available at http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment. Accessed Jan 2015

Gold (2013) Gold price Europe. Available at http://goldprice.org/gold-price-euros.html. Accessed Feb 2015

Gray C, Charter M (2007) Remanufacturing and product design: designing for the 7th generation. Tech. rep., The Center for Sustainable Design, Farnham, UK

Greenpeace (2009) Where does e-waste end up? Available at http://www.greenpeace.org/international/en/campaigns/detox/electronics/the-e-waste-problem/where-does-e-waste-end-up/. Accessed May 2015

Gui L, Atasu A, Ergun O, Toktay L (2013) Implementing extended producer responsibility legislation. J Ind Ecol 17:262–276

Hoornweg D, Bhada-Tata P, Kennedy C (2013) Environment: waste production must peak this century. Nature 502:615–617. Available at http://www.nature.com/news/environment-waste-production-must-peak-this-century-1.14032

HP (2013) Changes to regulations could save businesses 50 million gbp, shows hp report. Available at http://www8.hp.com/uk/en/hp-news/press-release.html?id=1167526. Accessed Jan 2015

Huisman J (2010) WEEE recast: from 4 kg to 65 %: the compliance consequences. UNU Expert opinion on the EU WEEE Directive. Tech. rep., United Nations University, Bonn

Huisman J, van der Maesen M, Eijsbouts R, Wang F, Balde C, Wielenga C (2012) The Dutch WEEE flows. Tech. rep., United Nations University, ISP-SCYCLE, Bonn

Hunt T (2013) Avoid the environmental effects of cell phones. Available at http://www.triplepundit.com/2013/03/effects-of-cell-phones/. Accessed Jan 2015

Kaffine D, O'Reilly P (2013) What have we learned about extended producer responsibility in the past decade? A survey of the recent EPR economic literature. Available at http://spot.colorado.edu/~daka9342/OECD_EPR_KO.pdf

KPMG (2012) Raw material scarcity and its impact on business. Available at https://www.kpmg.com/NL/nl/IssuesAndInsights/ArticlesPublications/Documents/PDF/Consumer-Markets/Raw-material-scarcity-def.pdf. Accessed Jan 2014

Krausmann F, Gingrich S, Eisenmenger N, Erb K, Haberl H, Fischer-Kowalski M (2009) Growth in global material use, GDP and population during the 20th century. Ecol Econ 68:2696–2705

Kukday K (2007) Making profit from mining of e-waste. Available at http://articles.timesofindia.indiatimes.com/2007-06-08/india-business/27973905_1_e-waste-generation-satish-sinha-ores. Accessed Jan 2015

Lifset R (1993) Take it back: extended producer responsibility as a form of incentive-based environmental policy. J Resour Manag Technol 21(4):163–175

Lindhqvist T (2000) Extended producer responsibility in cleaner production. PhD thesis. The International Institute for Industrial Environmental Economics Dissertation, Lund University, Sweden

Nash J, Bosso C (2013) Extended producer responsibility in the United States. Full speed ahead? J Ind Ecol 17(2):175–185

Noyes K (2014) Can urban mining solve the world's e-waste problem? Available at http://fortune.com/2014/06/26/blueoak-urban-mining-ewaste/. Accessed Jun 2015

OECD (2001) Extended producer responsibility: a guidance manual for governments. OECD, Paris

RREUSE (2012) WEEE compromise far from convincing for the European reuse sector. Available at http://www.endseurope.com/docs/120119b.pdf. Accessed May 2015

Revisor of Statutes MO (2007) Minnesota session laws 2007: video display and electronic device collection and recycling. Available at https://www.revisor.mn.gov/statutes/?id=115A&view=chapter#stat.115A.13. Accessed Feb 2015

Thompson P, Hollins O (2013) Operational group 2 – briefing paper. Available at https://ec.europa.eu/eip/raw-materials/en/system/files/ged/1013%20WP2%20Final%20Briefing%20Paper%20Feb%2013.pdf. Accessed Jan 2015

UNEP (2009) Recycling: from e-waste to resources. United Nations Environmental Programme and United Nations University. Available at http://www.unep.org/pdf/Recycling_From_e-waste_to_resources.pdf. Accessed May 2015

U.S. Congress (2013) Available at https://www.congress.gov/bill/113th-congress/house-bill/2791. Accessed Feb 2015

U.S. National Park Service (2014) Available at http://des.nh.gov/organization/divisions/water/wmb/coastal/trash/documents/marine_debris.pdf. Accessed Feb 2015

Willis P (2010) Market failures in remanufacturing. Center for Remanufacturing and Reuse, Aylesbury

WIPO (2014). Available at http://www.wipo.int/wipo_magazine/en/2014/03/article_0001.html. Accessed Feb 2015

ZeroWasteEurope (2014) Living planet report. Available at http://www.zerowasteeurope.eu/category/residual-waste/. Accessed Feb 2015

Zhang K (2011) Recycling of electronic waste II: proceedings of the second symposium. John Wiley & Sons, New Jersey

Part V
Regulation-Driven Environmental Responsibility in Supply Chains: Operational Perspectives

Chapter 15
Emissions Allocation Problems in Climate Change Policies

Nur Sunar

Abstract This chapter discusses prominent allocation problems that arise in the design and implementation of climate change policies. In particular, the chapter provides an overview of the operations management literature that analyzes greenhouse gas emissions allocation problems in supply chains and co-production systems, and the chapter includes a detailed discussion of the literature on the free allowance allocation rules in cap-and-trade markets. In addition, the chapter provides an overview of recently available climate change policies, and explains the implications of greenhouse gas emissions allocation for a firm in the absence of a climate change policy (particularly in the context of voluntary carbon offsetting).

15.1 Overview of the Chapter

In this chapter, we provide some background on recent climate change policies in the world; we discuss in detail the operations management literature that analyzes (greenhouse gas) emissions allocation problems in supply chains and co-production systems, and we review the literature on alternative rules for allocating free emission allowances[1] in cap-and-trade markets. Hereafter,

N. Sunar (✉)
Kenan-Flagler Business School, University of North Carolina at Chapel Hill,
300 Kenan Center Dr, Chapel Hill, NC 27599, USA
e-mail: Nur_Sunar@kenan-flagler.unc.edu

[1] In the European Union Emissions Trading System (EU ETS), each emission allowance represents the permit to emit 1 tonne of CO_2 or equivalent amount of nitrous oxide and perfluorocarbons (European Commission 2013).

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_15

unless otherwise specified, the term "emissions" will be used to refer to "greenhouse gas emissions."

The organization of the chapter is as follows. Section 15.2 provides the background of the recent status of climate change policies in the world, and explains the term "social cost of carbon," which is critical in environmental policy making.

The production of food and basic materials causes substantial emissions (Sunar and Plambeck 2015). Such production processes mostly involve co-production of multiple products simultaneously. Section 15.3 discusses emissions allocation among co-products and its implications for procurement and climate change policy.

The design of an intermediate product or a service by a company can impact the carbon footprint of a final product. For such final products, allocation of emissions among supply chain members can be necessary to incentivize supply chain members to invest in energy efficiency. Section 15.4 discusses the emissions allocation among supply chain members.

The scheme used to allocate emission allowances in a cap-and-trade market is likely to have a significant impact on profitability of regulated firms as well as the effectiveness and efficiency of the cap-and-trade market. Section 15.5 discusses the free allowance allocation schemes available in the EU ETS, and the efficiency and profitability implications of alternative schemes for free emission allowance allocation.

Section 15.6 explains that emissions allocation is crucial even in the absence of a climate change policy, and includes insights related to voluntary carbon offsetting. Section 15.7 summarizes the key insights.

15.2 Background on Climate Change Policies in the World and Social Cost of Carbon

15.2.1 State of the Climate Change Policies in the World

To keep the average global temperature increase (compared to pre-industrial levels) below 2 °C, all countries need to take action by adopting a climate change policy (World Bank Group & ECOFYS 2014). Currently, there is no global climate change policy in effect. A region adopting a climate change policy generally designs its own policy. This leads to a substantial variation in climate change policies across different parts of the world. There are two main policy tools currently in use for combating climate change: a carbon tax and a cap-and-trade system. Some regions have adopted either a cap-and-trade system or a carbon tax. For instance, Kazakhstan fully implemented a cap-and-trade market, whereas South Africa is scheduled to adopt a carbon tax.

Some other countries (including France, Portugal, and Ireland) have adopted a hybrid climate change policy under which both a cap-and-trade market and a carbon tax are in effect. For instance, companies located in France are required to pay a carbon tax for their CO_2 emissions associated with the use of various fuels not covered by the EU ETS (World Bank Group & ECOFYS 2014). There are also regions that have not yet adopted any climate change policies.

The adopted climate change policies are also very heterogeneous in scope. Some regions have implemented a national/multi-national cap-and-trade market while others have implemented a sub-national cap-and-trade market that only covers entities located in a particular part of the region. For instance, in New Zealand and Kazakhstan, a national cap-and-trade market is in effect, but in the United States, there are a few sub-national policies in effect (the U.S. has not yet implemented a federal carbon tax or cap-and-trade market). Examples of the latter include California's cap-and-trade market, which took effect in 2012 and covers emissions from various entities located in California, and the Regional Greenhouse Gas Initiative, a cap-and-trade market covering CO_2 emissions from each fossil-fuel-fired power plant that is larger than or equal to 25 megawatts and located in either Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Rhode Island, or Vermont (Regional Greenhouse Gas Initiative 2015).

Imposing a carbon tax or implementing a cap-and-trade system involves putting a price on emissions. However, the dynamics of the emissions price under these two policies are very different. A carbon tax guarantees a particular price per each unit of emissions. On the other hand, with a cap-and-trade system, the price of emissions allowance is highly uncertain and is formed as a result of regulated companies' activities. For instance, the variability in the emission allowance price in the EU ETS can be seen in Fig. 15.1. Different price dynamics under different policy designs and the region-specific climate change policies cause a high variation in emissions prices across different parts of the world. For instance, in 2014, emission allowance price in Kazakhstan was around \$2/tonne of CO_2, whereas the carbon tax in France was set to \$10/tonne CO_2 (World Bank Group & ECOFYS 2014).

15.2.1.1 Climate Change Policies and International Trade: Border Carbon Adjustment

There are large amounts of emissions which result from the activities of international trade. According to Davis and Caldeira (2010), in 2004 the emissions due to production of goods traded internationally accounted for around 25 % of global CO_2 emissions, and around 23 % of the emissions produced in China was due to another region's consumption of goods made in China. Due to such large emissions occurring as a result of international trade, policy makers in the E.U. and other regions have been contemplating a border

Fig. 15.1 2013–2014 Emission allowance price in the EU ETS primary emission allowance auctions. (Data source: European Energy Exchange)

carbon adjustment on imports from regions without a climate change policy. Directive 2009/29/EC of the European Parliament and of the Council made some revisions in the EU ETS. New provisions in this directive facilitate the implementation of a border carbon adjustment on imported products. The American Clean Energy and Security Act (also known as the Waxman-Markey Bill), a comprehensive legislation about national energy and climate change policies, was passed by the U.S. House of Representatives on June 26, 2009, but was not passed by the U.S. Senate. The bill consists of the following five titles: Clean Energy, Energy Efficiency, Reducing Global Warming Pollution, Transitioning to a Clean Energy Economy, Agriculture and Forestry Related Offsets. Title III of the bill ("Reducing Global Warming Pollution") proposes a border carbon adjustment on particular products that are imported from certain countries in the absence of a global action for climate change.

With a border carbon adjustment, buyers (i.e., importers) in a region with climate change policy can incur an additional cost due to emissions resulting from the production of the goods imported from regions without a climate change policy. For instance, with the border carbon adjustment in the form of an import emissions tax, buyers in the former region must incur an additional cost in proportion to emissions embodied in the products from the latter regions. According to World Trade Organization (WTO) rules, imported emissions and domestic emissions must be treated the same since they are alike products. As a result, the cost per unit of imported emissions has to be the same as the carbon tax or the emission allowance price in the importing region. In particular, if a cap-and-trade system (respectively, a carbon tax) is in effect in a region adopting a border carbon adjustment, then in that region the cost per 1 tonne of emissions embodied in an imported product should be equal to the allowance price (respectively, the carbon tax) in that region.

When is the implementation of such border carbon adjustments legal? According to WTO rules, implementing border adjustment can be allowed only under some exceptions, all of which are explained in Article XX of The General Agreement on Tariffs and Trade (GATT 1947). In particular, Article XX (b) and (g) are very relevant to countries that aim to implement border carbon adjustment on imported products from regions without climate change policy. Article XX: General Exceptions states these two exceptions as follows:

"Subject to the requirement that such measures are not applied in a manner which would constitute a means of arbitrary or unjustifiable discrimination between countries where the same conditions prevail, or a disguised restriction on international trade, nothing in this Agreement shall be construed to prevent the adoption or enforcement by any contracting party of measures:
. . . (b) necessary to protect human, animal or plant life or health;
. . . (g) relating to the conservation of exhaustible natural resources if such measures are made effective in conjunction with restrictions on domestic production or consumption; . . . "

Thus, if the border carbon adjustment fails to improve the environment, then its implementation is easily disputable under WTO rules. We next explain an important term, "social cost of carbon", which will be used repeatedly in the subsequent sections.

15.2.2 Measuring the Social Impact of Emissions: Social Cost of Carbon

As discussed in Sect. 15.2.1, there are various mechanisms available for policy makers to take action against climate change, and regions that adopt climate change policies usually design their own policies, resulting in a high worldwide variation in climate change policies. These observations open up the following questions: Which policy design achieves a higher social welfare? How should a social planner determine the welfare-maximizing climate change policy for its region? Clearly, a social planner who aims to maximize the social welfare in its region should consider the potential negative effects of climate change in policy making. How can these potential negative effects be measured? The estimated monetary value of the damage caused by an additional unit of carbon emissions is called the social cost of carbon (SCC). To implement effective policies that combat climate change's potential negative effects, it is essential to accurately estimate the SCC, however, there are many challenges in its estimation. In particular, there is uncertainty about future emissions, how emissions impact the climate, and the economic consequences resulting from potential climate-change-associated damages (Greenstone et al. 2013). There are three main integrated assessment models currently used to estimate the SCC: the Dynamic Integrated Climate Economy model (DICE), the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) and the Policy Analysis of the Greenhouse Effect (PAGE). Interested readers can find the details of these models in Greenstone et al. (2013), U.S. Federal Government Interagency Working Group on Climate Change (2010), and IPCC (2014). For federal rule making, in 2013 the U.S. adopted an estimate of \$36 per tonne of CO_2 for the SCC. However, it is acknowledged that it is very likely that the true SCC is higher than such estimates. The average SCC estimates increase over time since the stock accumulated in the atmosphere increases over time, and a different stock level is likely to impact climate change in a different way. The EPA's average estimate of the SCC (with a 3 % discount rate) is provided in Table 15.1 (EPA 2013).

Table 15.1 Average estimate of social cost of carbon (\$/tonne of CO_2)

Year	2020	2025	2030	2035	2040
Social cost of carbon	42	46	50	55	60

15.3 Emissions Allocation in Co-production Systems

According to Sunar and Plambeck (2015), nearly 50 % of anthropologic emissions are due to the production of food and basic materials, which usually involves a co-production system.[2] Given the prevalence of co-production systems, for an importer that aims to maximize its profit in a region with border carbon adjustment or for a policy maker intending to improve social welfare by means of an import emissions tax, it is crucial to assign emissions to an imported product. However, assigning emissions to a product is not straightforward if the product comes from a process that yields multiple products simultaneously. Under current voluntary standards, such as The Greenhouse Gas Protocol (developed by the World Resources Institute and the World Business Council on Sustainable Development) or PAS 2050 (developed by

[2] A process that yields multiple products simultaneously is called a "co-production system".

the British Standards Institute), firms are given the flexibility to choose one of the following three allocation rules to calculate the emissions associated with a product of a co-production system (Sunar and Plambeck 2015):

- value-based allocation,
- mass-based allocation, or
- system expansion (which will be referred to as expansion-based allocation for parallelism in the exposition).

Below, we consider a simple hypothetical co-production system to explain the calculation of the emissions intensity of each co-product[3] under different allocation rules. Suppose that a supplier produces products X and Y in a one-to-one ratio, and the unit price and mass of each product are as in Table 15.2. Also, assume that the emissions intensity of the supplier[4] is 1000 tonnes of CO_2 per tonne of Y, and the emissions intensity of a substitute product of Y is 500 tonnes of CO_2 per tonne of that product. Using these data, Table 15.3 shows the calculations of the emission intensity assigned to product X under value-, expansion- and mass-based allocations. As observed in Table 15.3, the value-based rule allocates the supplier's emissions intensity in proportion to the revenue ratio; the mass-based rule allocates the supplier's emissions intensity in proportion to the mass ratio; and the expansion-based allocation subtracts the substitute emissions intensity for product Y from the supplier's emissions intensity.

Table 15.2 Price and mass data for co-products X and Y

	Mass (tonne)	Selling price ($/tonne)
Product X	9	50
Product Y	1	200

Table 15.3 Emissions intensity assigned to Product X under alternative allocation rules

	Emissions intensity of Product X (tonnes of CO_2/tonne)
Value-based allocation	$1000 \times \frac{(50\times 9)}{(50\times 9+200\times 1)} = 692.31$
Mass-based allocation	$1000 \times \frac{9}{9+1} = 900$
Expansion-based allocation	$1000 - 500 = 500$

[3] The term "emissions intensity of a co-product X" means the emissions allocated to co-product X as a result of 1 tonne of production of that co-product.

[4] The supplier's emissions per 1 tonne of product X or Y is called the emissions intensity of the supplier.

As demonstrated by this simple example, the choice of allocation rule significantly affects the emissions intensity assigned to each co-product. Understanding the implications of alternative allocation rules for importers' profits, social welfare and global emissions is especially important in the context of border carbon adjustment. (Allocating emissions among co-products is also quite important in the absence of climate change policy. The implications of emissions allocation for firms that voluntarily offset their supply chain emissions will be discussed in Sect. 15.6.) In the context of border carbon adjustment, Sunar and Plambeck (2015) study the following research questions:

- Should a social planner in the region with climate change policy implement border carbon adjustment? If so, what is the socially optimal allocation rule among currently available allocation rules?
- What are the implications of three currently available allocation rules for importers' profits, global emissions and social welfare?
- What is the impact on importers' profitability of their flexibility to choose their allocation rules ?

To answer these research questions, Sunar and Plambeck (2015) introduce and analyze the following supply chain model. There are two regions: a region with a climate change policy and a region without a climate change policy. The cost of emissions is positive in the region with the climate change policy whereas there is no cost of emissions in the other region. The supplier is located in the region without climate change policy and produces a primary product X that is only sold in the region with the climate change policy, and multiple co-products, each of which is only sold in the region without climate change policy. All co-products are produced in a one-to-one ratio with the primary product X. The price of product X is set by the supplier whereas all other co-products are sold at a fixed price. The importers of product X (which are located in the region with the climate change policy) compete in quantity, and each of them faces a downward sloping general demand curve. When the supplier produces one unit of product X, it incurs a production cost and produces one unit of each co-product and some emissions. The supplier's level of emissions per 1 tonne of product X is called the emissions intensity of the supplier. Each importer is subject to an emissions cost in proportion to the sum of its direct and indirect emissions. An importer's indirect emissions are equal to the emissions embodied in its imported product X, which depends on the allocation rule used to assign an emissions intensity to product X. With a border carbon adjustment, the unit emissions cost in this model represents the carbon tax or the expected emission allowance price. Without a climate change policy, the unit emissions cost could be interpreted as the voluntary carbon offset price. The discussion of the results in Sunar and Plambeck (2015) with the latter interpretation of the unit emissions cost can be found in Sect. 15.6.

The sequence of events is as follows. The supplier sets the price of product X to maximize its profit. Next, each importer chooses its order quantity for product X and, if importers are given the flexibility to choose their allocation rules, the allocation rule from either value-, expansion- or mass-based allocations. The objective of the social planner in the region with the climate change policy is to maximize the social welfare in that region.

Sunar and Plambeck (2015) discuss that there are various industries (ranging from agricultural to mining/metallurgical industries) that satisfy the model explained above, and demonstrate a numerical example based on rare earth oxide supply chains. In this example, they consider a Chinese company, Inner Mongolia Baotou Rare Earth Company that produces iron ore and cerium oxide in a fixed ratio from its Bayan Obo mine. Iron ore is sold in China at a fixed price and the cerium oxide is sold in the U.S., mainly to the U.S. flat glass manufacturers. Inner Mongolia Baotou has the market power to set the price for cerium oxide since it holds the global monopoly in rare earth production (more than 90 % of global rare earth elements are produced by Baotou). In that setting, a relevant question for the U.S. flat glass manufacturers would be the following: Which allocation rule should a U.S. flat glass manufacturer use to calculate emissions embodied in cerium oxide in the presence of border carbon adjustment? From a policy making perspective, the relevant questions are as follows. Should the U.S. government implement border carbon adjustment? If the government implements border carbon adjustment, which allocation rule maximizes the social welfare in the U.S.?

We next highlight some of the results and policy related insights derived by Sunar and Plambeck (2015). Sunar and Plambeck (2015) show with a general demand function that compared to the case without a border carbon adjustment, a border carbon adjustment with value-based allocation can strictly increase emissions whereas a border carbon adjustment with either expansion- or mass-based allocation always decreases emissions. Sunar and Plambeck (2015) further show that, with an iso-elastic demand curve, a border adjustment with value-based allocation strictly increases emissions if the price elasticity of demand is moderate. The intuition behind this result is explained by Sunar and Plambeck (2015) as follows: The value-based allocation is an increasing function with respect to the price of product X. Therefore, implementing border carbon adjustment with value-based allocation motivates the supplier to reduce the price of product X and sell more of the product. Under this scenario, the price reduction is so deep that the new effective purchasing cost per product X is smaller than the original one, implying an increase in total production. Recall from Sect. 15.2.1.1 that the legality of border adjustment depends on whether it is beneficial to the environment. Based on this, Sunar and Plambeck (2015) conclude that implementing border carbon adjustment with value-based allocation can violate WTO rules, and thus may be illegal. Other unexpected non-monotonicity results proved by Sunar and Plambeck (2015) show that under border carbon adjustment with value-based allocation, increasing the unit emissions cost or fixing the rule to the maximum of the currently available allocation rules (rather than allowing importers to choose their allocation rules) can strictly increase emissions and each importer's profit. The intuition behind these results is similar to the one explained above.

Should the policy maker implement the border carbon adjustment? If so, which allocation rule maximizes the social welfare? Sunar and Plambeck (2015) show that, among currently available allocation rules, implementing border carbon adjustment with the rule that minimizes emissions maximizes social welfare if and only if the SCC is sufficiently high. Social welfare with the socially optimal allocation rule is expected to be lower than the unconstrained optimal welfare achieved by designing an allocation rule. This is because with currently available allocation rules the social planner in the region with climate change policy cannot fully extract the supplier's profit. This conclusion leads to the question of how to design an allocation rule to achieve an unconstrained optimal social welfare. Focusing on the unconstrained social planner's problem of choosing the optimal positive-valued function as an allocation rule to maximize the social welfare, an earlier version of Sunar and Plambeck (2015) identifies the socially optimal unconstrained allocation design and shows that implementing border adjustment with that allocation rule maximizes social welfare. The earlier version of Sunar and Plambeck (2015) concludes that the implementation of the socially optimal unconstrained allocation rule is very unlikely because (1) it extracts the entire profit of the supplier for the benefit of the region with climate change policy and (2) it overallocates the emissions intensity to product X under realistic conditions, and thus the emissions intensity assigned to product X is strictly higher than the total emissions intensity of the supplier.

15.4 Emission Allocation Among Supply Chain Players

Many companies have recently started to collaborate with their supply chain partners to reduce the carbon footprint of their products. As we will discuss in Sect. 15.6, even in the absence of climate change policy, companies have been taking initiatives (such as voluntarily offsetting emissions) to improve the environmental performance of their supply chains. According to Caro et al. (2013), 86 % of Carbon Disclosure Project 2011 respondents claimed that they had been collaborating with their suppliers to reduce their carbon footprints. Large amounts of emissions are often embodied in the supply chain of a company. On average, the direct emissions of a firm constitute less than 15 % of the firm's entire supply emissions (Matthews et al. 2008). The carbon footprint of a product can be affected by the product design or service of many supply chain members. Caro et al. (2013) use the following example to explain that a joint effort by supply chain members can be necessary to reduce emissions: Eastman Chemical can reduce the carbon footprint of its products by delivering them to the customer in a molten state; however, this type of delivery requires operational coordination with customers and costs more. Considering such interactions and the joint effort to improve environmental performance of a supply chain, determining how much of the emissions associated with the final product can be assigned to each supply chain member might not be straightforward. In the remainder of this section, we discuss Caro et al. (2013) and Granot et al. (2014), which study emissions allocation among supply chain members. We first discuss Caro et al. (2013).

Caro et al. (2013) study a supply chain setting with multiple firms and multiple processes, focusing on how the firms in a supply chain can implement carbon abatement initiatives for their processes. In their model, every firm in the supply chain can implement a finite set of abatement actions to reduce the carbon footprint (i.e., emissions) of processes in the supply chain. Moreover, the firms can also choose the amount of effort for such actions, with an associated increasing cost of implementation. Caro et al. (2013) assume that the carbon footprint of a given process is decreasing in the firms' efforts. In this setting, Caro et al. (2013) represent the relationship between the firms and the processes using a matrix whose entries take binary values to indicate whether a given firm can reduce the carbon footprint of a given process.

Caro et al. (2013) first consider a social planner who sets a carbon footprint allocation rule to attempt to achieve the social first-best solution for the supply chain. Under such an allocation rule, every supply chain member can first exert an effort to reduce its carbon footprint, and then must make a payment based on its resulting carbon footprint and the social planner's allocation rule. Viewing this allocation rule as a social mechanism, Caro et al. (2013) describe a decentralized game between the supply chain members and establish that the social planner needs to enforce double counting to induce the first-best solution with a differentiable and increasing allocation rule. Next, Caro et al. (2013) examine a practical setting in which one of the supply chain members, namely the carbon leader, pays for all of the emissions throughout the supply chain. The insights related to that practical setting will be discussed in Sect. 15.6. The double-counting result of Caro et al. (2013) suggests the necessity of designing fairer rules that avoid double counting, which has been examined by Granot et al. (2014).

Granot et al. (2014) introduce and analyze an emissions allocation game among supply chain (or supply network) members in a cooperative game theory setting. Emissions of each supply network member are fixed, and in the case of a co-product manufacturer, the provided fixed emissions are assumed to be calculated based on value-based allocation. The objective in Granot et al. (2014) is to identify an easy-to-implement rule that allocates total supply chain (or total supply network) emissions associated with a product to the supply chain (or supply network) members without the use of double counting. Granot et al. (2014) show that allocating emissions responsibility equally among downstream firms is the Shapley value of the game, and thus it is in the core. In this context, the Shapley value can be interpreted as the average marginal cost contributions in a coalition. Under their identified rule, (1) all supply chain emissions are allocated and double-counting is avoided and (2) emissions assigned to a supply chain player or a set of supply chain players are less than or equal to the emissions for which it is responsible. An interesting research direction discussed by Granot et al. (2014) is whether such an allocation rule incentivizes a supply chain member to invest and collaborate with other supply chain members to reduce emissions.

15.5 Emission Allowance Allocation in Cap-and-Trade Markets

The EU ETS is an important cap-and-trade market, since it is the first and by far the largest international cap-and-trade market in the world as of 2013. We therefore focus our attention on the EU ETS in this section. We next provide some background on the EU ETS, which will be necessary for understanding the significance of the allowance allocation problem in the EU ETS.

The EU ETS was launched in 2005 to reduce emissions in the EU, with growth and development occurring in three phases so far. Phase I (the trial period for the EU ETS) was in effect between 2005 and 2007. In this phase, most of the emission allowances were distributed for free, and the EU ETS covered around 40 % of the carbon dioxide emissions in the EU from emissions intensive sectors. In Phase II, which took place between 2008 and 2012, the scope of the EU ETS was significantly extended: Iceland, Norway and Liechtenstein joined the EU ETS, and the aviation sector was added to the EU ETS (European Commission 2013). In Phase III (in effect since 2013), the EU ETS has covered nearly 45 % of the emissions in the EU. In particular, it has covered (1) carbon dioxide emitted by energy-intensive industries (such as oil refining, pulp and paper, steel and glass), power and heat generators and the aviation sector, (2) nitrous oxide from various production processes, and (3) perfluorocarbon emitted by aluminum producers. Phase IV will be implemented beginning in 2021 and will last until 2028.

The EU ETS uses a "cap-and-trade" system. The term "cap" refers to the total emissions produced by regulated entities. In the EU ETS, the cap is determined at the EU level and it has been set to decrease over time. Subject to this cap, firms can receive some emission allowances for free and buy additional emission allowances at auctions. An emission allowance represents a permit to emit 1 tonne of CO_2 or the equivalent amount of nitrous oxide and perfluorocarbons (European Commission 2013). Regulated firms must have enough emission allowances to cover their emissions. If the emission allowances of a firm are less than its actual emissions in the previous year, then the firm is subject to high penalties. The penalty in 2013 was 100 Euros per tonne of CO_2. There are alternative ways for matching emission allowances with annual emissions. Since the launch of the EU ETS, free emission allowances have been distributed to regulated entities based on various allocation rules. Unlike previous phases, in the third phase power generators are not eligible for free emission allowances (European Commission 2013), but manufacturing firms can still receive such allowances. If free allowances allocated to a firm are less than its emissions, the firm can buy additional emission allowances by participating in auctions, or use emission allowances it saved from previous years, or (to some extent) buy compliance carbon offsets to match allowances with emissions. Companies are also allowed to sell their emission allowances in auctions or transfer them to future periods for compliance.

15.5.1 Free Allowance Allocation in the EU ETS

In the EU ETS, three main allocation schemes have been used to distribute the allowances to participating entities: grandfathering, benchmarking, and auctions. Grandfathering and benchmarking have been used to allocate the initial free emission allowances among market participants. The emission allowances that are not distributed for free have been sold via auctions. Under the *grandfathering* scheme (in Phase I and Phase II) free emission allowances were distributed based on the entities' historical emissions. However, there were concerns about grandfathering because (1) by design, it rewarded the larger emitters by assigning more free emission permits and (2) controversial outcomes, such as over-allocation of free emission allowances, were observed.

In Phase III, the *benchmark* allocation rule was introduced to allocate free emission allowances to installations. Article 3(e) of (The European Parliament and of the Council 2003) defines an installation as the following:

> ... a stationary technical unit where one or more activities listed in Annex I are carried out and any other directly associated activities which have a technical connection with the activities carried out on that site and which could have an effect on emissions and pollution.

In Phase III, electricity power generators are not eligible to receive any free allowances but manufacturing facilities receive some free allowances based on the benchmark allocation rule.

The benchmark allocation calculates the free allowance allocated to an installation as follows (Ecofys 2011; Lecourt et al. 2013):

$$B \times H \times L \times C, \tag{15.1}$$

where B is the benchmark factor, H is the historical activity level, L is the carbon leakage exposure factor, and C is a cross-sectional correlation factor or a linear reduction factor. The factors B, L and C are provided by the EU ETS. However, the historical activity level H should be determined and reported by the installation.

An installation could use various types of benchmark factors determined by the EU ETS, but as a rule, the priority should be given to the factor that is calculated based on the average emissions intensity of the 10 % most efficient installations in the EU ETS in 2007–08 (Lecourt et al. 2013). This factor is usually expressed in tonnes of $CO_2e/1$ tonne of output. If this benchmark factor is not available, then installations can use fuel or heat benchmarking factors, which are expressed in tonnes of $CO_2e/1$ terajoule (TJ) of heat consumed and tonnes of $CO_2e/1$ TJ of fuel consumed, respectively. As suggested by (15.1), the allocation of free emission allowances is adjusted depending on whether that sector is exposed to carbon leakage risk. The annual carbon leakage exposure factors in Table 15.4 suggest that if an installation is not exposed to the carbon leakage risk, then it receives fewer free allowances, and purchases more allowances via auctions compared to an installation exposed to that risk, and the free allowance allocation decreases every year since the exposure factor decreases every year. The cross-sectional correlation factor can be included in allocation calculations to ensure that the total allocated free allowances does not exceed the total available free allowances for "non-electricity generators". The default method for a firm to determine its historical activity level is to find the median annual production quantity between 2005 and 2008 and between 2009 and 2011, and use the maximum of those medians. If none of the benchmarking schemes can be applied (due to lack of data or infeasibility of obtaining heat/fuel measurements), the *process emissions approach*, wherein the allocated free allowance is equal to 97 % of the process emissions, should be used to calculate the free allowance allocation.

Table 15.4 Annual carbon leakage exposure factors from 2015–2020 in the EU ETS

Year	2015	2016	2017	2018	2019	2020
L (high carbon leakage risk)	1	1	1	1	1	1
L (low carbon leakage risk)	0.6571	0.5857	0.5143	0.4429	0.3714	0.3000

15.5.2 Why is Free Allowance Allocation Important?

Coase (1960) suggests that if a cap-and-trade market satisfies certain conditions, then equilibrium outcomes of the market are not affected by the initial allocation of emission allowances. Montgomery (1972) formally analyzes this idea in a setting such that the equilibrium outcomes in a permit market are independent of the initial allocation of the permits, a property called the "independence property."

The failure of the independence property implies that the initial free (emission) allowance allocation rule has important implications for market efficiency, the equilibrium emission allowance price, regulated firms' equilibrium production quantities and profits in a cap-and-trade market. There is a rich literature on the failure of the independence property in real cap-and-trade markets due to various complexities of those markets. Hahn and Stavins (2010) discuss various conditions—some of which are shown in Hahn (1984), Stavins (1995), and Montero (1998)—under which the independence property might fail in a cap-and-trade market. Examples of these conditions include transaction costs, heterogeneous regulatory rules for firms, the presence of market power, and regulatory uncertainty. This literature mostly focuses on deriving market-level or sector-level insights by studying the impact of initial allocation rules on the efficiency and effectiveness of a cap-and-trade market. Burtraw et al. (2001) numerically analyze the implications of grandfathering and the generation performance standard for a cap-and-trade market for electricity markets, and show that the initial allocation rule in a cap-and-trade market has a substantial effect on cost and electricity price. (Unlike grandfathering, generation performance standard allocates free allowances based on current electricity generation share.) Liu et al. (2012) examine grandfathering, output-based, generation performance standard allocation rules, and the auction to study the efficiency of an emissions trading-system, and show that the market efficiency is significantly affected by the allocation rule with a positive transaction cost. Böhringer and Lange (2005) compare and contrast an emissions-based allocation rule with an output-based allocation rule, and find that the output-based allocation rule results in higher equilibrium production quantity and more efficiency than the emissions-based allocation rule. The empirical analysis by Fowlie et al. (2014) shows that a dynamic setting with entry and exit decisions based on initial allowance allocation can fail to satisfy the independence property. Focusing on the European cement industry, Demailly and Quirion (2006) show that there is a large difference between grandfathering and output-based allocation rules with regard to their impacts on competitiveness. Goulder et al. (2010) empirically examine the implications of alternative allowance allocation rules for industry profits and total production by focusing on the U.S. economy, and show that the initial allowance allocation has a large impact on industry profits.

As we discussed above, there is strong evidence that the free allowance allocation rules significantly affect market efficiency, regulated firms' profits and production quantities. Despite their importance and relevance, the implications of the free allowance allocation rules for a regulated firm's operations are understudied in the literature. To the best of our knowledge, there is one paper that studies operational decisions under different allocation rules: Zhao et al. (2010) consider the case of a power company that chooses sales and long-run capacity, and show the existence of a long-run equilibrium for electricity power generators under the following free allowance allocation rules: (1) new capacity based allocation, and (2) actual production history. We believe that more research is needed to gain operational insights on the implications of the free allowance allocations.

15.6 Emissions Allocation in the Context of Voluntary Actions to Improve Environmental Impact

Section 15.3 through Section 15.5 focus on emissions allocation problems under various climate change policies. Many firms that are not subject to a climate change policy have recently taken voluntary actions to improve their environmental impact. Many firms that are not subject to a climate change policy take voluntary actions to improve their environmental impact. One of these common actions is voluntarily committing to offset emissions. We first provide some background on voluntary offsetting, and then discuss offsetting-related insights for firms.

Firms that voluntarily commit to offset their emissions usually buy carbon offsets from voluntary offset markets, thereby constituting the demand in those markets. The supply in the voluntary offset markets is determined based on various environmental projects. Below we summarize five main sources of voluntary carbon offsets:

1. *Forestry and Land Use:* These projects protect, restore or create forests, or improve soil management. In 2013, 45 % voluntary offset transactions was generated by forestry and land use projects (Forest Trends' Ecosystem Marketplace 2014).
2. *Renewable Energy:* Renewable energy offsets include hydro, biogas, wind and solar power. Renewable energy offsets were the second largest category by transaction volume, constituting of 31 % of transaction volume in voluntary offset markets in 2013 (Forest Trends' Ecosystem Marketplace 2014).
3. *Household Devices:* These projects subsidize fuel efficient home devices that reduce deforestation and improve human health. For instance, in developing countries, billions of people rely on biomass (such as charcoal, fuelwood etc.) and traditional cook-stoves for cooking, which could be hazardous to human health. Cook-stove offsets are used to subsidize the fuel efficient cook-stoves.
4. *Energy Efficiency and Fuel Switching:* These projects can subsidize the cost of an energy/fuel efficiency improvement in a building or a facility. One of the main fuel efficiency projects is co-generation plants. Traditional thermal power plants produce heat as waste during electricity generation, but cogeneration plants are able to use the by-product heat in the generation process, thereby using the fuel input more efficiently.
5. *Methane:* One of the important projects in this category is the methane capture projects in coal mines.

Recently, there has been a significant demand for voluntary carbon offsets. The total transaction volume and the price in voluntary carbon offset markets in 2009–2013 can be seen in Figs. 15.2 and 15.3, respectively. The industry surveys by Ecosystem Marketplace & New Carbon Finance (2009)

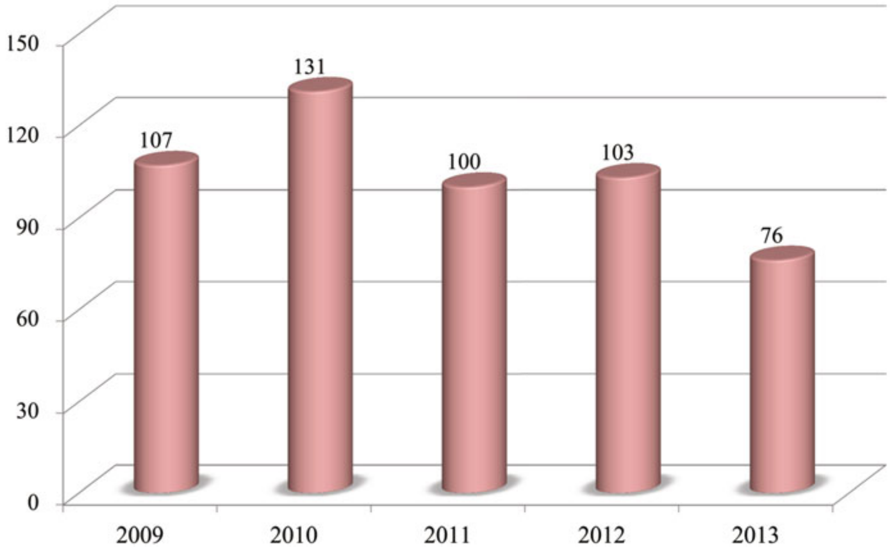

Fig. 15.2 Total transaction volume of voluntary offsets ($MtCO_2e$). (Data source: Forest Trends' Ecosystem Marketplace—Sharing the stage: State of the voluntary carbon markets 2014)

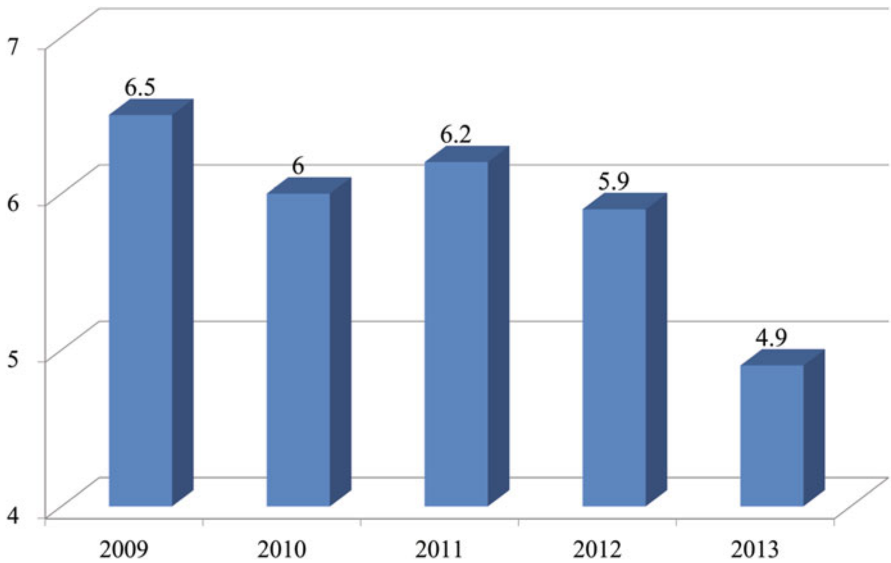

Fig. 15.3 Average price of voluntary offsets ($\$/tCO_2e$). (Data source: Forest Trends' Ecosystem Marketplace—Sharing the stage: State of the voluntary carbon markets 2014)

and Forest Trends' Ecosystem Marketplace (2014) show that there are various motivations for the voluntary purchase of carbon offsets. Top motivations include combatting the global warming, public relations and branding, corporate social responsibility and anticipation of regulation (which is also called "pre-compliance"). The management literature suggests that a company can gain various benefits by taking voluntary actions to reduce its greenhouse gas emissions and improve its environmental performance. According to Finster and Hernke (2014), as a result of voluntary environmental commitment, a company can gain competitive advantage by product innovation, enhancing corporate reputation, and increasing market share. Finster and Hernke (2014) further suggest that such a company might have better access to capital, and benefit from a positive impact on investors' valuations. Moreover, Finster and Hernke (2014) argue that a company's voluntary commitment to improve environmental impact might be beneficial to its human resources since the company's commitment for improved environmental performance might increase the motivation and involvement of the employees, and enable better access to human resources at various other institutions.

Many companies in different sectors (including retail, manufacturing, airline, energy and finance) have started to voluntarily offset their greenhouse gas emissions. Companies that offset their emissions include (but are not limited to) Walmart, Unilever, General Electric Company, DuPont, ConAgra Foods, Inc., Interface, Delta Air Lines, BP, Exxon Mobil Corporation, Royal Dutch Shell, Wells Fargo & Company and the Walt Disney Company (World Bank Group & ECOFYS 2014; CDP 2013). The scope of the voluntarily offset emissions changes from company to company. To familiarize the reader with the emission scopes, we introduce the following definition.

Definition 1. Based on the origin of the emissions, a company's emissions can be classified into three scopes:

- *Scope 1 emissions:* Direct emissions of a company.
- *Scope 2 emissions:* Indirect emissions due to the generation/use of electricity, heating and cooling.
- *Scope 3 emissions:* Indirect emissions due to other organizations which are not owned by the company or indirect emissions due to individuals which cannot be directly controlled by the company. Examples include emissions from employee travel and a supplier's emissions.

Some companies offset only their Scope 1 emissions while others offset their entire supply chain emissions, including Scope 3 emissions. For instance, Interface has committed to offset its entire supply chain emissions related to its "cool carpet product" (Sunar and Plambeck 2015). MacMillan and Walmart have made voluntary commitments to reduce their supply chain emissions (Goldstein 2014; Sunar and Plambeck 2015). Natura Cosmeticos has committed to offset its entire supply chain emissions (Caro et al. 2013). Offsetting the entire supply chain emissions rather than direct emissions is a huge undertaking for companies because, on average, indirect emissions constitute more than 85 % of the entire supply chain emissions (Matthews et al. 2008). Motivated by this fact, Sunar and Plambeck (2015) study the following research questions, using the model explained in Sect. 15.3:

- Should a company that procures a product from a co-product supplier voluntarily commit to offset its supply chain emissions?
- If a company commits to offset its supply chain emissions, which allocation rule should the company use to calculate emissions embodied in its procured product?

Sunar and Plambeck (2015) show that if the supplier is a co-product manufacturer, then under value-based allocation, buyers (i.e., importers) might benefit from voluntarily offsetting its entire supply chain emissions rather than its direct emissions only. Sunar and Plambeck (2015) show this result in a setting where buyers do not gain any marketing or other benefits (which are discussed at the beginning of this section) from offsetting. They explain the intuition of that result as follows: value-based allocation is an increasing function with respect to the price of the procured co-product. By voluntarily offsetting the supply chain emissions, buyers motivate the supplier to reduce its price and sell more. For instance, with an isoelastic demand curve, if the price elasticity of demand is moderate, such a price reduction by the supplier is so large that the effective unit procurement cost achieved with offsetting entire supply chain emissions is strictly smaller than the effective unit procurement cost achieved with offsetting direct emissions only. Another important result showed by Sunar and Plambeck (2015) is that, under value-based allocation, an increase in voluntary offset price strictly increases each buyer's profit. This implies that a buyer might improve its profitability by purchasing more expensive carbon offsets in voluntarily offsetting its entire supply chain emissions.

Caro et al. (2013) investigate a practical setting (based on the model described in Sect. 15.4) in which one of the supply chain members, namely the *carbon leader*, offsets its entire supply chain emissions. In this setting, Caro et al. (2013) characterize the carbon leader's profit-maximizing contract design. Viewing the case where efforts can be verified as a benchmark, they show that the resulting contract in this benchmark case is analogous to the social planner's allocation rule explained in Sect. 15.4. Caro et al. (2013) also show that, if efforts by other supply chain members cannot be verified, the carbon leader can design linear-payment contracts that are contingent on emissions to induce the efforts achieved in the benchmark case. Lastly, they establish that the carbon leader may also need to resort to double counting to maximize its profits.

15.7 Summary and Concluding Remarks

In this chapter, we discuss key emission allocation problems in co-production systems and supply chains, as well as the free emission allowance allocation in the EU ETS. In Sect. 15.3 we review important insights for policy makers and buyers (i.e., importers) that procure a product from a co-product supplier. Sunar and Plambeck (2015) show that, in a co-production system, the choice of allocation (to assign emissions to each co-product) significantly impacts social welfare, emissions and buyers' profits. They establish that allocating the supplier's emissions based on the economic value of co-products can have unexpected consequences in the context of border carbon adjustment and voluntary carbon offsetting if the co-product supplier can influence the price of the procured co-product. In particular, Sunar and Plambeck (2015) show that (1) implementing a border carbon adjustment or (2) an increase in the unit emissions cost can strictly increase global emissions and the emissions of each supply chain member. Based on (1), Sunar and Plambeck (2015) conclude that a border carbon adjustment with value-based allocation may be illegal since under WTO rules, the legality of a border carbon adjustment depends on whether it improves the environment. In addition, Sunar and Plambeck (2015) show that the current practice of giving buyers the flexibility to choose their allocation rules, can strictly decrease buyers' profits, compared to the case where buyers fix their allocation rules in advance. In the absence of a border carbon adjustment, Sunar and Plambeck (2015) find that under value-based allocation, each buyer can improve its profit by voluntarily offsetting its entire supply chain emissions (rather than its direct emissions), or by purchasing the more expensive carbon offsets.

In Sect. 15.4, we discuss the problem of emissions allocation among supply chain members, which is studied by Caro et al. (2013) and Granot et al. (2014). Caro et al. (2013) show that double-counting can be necessary in assigning emissions to supply chain members whether the entity performing the assignment is a social planner who aims to achieve the first-best solution, or a carbon leader firm that pays for the entire supply chain emissions and aims to maximize its profit by designing a contract contingent on emissions of supply chain members. Granot et al. (2014) identify an allocation rule that avoids double counting, and show that this allocation is the Shapley value of their collaborative emissions allocation game.

In Sect. 15.5, we argue that, in a cap-and-trade market, the free emission allowance allocation rules can have a significant impact on market efficiency as well as the regulated firms' profits and production quantities. Given the scope of the existing and emerging cap-and-trade markets, more research is needed to gain deeper insights on the implications of free emissions allowance allocation rules for regulated firms' profits and the efficiency.

Acknowledgements The author greatly appreciates the feedback and comments she received from Atalay Atasu, Beril Toktay, and other participants of Georgia Tech Sustainability Workshop in 2015. Their comments helped the author significantly improve this chapter.

References

Böhringer C, Lange A (2005) Economic implications of alternative allocation schemes for emission allowances. Scand J Econ 107(3):563–581

Burtraw D, Palmer K, Bharvirkar R, Paul A et al (2001) The effect of allowance allocation on the cost of carbon emission trading. Resources for the future. Discussion Paper 01-30. http://core.ac.uk/download/pdf/9308119.pdf

Caro F, Corbett C, Tan T, Zuidwijk R (2013) Double counting in supply chain carbon footprinting. Manuf Serv Oper Manag **15**(4), 545-558 (2013)

CDP (2013) Carbon Disclosure Project, use of internal carbon price by companies as incentive and strategic planning tool: a review of findings from CDP 2013 disclosure. https://www.cdp.net/CDPResults/companies-carbon-pricing-2013.pdf. Accessed 1 Mar 2015

Coase RH (1960) The problem of social cost. J Law Econ 3:1–44

Davis SJ, Caldeira K (2010) Consumption-based accounting of CO_2 emissions. Proc Natl Acad Sci 107(12):5687–5692

Demailly D, Quirion P (2006) CO_2 abatement, competitiveness and leakage in the European cement industry under the EU ETS: grandfathering versus output-based allocation. Clim Pol 6(1):93–113

Ecofys (2011) Allocation in Phase 3 of the EU ETS: presentation of allocation rules. http://ec.europa.eu/clima/policies/ets/cap/allocation/docs/gen_en.pdf. Accessed 3 Feb 2015

Ecosystem Marketplace & New Carbon Finance (2009) Fortifying the foundation: state of the voluntary carbon markets 2009. http://www.ecosystemmarketplace.com/documents/cms_documents/StateOfTheVoluntaryCarbonMarkets_2009.pdf. Accessed 1 Mar 2015

EPA (2013) The social cost of carbon. http://www.epa.gov/climatechange/EPAactivities/economics/scc.html. Accessed 1 Mar 2015

European Commission (2013) The EU emissions trading system (ETS). http://ec.europa.eu/clima/publications/docs/factsheet_ets_en.pdf. Accessed 1 Mar 2015

Finster MP, Hernke MT (2014) Benefits organizations pursue when seeking competitive advantage by improving environmental performance. J Ind Ecol 18(5):652–662

Forest Trends' Ecosystem Marketplace (2014) Sharing the stage: state of the voluntary carbon markets 2014. http://www.forest-trends.org/documents/files/doc_4841.pdf. Accessed 3 Jan 2015

Fowlie M, Reguant M, Ryan and Ryan SP (2016) Market-based emissions regulation and industry dynamics. J Polit Econ 124(1):249–302

Goldstein A (2014) MacMillan: low-carbon courage. An Ecosystem online article. http://www.ecosystemmarketplace.com/pages/dynamic/article.page.php?page_id=10148&section=news_articles&eod=1. Accessed 23 Feb 2015

Goulder LH, Hafstead MA, Dworsky M (2010) Impacts of alternative emissions allowance allocation methods under a federal cap-and-trade program. J Environ Econ Manag 60(3):161–181

Granot D, Granot F, Sosic G (2014) Allocation of greenhouse gas emissions in supply chains. Working paper, University of British Columbia

Greenstone M, Kopits E, Wolverton A (2013) Developing a social cost of carbon for us regulatory analysis: a methodology and interpretation. Rev Environ Econ Policy 7(1):23–46

Hahn RW (1984) Market power and transferable property rights. Q J Econ 99(4):753–765

Hahn RW, Stavins RN (2010) The effect of allowance allocations on cap-and-trade system performance. NBER. Technical report

IPCC (2014) Summary for policymakers: climate change 2014, mitigation of climate change. http://mitigation2014.org/report/summary-for-policy-makers. Accessed 15 Nov 2015

Lecourt S, Pallière C, Sartor O (2013) The impact of emissions-performance benchmarking on free allocations in EU ETS phase 3. European University Institute. Working paper

Liu B, He P, Zhang B, Bi J (2012) Impacts of alternative allowance allocation methods under a cap-and-trade program in power sector. Energy Policy 47:405–415

Matthews H, Hendrickson C, Weber C (2008) The importance of carbon footprint estimation boundaries. Environ Sci Tech 42(16):5839–5842

Montero JP (1998) Marketable pollution permits with uncertainty and transaction costs. Resource Energy Econ 20(1):27–50

Montgomery WD (1972) Markets in licenses and efficient pollution control programs. J Econ Theory 5(3):395–418

Regional Greenhouse Gas Initiative (2015) About the regional greenhouse gas initiative (RGGI). http://www.rggi.org/docs/Documents/RGGI_Fact_Sheet.pdf. Accessed 1 Mar 2015

Stavins RN (1995) Transaction costs and tradeable permits. J Environ Econ Management 29(2):133–148

Sunar N, Plambeck E (2016) Allocating emissions among co-products: implications for procurement and climate policy. Manuf Service Oper Management, 10 Feb 2016

The European Parliament and of the Council (2003) Directive 2003/87/EC of the European Parliament and of the Council. Official Journal of the European Union. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32003L0087&from=EN. Accessed 1 Jul 2015

US Federal Government Interagency Working Group on Climate Change (2010) Appendix 15A. Social cost of carbon for regulatory impact analysis under Executive Order 12866 United States Government

World Bank Group & ECOFYS (2014) State and trends of carbon pricing 2014. http://documents.worldbank.org/curated/en/2014/05/19572833/state-trends-carbon-pricing-2014

Zhao J, Hobbs BF, Pang JS (2010) Long-run equilibrium modeling of emissions allowance allocation systems in electric power markets. Oper Res 58(3):529–548

Chapter 16
Variability in Emissions Cost: Implications for Facility Location, Production and Shipping

Özge İşlegen, Erica L. Plambeck, and Terry A. Taylor

Abstract As countries around the world formulate policies to mitigate greenhouse gas (GHG) emissions, policymakers must weigh the merits of implementing an emissions tax or a cap-and-trade system. A primary barrier to the adoption of a cap-and-trade system is the idea that variability and uncertainty in the permit price (and hence a firm's emissions cost) has an adverse impact on domestic manufacturing firms. An emissions tax, on the other hand, can establish a fixed, certain emissions cost. Analysis in this chapter, however, suggests that variability in the emissions cost under a cap-and-trade system is beneficial, stimulating domestic manufacturing, compared to a mean-equivalent emissions tax. Hence, if emissions intensity among foreign competitors located in the region without climate policy is high, then variability in the emissions cost decreases expected emissions from production. Although global emissions may increase after a region initiates climate policy, due to a shift in manufacturing to a region without climate policy and increased transportation, that "leakage" phenomenon might be mitigated by adopting a cap-and-trade system, compared to a mean-equivalent tax.

Ö. İşlegen (✉)
Kellogg School of Management, Northwestern University, Evanston, IL 60208, USA
e-mail: o-islegen@kellogg.northwestern.edu

E.L. Plambeck
Stanford Graduate School of Business, Stanford University, Stanford, CA 94305, USA
e-mail: elp@stanford.edu

T.A. Taylor
Haas School of Business, University of California, Berkeley, Berkeley, CA, USA
e-mail: taylor@haas.berkeley.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_16

16.1 Introduction

In the absence of a global climate policy, a state may act alone to reduce greenhouse gas (GHG) emissions by imposing a tax on emissions or a cap-and-trade system. For example, in July 2012, Australia introduced an emissions tax of $23AUD per tonne of carbon dioxide equivalent emissions (Australian Government Clean Energy Regulator 2014), but repealed that tax in July 2014 (Hannam 2014). The European Union (E.U.) has operated a cap-and-trade system since 2005, and the state of California has done so since 2012. A cap-and-trade system limits the total amount of GHG emissions. Government issues a corresponding number of permits for emissions, which may be auctioned or given away. Businesses buy and sell permits as needed, allowing market forces to distribute and price the permits. In contrast to a fixed tax on emissions, a cap-and-trade system introduces *variability* and *uncertainty* in the cost of emissions. For example, the price of a permit in the E.U. has varied substantially, from a peak of €32 in April 2006 to below €3 per tonne of carbon dioxide equivalent in January 2013 (The Guardian 2013).

Policymakers need to assess the economic and environmental consequences of such unilateral action. A primary barrier to the adoption of either an emissions tax or cap-and-trade system is the concern that manufacturing will shift to a region with no climate policy, thereby increasing GHG emissions in that region. A related barrier to adoption of a cap-and-trade system is the concern that variability in the cost of emissions is undesirable for firms, and so might exacerbate the shift in manufacturing.

This chapter aims to provide guidance to policymakers and helps to bridge and extend the literatures on climate policy and on facility location by answering the following questions: How does instituting a climate policy (emissions tax versus a cap-and-trade system) affect the equilibrium number of manufacturers that choose to locate in the region with climate policy (and the region without climate policy) and their production and export quantities? What are the implications for global GHG emissions? The most important contribution is to show that increased variance in the cost of emissions can cause more firms to locate in the region with climate policy and increase production therein.

The operations management literature on facility location contains few papers that address cost variability or uncertainty. In Snyder's (2006) survey of 152 papers on facility location under uncertainty, only eight papers consider either production cost or transportation cost uncertainty. Only one of those eight papers incorporates uncertainty in both transportation costs and production costs, and it is not representative of emissions cost uncertainty (Jornsten and Bjorndal 1994). Melo et al. (2009) review the facility location literature in the supply chain context and note that papers integrating stochasticity into this literature are still scarce. The sources of uncertainty covered in this literature include customer demand, exchange rate, travel time, amount of returns in reverse logistics, supply lead time, transportation cost, and holding cost (Melo et al. 2009, Table 1). Chen et al. (2014) review the literature on the interface of facility location and sustainability. The review includes papers which consider climate change performance as a factor when choosing the location of manufacturing facilities (Chen et al. 2014, Table 5). Other recent papers, which incorporate carbon emissions concerns into the supply chain design problems, include (Diabat and Simchi-Levi 2010; Benjaafar et al. 2013; Jin et al. 2014). However, these papers do not focus on the variability in permit prices under the cap-and-trade system; they assume the permit price is relatively stable over the firm's planning horizon and is exogenous from the viewpoint of individual firms.

In climate policy literature on whether an emissions tax or a cap-and-trade system is socially optimal, the seminal paper by Weitzman (1974) focuses on how society is affected by uncertainty in emissions quantity versus emissions cost. If the expected social cost of uncertainty in emissions quantity and the resulting environmental damage is higher, then a cap-and-trade system (fixing the amount of emissions) is optimal. If the expected social cost of uncertainty in the emissions cost is higher, then an emissions tax is optimal. Nordhaus (2007) adopts the latter, pro-tax view, emphasizing the adverse economic impacts of variability and uncertainty in the permit price under a cap-and-trade system. Goulder and Schein (2013) provide a broad overview of the equivalences and trade-offs in adopting a tax versus cap-and-trade system. In particular, like Nordhaus (2007), Goulder and Schein (2013) emphasize the adverse economic impacts of variability and uncertainty in the permit price under a cap-and-trade system, and observe that some business groups abhor that uncertainty. To reduce that variability and uncertainty, Goulder and Schein (2013) recommend imposing a floor and ceiling on the permit price, and Weber and Neuhoff (2010) provide theoretical support for doing so.

Conventional wisdom in policy circles also supports the idea that variability in the emissions cost is undesirable. William D. Nordhaus states that: "The high level of volatility is economically costly and provides inconsistent signals to private-sector decision makers. Clearly, a carbon tax would provide consistent signals and would not vary so widely from year to year, or even day to day" (Nordhaus 2009, p. 6). Janet E. Milne also emphasizes the complexity that the volatility of permit prices under a cap-and-trade system adds: "The straightforwardness of carbon taxes makes them economically efficient, as the Congressional Budget Office has recognized. ... Cap-and-trade proposals can build in features that limit the price exposure and allow flexibility in annual compliance, but add more layers of complexity (Milne 2008)." Shapiro (2009) notes that the variability in energy prices can result in underinvestment in climate-friendly fuels and the volatility in permit prices would attract financial speculation.

The potential to influence GHG emissions through facility location and inter-regional trade is substantial. Transportation of manufactured goods currently contributes nearly 10 % of global carbon dioxide (CO_2) emissions and, absent climate change policy, is expected to grow 3 % per annum through 2030 due to increased consumption and lengthening of supply chains (McKinnon 2008). Manufacturing contributes more than 30 % of global greenhouse gas emissions (Bernstein et al. 2007). The emission-intensity of manufacturing differs around the world. Therefore, shifting of manufacturing from a region with climate policy to a region without climate policy might substantially increase emissions from manufacturing and transportation.

An extensive literature, surveyed in Condon and Ignaciuk (2013), examines the impact of a unilateral climate policy in shifting manufacturing and GHG emissions to a region without climate policy. Much of that literature does not address variability in the emissions cost. Furthermore, much of that literature is based on computable general equilibrium models of the entire economy, which assume perfect competition. However, the papers most closely related to this chapter restrict attention to a single industry, in order to deal with the complexity of imperfect competition. In modeling a cap-and-trade system, the single-industry papers and this chapter assume that firms in the industry are price-takers in the market for emissions permits, which spans many industries (Fowlie et al. 2016); in other words, the emissions cost is a model parameter. Among single-industry papers, for example, Fowlie et al. (2016) empirically estimate a model of how cement manufacturers dynamically adjust their capacities and choose production quantities over time. Mathiesen and Maestad (2004), Demailly and Quirion (2008), and Lanz et al. (2013) use partial equilibrium models to measure the impact of sub-global climate policies on the emissions from the steel, cement and copper industries, respectively.

In the operations management literature, Drake (2015) studies the effect of regionally asymmetric emissions regulations in models of imperfect competition. Drake (2015) does so with a focus on discrete technology choice and border adjustment without uncertainty while Drake et al. (2015) investigate the impact of emissions price uncertainty on the expected profit of a single firm with a discrete technology choice and variable capacity costs. This chapter focuses on the impact of emissions price uncertainty on the facility location and trade decisions of firms in an imperfect competition model.

This chapter incorporates an emissions cost (which is a random variable in the cap-and-trade scenario, and is a constant in the tax scenario) into Venables' widely used model of international trade for a single product (Venables 1985). Region 1 has climate policy and Region 2 does not. Each region has a variable cost of production, emissions intensity of production, and demand function. There is a unit cost to transport goods between the regions. Initially, all firms know the distribution of the emissions cost, which will effectively increase the unit cost of production in Region 1. A firm may establish a production facility in Region 1 or 2, and incurs a fixed cost (potentially different in different regions) to do so. Then, all firms realize the emissions cost and choose quantities to produce and export in a Cournot equilibrium. The equilibrium number of firms building production facilities in each region is uniquely determined by each having net zero expected profit.

Section 16.2 describes our two-region, single-product model of facility location under uncertain production costs and the equilibrium number of firms in each region, optimal domestic sales and exports of each firm. We present several analytical results in Sect. 16.3 where we discuss the behavior of several key attributes of interest with respect to the magnitude and uncertainty of the emissions cost. In Sect. 16.4, we provide the outcome of several numerical experiments where we extend the problem to the asymmetric limited capacity case, followed by the conclusions in Sect. 16.5.

16.2 Model Formulation

In our model, we consider two regions producing and trading a commodity. Region 1 adopts a climate policy. Each firm in Region 1 incurs a cost per unit GHG emissions related to the production and shipment of a commodity, T. Let e_i denote the emissions intensity of production, emissions per unit of production, in region $i = 1, 2$ and let e_s denote the emission intensity of shipping, emissions per unit shipped from one region to the other. A firm in Region 1 pays $e_1 T$ per unit produced and $e_s T$ per unit shipped to Region 2. T is an almost surely strictly positive random variable with mean μ and variance σ^2. Note that, in the emissions tax setup, we have no variability in the emission cost, implying $T = \mu$ almost surely $(\sigma^2 = 0)$ whereas in a cap-and-trade system $\sigma^2 > 0$ due to the uncertainty induced by the free market pricing. Region 2 has no climate policy.

Let n_i denote the number of firms that incur a fixed cost f_i to establish the capability to produce in region i. After doing so, each firm realizes the demand for this commodity in both regions and the permit price $T = \tau$. Each firm decides how much to produce: The variable cost per unit production in Region 2 is c_2, and the effective variable cost per unit production in Region 1 is $c_1 = \underline{c_1} + \tau$, the sum of per unit production cost and the permit price, respectively. The cost to ship a unit from one region to the other is s. The selling price per unit in region $i \in \{1, 2\}$ is:

$$p_i \ = D_i - Q_i, \tag{16.1}$$

where Q_i is the total quantity sold in region i. We assume that the uncertainty in demand is represented by D_i which embodies the effects of all factors other than price that affect demand. D_i is an almost surely strictly positive random variable, and d_i represents the corresponding realization. The supply-demand equation is:

$$Q_i = n_i y_i + n_j x_j \quad \text{for } i, j = 1, 2, \ i \neq j, \tag{16.2}$$

where y_i represents a firm's sales in its domestic market and x_i represents its export quantity, both chosen to maximize each firm's profit Π_i, operating in region i, according to

$$\Pi_1 = \max_{y_1,\, x_1 \geq 0} \{(p_1 - c_1)y_1 + (p_2 - c_1 - s)x_1 - f_1\} \quad (16.3)$$
$$\text{with } p_1 = d_1 - y_1 - Q_1^- \text{ and } p_2 = d_2 - x_1 - Q_2^-$$
$$\Pi_2 = \max_{y_2,\, x_2 \geq 0} \{(p_2 - c_2)y_2 + (p_1 - c_2 - s)x_2 - f_2\} \quad (16.4)$$
$$\text{with } p_2 = d_2 - y_2 - Q_2^- \text{ and } p_1 = d_1 - x_2 - Q_1^-,$$

with Q_i^- denoting the aggregate quantity supplied by other firms to region $i = 1, 2$.

In equilibrium, active firms have non-negative expected profit, but the entry of an additional firm would reduce expected profit below zero. This equilibrium condition will be expressed by setting $E[\Pi_i] = 0$ if the number of active firms n_i is strictly positive, and $E[\Pi_i] < 0$ if n_i is zero,[1] for each region $i = 1, 2$. Doing so ignores the fact that the number of active firms should take only integer values but, as noted by Venables (1985), provides a good approximation when the number of firms is large.

In Sect. 16.3, we present analytical results for two scenarios. In the first scenario, we consider "imperfect competition," where $f_i > 0$ for $i = 1, 2$, and, following Venables (1985), we assume existence of an equilibrium with a strictly positive number of firms active in each region, which supply both their domestic and export markets.[2] We also assume, for analytic tractability, that the regions are differentiated only in that Region 1 has climate policy, i.e., $D_1 = D_2 = D$ almost surely, $f_1 = f_2 = f$, $c_2 = c$ and $c_1 = c+\tau$.[3] Finally, we assume that the variance of $D + T$ is not less than the variance of D.

In the second scenario, we consider the case of "perfect competition," where the fixed costs $f_i \to 0$ for $i = 1, 2$. Hence, in equilibrium, each region is supplied only from the region with the lowest variable cost to do so, at a price corresponding to that variable cost. In a knife-edge case, in which the variable cost of Region 1 production is identical to the variable cost of Region 2 production and shipping, we focus on the equilibrium with only local production. For brevity of exposition, we also make the plausible assumption that D_1 and D_2 are sufficiently large with high probability, such that consumption occurs in each region with strictly positive probability.

16.3 Analytical Results

Throughout this section, we use the terms "domestic" and "foreign" to refer to Region 1 (with climate policy) and Region 2 (without climate policy), respectively.

[1] Expectation is over the joint uncertainty induced by T and $\{D_i\}$.

[2] This assertion can be justified under some mild technical assumptions; see Lemma 1 in Sect. 16.3 for further details.

[3] Whenever a result is valid without this assumption, we differentiate these parameters and random variables by specifying the corresponding region index i.

Lemma 1. *Consider imperfect competition.*

(a) For any given $n_1 > 0$, $n_2 > 0$, the optimal sales quantities for each firm in Region 1 and 2 are

$$y_1^* = \frac{d_1 - c - (1+n_2)\tau + n_2 s}{n_1 + n_2 + 1}, \tag{16.5}$$

$$x_1^* = \frac{d_2 - c - (1+n_2)(\tau + s)}{n_1 + n_2 + 1}, \tag{16.6}$$

$$y_2^* = \frac{d_2 - c + n_1(s+\tau)}{n_1 + n_2 + 1}, \tag{16.7}$$

$$x_2^* = \frac{d_1 - c + n_1\tau - (1+n_1)s}{n_1 + n_2 + 1}, \tag{16.8}$$

provided that $y_i^* > 0$, $x_i^* > 0$, $i = 1, 2$. The corresponding prices are

$$p_1^* = \frac{d_1 + n_1(c+\tau) + n_2(c+s)}{n_1 + n_2 + 1}, \tag{16.9}$$

$$p_2^* = \frac{d_2 + n_1(c+\tau+s) + n_2 c}{n_1 + n_2 + 1}. \tag{16.10}$$

For $D_1 = D_2 = D$ a.s., a necessary and sufficient condition for strict positivity of y_i^*, x_i^*, and p_i^* for $i = 1, 2$ is $\underline{\tau} < \tau < \overline{\tau}$, where $\underline{\tau} = -(d-c)/n_1 + ((n_1+1)/n_1)s$ and $\overline{\tau} = (d-c)/(1+n_2) - s$.

(b) Assuming $\tau \in (\underline{\tau}, \overline{\tau})$, and D_1 and D_2 are equal to a deterministic value d with probability 1, the number of firms at equilibrium is unique and given by:

$$n_1^* = \frac{1}{2}\left(\sqrt{\frac{4(d-c)[(d-c-s)(s^2+\sigma^2) - \mu s^2] + s^2[(\mu+s)^2 + 2\sigma^2]}{(2f - s^2 - \mu^2 - \sigma^2)(s^2 + \mu^2 + \sigma^2)}} - \frac{\mu[2(d-c) - s] + s^2}{s^2 + \mu^2 + \sigma^2}\right), \tag{16.11}$$

$$n_2^* = n_1^* + \frac{\mu[2(d-c) - s] - \mu^2 - \sigma^2}{s^2 + \mu^2 + \sigma^2}, \tag{16.12}$$

provided that $n_1^* > 0$ and $n_2^* > 0$.

Remark 1. Both n_1^* and n_2^* are monotonic decreasing in f. Therefore, there exists an upper bound $\overline{f}$, such that the condition of $f < \overline{f}$ implies positivity of n_1^* and n_2^*.

16.3.1 The Impact of Instituting a Climate Policy

We say that a climate policy is introduced in a region if an emissions tax ($T = \mu$) or a cap-and-trade system (T is a random variable with mean μ and variance σ^2) is imposed on the firms in that region. We next quantify the impact of introducing such policies on firms.

First, we consider the case of fixed number of firms, n_1 and n_2. Examining Lemma 1(a), it is easy to see that instituting a climate policy in Region 1 reduces the domestic sales and the exports of each firm in Region 1, y_1 and x_1, and increases the respective quantities in Region 2, y_2 and x_2. Therefore, the total domestic production, $n_1(x_1 + y_1)$, decreases and the total foreign production, $n_2(x_2 + y_2)$, increases with a climate policy. The total production $n_1(x_1 + y_1) + n_2(x_2 + y_2)$ and the total shipping quantity $n_1x_1 + n_2x_2$ decrease with a climate policy. This implies that the total emissions, $e_1[n_1(x_1 + y_1)] + e_2[n_2(x_2 + y_2)] + e_s[n_1x_1 + n_2x_2]$, decreases with climate policy provided that the emissions intensity in Region 2, e_2, is not too large compared to the emissions intensity in Region 1, e_1. However, if production in Region 2 is much more emissions intensive compared to Region 1, introducing a climate policy in Region 1 can increase the total emissions. Also, as one would expect, a climate policy in Region 1 reduces consumer surplus in Region 1 and 2, $(d_i - p_i)^2/2$ for $i = 1, 2$, and raises government revenue, $\tau n_1(x_1 + y_1)$, (which can increase social welfare by reducing the need for other taxes that distort the economy). Firms have zero expected profits in equilibrium. Hence the climate policy will increase social welfare in Region 1 to the extent that tax revenue is valuable and (in the aforementioned parameter region in which the climate policy reduces GHG emissions) the social cost of GHG emissions is high.

Next, we investigate the effects of imposing a climate policy on the number of firms and production quantities in each region. Note that, the result reported in Proposition 1 holds for both an emissions tax (i.e., $\mu > 0$ and $\sigma = 0$) and a cap-and-trade system (i.e., $\mu > 0$ and $\sigma > 0$).

Proposition 1. *(a) Under imperfect competition, instituting a climate policy decreases the number of firms in Region 1 and increases the number of firms in Region 2 (where at least one of the changes is strict). Moreover, the expected domestic production $n_1E[x_1 + y_1]$ strictly decreases and expected foreign production $n_2E[x_2 + y_2]$ strictly increases.*
(b) Under perfect competition, instituting a climate policy decreases the total domestic production and increases the total foreign production, almost surely.

The above results imply that instituting either type of climate policy in Region 1 can increase total expected emissions from the industry. A climate policy shifts production from Region 1 to Region 2, so an increase in expected emissions occurs when emissions intensity is high in Region 2. Indeed, concern that a climate policy will cause production to move offshore is a primary impediment to its adoption. Conventional wisdom is that uncertainty in the emissions cost, inherent in a cap-and-trade system, will increase the offshoring. We will explore this effect in Sect. 16.3.2.

Proposition 2 shows that instituting an "emissions tax" (changing the emissions cost from $T = 0$ to $T = \mu > 0$) can increase total expected emissions from the industry by increasing the expected number of units that are shipped. This perverse outcome tends to occur when the tax and the emissions intensity of shipping are large.

Proposition 2. *(a) Under imperfect competition and an emissions tax (i.e., $T = \mu > 0$ and $\sigma = 0$), total shipments $n_1x_1 + n_2x_2$ are strictly convex in the emissions tax μ. There exists a threshold $\overline{\mu} \in (0, (\sqrt{2}-1)s)$ such that total shipments, when compared to the case of no emissions tax, are lower if and only if the emissions tax is sufficiently small, i.e.,*

$$n_1x_1 + n_2x_2|_{\mu\in(0,\overline{\mu})} < n_1x_1 + n_2x_2|_{\mu=0} < n_1x_1 + n_2x_2|_{\mu\in(\overline{\mu},(\sqrt{2}-1)s)}. \tag{16.13}$$

(b) In the scenario of part (a), for any $\varepsilon \in (0, \overline{\mu})$, $\mu_l \in (\varepsilon, \overline{\mu})$, and $\mu_h \in (\overline{\mu}, (\sqrt{2}-1)s)$, there exists a threshold $\overline{e}_s \in [0, \infty)$ such that if the emissions intensity per unit shipped $e_s > \overline{e}_s$, then total emissions $\mathcal{E}$, when compared to the case of no emissions tax, are lower if the emissions tax is small and are higher if the emissions tax is large.

$$\mathcal{E}|_{\mu\in(\varepsilon,\mu_l)} < \mathcal{E}|_{\mu=0} < \mathcal{E}|_{\mu\in(\mu_h,(\sqrt{2}-1)s)}. \tag{16.14}$$

(c) Under perfect competition, instituting a large emissions tax ($\mu > \underline{\mu} = c_2 - c_1 - s$) strictly increases total expected shipments if and only if $\underline{\mu} > 0$, $\mu > c_2 - c_1 + s$, and $E[D_1 - c_2 - s]^+ > E[D_2 - c_1 - s]^+$.[4] Instituting a small emissions tax $\mu \in (0, \underline{\mu})$ strictly reduces total expected shipments.

The intuition for Proposition 2 is that by making production in Region 1 less attractive, an emissions tax reduces exports from Region 1 and increases exports from Region 2. Because the emissions tax has a direct impact on Region 1 exports, and only an indirect impact on Region 2 exports, it is natural that the export-reduction effect in Region 1 would outweigh the export-increase effect in Region 2. This result and intuition hold when the emissions tax is small. However, it is reversed when the emissions tax is large. Under imperfect competition, the effect of a large emissions tax is to sharply curtail production in Region 1. The vast majority of Region 1's demand is filled by exports from Region 2, and this leads to an increase in total exports.

In the scenario with perfect competition, shipping occurs in only one direction, if at all. Suppose that $\underline{\mu} = c_2 - c_1 - s > 0$, meaning that Region 1 exports to Region 2 in the absence of the emissions tax. A small emissions tax

[4] The shorthand $[\cdot]^+$ refers to capping the input, $x \in R$, by 0 from below, i.e., $[x]^+ = max(x, 0)$.

$\mu \in (0, \underline{\mu})$ reduces exports from Region 1, and hence total shipping. A large emissions tax $\mu > \underline{\mu}$ prevents exports from Region 1, and it causes Region 2 to export to Region 1 if and only if $\mu > c_2 - c_1 + s$. Then, the inequality $E[D_1 - c_2 - s]^+ > E[D_2 - c_1 - s]^+$ means that expected exports from Region 2 (the exports turned on by the emissions tax) exceed the expected exports from Region 1 that were turned off by the emissions tax. Hence total expected shipping increases.

In short, in both scenarios, a small emissions tax reduces shipping by reducing exports from Region 1 (and having relatively little or no effect on exports from Region 2) whereas a large emissions tax increases shipping by increasing exports from Region 2 by more than it reduces exports from Region 1.

16.3.2 The Impact of Variability in Emissions Cost

The propositions in this section suggest that a cap-and-trade system generates more domestic competition, production, and consumer surplus compared to a emissions tax with the same mean cost of emissions, i.e, a mean-equivalent emissions tax, under the assumptions specified at the beginning of this section.

Formally, propositions in this section examine impacts of increasing the standard deviation of the emissions cost, σ. That may be interpreted as an increase in the variability or uncertainty regarding the emissions cost. For brevity, the propositions use only the term "variability".

In Proposition 3 below, we find that the variability in the permit prices under a cap-and-trade system increases the number of firms in the region with climate policy.

Proposition 3. *Under imperfect competition, the number of active firms in the region with climate policy, n_1, is strictly increasing in the variability in the emissions cost, σ.*

Corollary 1. *Under imperfect competition, the number of active firms in the region with climate policy is strictly greater under a cap-and-trade system than a mean-equivalent emissions tax.*

The intuition is that, for a given number of active firms in each region, a firm's profit from producing in Region 1 is a convex function of the realized emissions cost τ. Hence variance in τ increases the expected profit of a firm in Region 1, which pushes more firms to enter Region 1. The countervailing indirect force is that, for a given number of active firms in each region, variance in τ also increases the expected profit of a firm in Region 2, which tends to push more firms to enter Region 2 and decrease the expected profit of a firm in Region 1. However, the direct benefit of variance to a firm in Region 1 dominates the indirect effect and hence, the variance increases the number of firms in Region 1. The proposition below shows that variance in the emissions cost can also increase the expected production in Region 1.

Proposition 4. *Under imperfect competition, there exists $\overline{\sigma} > 0$ such that as the variability in the emissions cost, σ, increases on $\sigma \in (0, \overline{\sigma}]$, total expected production in Region 1, $n_1 E[x_1 + y_1]$, strictly increases and total expected production in Region 2, $n_2 E[x_2 + y_2]$, strictly decreases.*

An immediate interpretation of Proposition 4 is that, within the imperfect competition setup, domestic expected production is strictly higher and foreign expected production is strictly lower under a cap-and-trade system than their mean-equivalent emissions tax counterparts, provided that the variance of the emissions cost is not too large.

In the scenario with perfect competition, a firm always has zero profit, so does not benefit from the variability in emissions cost inherent in a cap-and-trade system. Nevertheless, a cap-and-trade system may result in greater expected domestic production.

Proposition 5. *Under perfect competition, domestic expected production is higher and foreign expected production is lower under a cap-and-trade system than a mean-equivalent emissions tax if $\mu > s + c_2 - c_1$.*

The logic is simple. A high emissions tax $\mu > s + c_2 - c_1$ shuts down domestic production, whereas a mean-equivalent cap-and-trade system allows for domestic production to occur (which also reduces imports and hence foreign production) at low realizations of the emissions cost.

In addition to increasing expected domestic production, a cap-and-trade policy results in strictly higher overall expected production than a mean-equivalent emissions tax.

Proposition 6. *(a) Under imperfect competition, the total expected production $n_1 E[x_1 + y_1] + n_2 E[x_2 + y_2]$ increases in σ.*

(b) Under imperfect and perfect competition, the total industry expected production is greater under a cap-and-trade system than a mean-equivalent emissions tax.

To understand the implication for emissions, consider the simple case in which emission intensity is homogeneous ($e_1 = e_2$) and large relative to the emissions intensity of shipping e_s. Increasing overall production increases emissions. Hence Proposition 6(b) suggests that an emissions tax must be lower than the mean permit price in a cap-and-trade system in order to achieve the same emissions as the cap-and-trade system. With an emissions tax exactly equal to the mean permit price, emissions will be lower with the tax than in the cap-and-trade system.

One might think that expected government revenue would be relatively high under the cap-and-trade system because of the increase in domestic expected production. That is true in the scenario with perfect competition under the condition $\mu > s + c_2 - c_1$ (by logic similar to the proof of Proposition 5). It is not necessarily true in the scenario with imperfect competition because when the realized emissions cost is high, domestic production and associated emissions are relatively low, and revenue is the product of the two.

The proposition below shows that variability in the emission cost can benefit the consumers in the region with climate policy.

Proposition 7. *Under imperfect competition, given a sufficiently small mean emissions tax, $\mu \leq s$, domestic expected consumer surplus is increasing in the variability of the emissions cost σ.*

An immediate corollary of Proposition 7 is that, for imperfect competition, as long as mean permit price is not too high, domestic expected consumer surplus is higher under a cap-and-trade system than a mean-equivalent emissions tax setup.

16.4 Numerical Analysis for the U.S. Southwest Cement Industry

In a numerical example motivated by the U.S. Southwest cement industry, this section incorporates capacity constraints and the potential for a permit price spike under a cap-and-trade system, because such price spikes are seen as a particularly pernicious form of variability (Goulder 2013). An extreme price spike, modeled in the numerical example, compels cement manufacturers to idle their production facilities, thus preventing them from recovering sunk costs of capacity. Nevertheless, in the numerical example, consistent with the results in the previous section for the simpler model without capacity constraints, a cap-and-trade system with price spikes induces more firms to locate in the region with climate policy than does a mean-equivalent emissions tax.

Policy analysts are concerned about price spikes because various existing cap-and-trade systems have exhibited extreme price spikes. For example, permit prices under the RECLAIM program for nitrogen oxides (NO_x) rose from an average of \$4284 per ton in 1999 to almost \$45,000 per ton, contributing to the disruptive price spike in the California wholesale electricity spot market in 2000 (Ellerman et al. 2003).

In addition to incorporating capacity constraints and the potential for a permit price spike, this section eliminates assumptions made in the previous analysis that firms are symmetric and their equilibrium production quantities are characterized by an “interior solution”. Instead, a firm may produce zero quantity or produce at the capacity constraint.

This section focuses on production and trade of cement within the U.S. Southwest, i.e., California, Arizona and Nevada. This is motivated by the observation that the U.S. Southwest imports at most negligible amounts of cement from other U.S. states, according to Miller and Osborne (2014).

Imports to the U.S. Southwest cement market from other countries also are very small.[5] Region 1 corresponds to the state of California, which introduced a cap-and-trade system in November 2012, and Region 2 represents Arizona and Nevada, which have no emissions tax or cap-and-trade system.

We fit a linear demand function for each region i, $Q_i = D_i - a_i p_i$ for $i = 1, 2$. We assume that the average capacity of a plant in California, Nevada and Arizona is equal to the average clinker capacity of an active plant in the U.S., $K_1 = K_2 =$ 1,104,167 metric tons per year (Van Oss 2013, Table 5). The variable investment cost of such a new state-of-the-art conventional cement plant was approximately \$236.7 per metric ton in 2011 dollars and the fixed capacity investment is $F_1 = F_2 =$ \$261,378,850. The details of the above calculations can be found in the Appendix.

We assume the useful life of a cement plant is 30 years and the cost of capital is 8 %. At time zero, the firms in each region will decide whether to enter the market. If a firm chooses to enter the market, they will build a cement plant with an average capacity of 1,104,167 metric tons per year. Then, for 30 years, at the start of each year the permit price is realized and the firm decides how much to produce. We assume the distribution of the permit price is stationary.

Operations and maintenance (O&M) costs for a typical existing plant were approximately \$46 per metric ton in 2011 (International Energy Agency Energy Technology Systems Analysis Programme 2010).[6] We assume that O&M costs are the same in California, Arizona, and Nevada, and represent the variable production cost ($c_1 = c_2 =$ \$46 per metric ton).

In 2011, around 97 % of the Portland cement shipments to the customers were made by truck (Van Oss 2013, Table 10). The average emissions intensity of trucking is 50 g of CO_2 per metric ton of cement per kilometer (Schipper et al. 2011). Assuming an average shipping distance of 196.34 km (122 miles) as estimated in Miller and Osborne (2014), the emissions intensity of shipping one metric ton of clinker between California and other states is 0.01 metric tons of CO_2. A crude estimate of the shipping cost of cement is \$18 in 2011 dollars (Van Oss 2004, p. 16.5).[7]

In 2010, the average emissions intensity of cement manufacturing in the United States was approximately 0.89 metric tons of CO_2 per metric ton of

[5] In 2010, as opposed to the 6.6 million metric tons of clinker produced in California, 242,000 metric tons of hydraulic cement and clinker were imported to California ports in Los Angeles, San Diego, and San Francisco from other countries (Van Oss 2012, Tables 5 and 18); in 2011, as opposed to the 7,193,000 metric tons of clinker produced in California, the foreign imports accounted for only 121,000 metric tons. The Nogales customs district in Arizona had a negligible amount of clinker import in 2010 and 2011 from Mexico.

[6] The O&M cost includes labor, power, and fuel costs but no depreciation. The O&M cost in 2007 Euros was converted to 2011 U.S. dollars by using a 2007 average exchange rate of \$1 = €0.76, and 2007 and 2011 average consumer price indices of 207.342 and 224.939, respectively (U.S. Department Of Labor, Bureau of Labor Statistics 2013).

[7] 2004 and 2011 annual average consumer price indices as given by U.S. Department Of Labor, Bureau of Labor Statistics (2013) are 188.9 and 224.939, respectively.

clinker (Van Oss 2013, pp. 16.1, 16.2) excluding very minor carbon dioxide equivalent emissions of methane and nitrous oxide (N_2O). We will use this as the emissions intensity of cement plants in California, Arizona and Nevada. The California Air Resources Board provides 0.786 metric tons of CO_2 worth of free allowances per metric ton of adjusted clinker and mineral additives produced. Then, a cement plant manufacturing one metric ton of clinker will pay $0.89 - 0.786 = 0.104$ times the permit price.

The 2013 reserve price in auctions for permits in the California cap-and-trade system is \$10.71. We assume if there is no price spike, the permit price under the cap-and-trade system is \$10.71 per tonne of carbon dioxide equivalent. Motivated by the examples of extreme price spikes in cap-and-trade systems provided by Nordhaus (2007) and Goulder and Schein (2013), we assume that the permit price will increase to \$100 per tonne of emissions if there is a price spike.

Varying the probability of a price spike from zero to one, we calculate n_1, the equilibrium number of firms that establish production facilities in Region 1 (California) under the cap-and-trade system and under a mean-equivalent tax on emissions. That number n_1 is greater under the cap-and-trade system than under the mean-equivalent tax on emissions for all levels of the probability of a price spike. That number n_1 is strictly greater under the cap-and-trade system than under the mean-equivalent tax when the probability of a price spike is between 0.1 and 0.5.

In summary, the numerical example suggests that with capacity constraints and the threat of an extreme price spike under a cap-and-trade system, a cap-and-trade system can attract more firms to locate production facilities in the region with climate policy than a mean-equivalent tax would.

16.5 Conclusion

This chapter discusses the impact of adopting regional climate policies, in particular, a cap-and-trade system versus an emissions tax, to reduce the GHG emissions in energy-intensive industries. Instituting a climate policy increases the production cost in the region with the climate policy, and hence reduces the total production and competition among firms. On the other hand, the production and competition in the region without the climate policy increase. The models including the facility location, production and shipping decisions of firms show that instituting a regional climate policy increases total emissions when the emissions intensity in the region without climate policy is high, or when the emissions intensity of shipping is high and the emissions tax is moderate. In contrast to conventional wisdom in some academic and policy circles, these models indicate that the emissions cost variability and uncertainty inherent in a cap-and-trade system can encourage competition among firms and increase production relative to a mean-equivalent emissions tax. In particular, the equilibrium number of firms that locate production facilities in the region with climate policy, expected consumer surplus in the region with climate policy, and the total number of firms increase in the variability of the emissions cost. Moreover, variability in the permit price decreases expected production in the region without climate policy. This implies that if emissions intensity in the region without climate policy is high, then variability in the permit price decreases expected emissions from production. Hence a cap-and-trade system might be preferable for a region planning to adopt a climate policy.

Appendix

Proof (Lemma 1).

(a) In this proof, we assume that $n_1 > 0$ and $n_2 > 0$, $c_1 = c + \tau$, and $c_2 = c$. The first-order conditions for (16.3), (16.4) yield:

$$FOC_{y_i}: \; y_i = p_i - c_i \geq 0, \tag{16.15}$$
$$FOC_{x_i}: \; x_i = p_j - c_i - s \geq 0 \tag{16.16}$$

for $i, j = 1, 2$, $i \neq j$.

Using (16.1) and (16.2), we obtain:

$$d_1 - p_1 = n_1 y_1 + n_2 x_2, \tag{16.17}$$
$$d_2 - p_2 = n_2 y_2 + n_1 x_1. \tag{16.18}$$

Using (16.15) for $i = 1$, (16.16) for $i = 2$ and (16.17), we can solve for the optimal price in Region 1, given by (16.9). Following a similar procedure, the optimal price in Region 2 is given by (16.10). By the equalities in (16.15) and (16.16), the optimal sales quantities for each firm in Region 1 and 2 are given by (16.5)–(16.8), respectively.

Next, for $D_1 = D_2 = D$ a.s., we derive the conditions that ensure positivity of y_i^* and x_i^*, $i = 1, 2$. Note that

$$x_1^* = y_1^* - \frac{(1 + 2n_2)s}{n_1 + n_2 + 1},$$
$$x_2^* = y_2^* - \frac{(1 + 2n_1)s}{n_1 + n_2 + 1}.$$

Given that the transportation cost is strictly positive ($s > 0$), and the number of firms in each region are non-negative ($n_1 \geq 0$ and $n_2 \geq 0$), we have $x_1^* < y_1^*$ and $x_2^* < y_2^*$. This, in turn, implies that it suffices to identify the necessary and sufficient conditions on τ for x_1^* and x_2^* to be strictly positive:

$$x_1^* > 0 \Leftrightarrow d - c - (1 + n_2)(s + \tau) > 0,$$
$$\Leftrightarrow \tau < \frac{d - c}{1 + n_2} - s.$$

Hence, the upper bound on τ is $\overline{\tau} = (d - c)/(1 + n_2) - s$.

$$x_2^* > 0 \Leftrightarrow d - c + n_1\tau - (1 + n_1)s > 0,$$
$$\Leftrightarrow \tau > -\frac{d - c}{n_1} + \frac{n_1 + 1}{n1}s.$$

Hence, the lower bound on τ is $\underline{\tau} = -(d - c)/n_1 + (n_1 + 1)s/n_1$. For a given (n_1, n_2) pair, $x_i^* > 0$ and $y_i^* > 0$ for $i = 1, 2$ if and only if $\tau \in (\underline{\tau}, \overline{\tau})$. This completes the proof of part (a) of the claim. Next, we proceed with deriving the number of firms at equilibrium.

(b) We assume that the optimal sales quantities for the problem in (16.3), (16.4) are given by (16.5) through (16.8) provided that $y_i^* > 0$ and $x_i^* > 0$ for $i = 1, 2$. By inserting the optimal sales quantities into the objective function in (16.3), (16.4), we find the optimal objective function value for each individual firm in Region 1 and 2, respectively:

$$\Pi_1 = \frac{[d_1 - c - (1 + n_2)\tau + n_2 s]^2 + [d_2 - c - (1 + n_2)(\tau + s)]^2}{(n_1 + n_2 + 1)^2} - f_1, \tag{16.19}$$

$$\Pi_2 = \frac{[d_2 - c + n_1(s + \tau)]^2 + [d_1 - c + n_1\tau - (1 + n_1)s]^2}{(n_1 + n_2 + 1)^2} - f_2. \tag{16.20}$$

Then, assuming D_1 and D_2 are equal to a deterministic value d with probability 1 and $f_1 = f_2 = f$, the expected profit of a firm in each region before observing the permit price $T = \tau$ is:

$$\begin{aligned} E\Pi_1 = {} & (n_1 + n_2 + 1)^{-2}\big\{2(d - c)(d - c - s) + (1 + 2n_2 + 2n_2^2)t^2 \\ & -2[2(d - c) - s](1 + n_2)\mu + 2(1 + n_2)^2(\mu^2 + \sigma^2)\big\} - f, \end{aligned} \tag{16.21}$$

$$\begin{aligned} E\Pi_2 = {} & (n_1 + n_2 + 1)^{-2}\big\{2(d - c)(d - c - s) + (1 + 2n_1 + 2n_1^2)t^2 \\ & +2[2(d - c) - s]n_1\mu + 2n_1^2(\mu^2 + \sigma^2)\big\} - f. \end{aligned} \tag{16.22}$$

Note that this is an unconditional expectation over τ due to the assumption that $y_i^* > 0$ and $x_i^* > 0$ for $i = 1, 2$ or according to part (a) of the lemma, $\tau \in (\underline{\tau}, \overline{\tau})$. Solving for the equilibrium number of firms (n_1^*, n_2^*) by equating $E\Pi_1$ and $E\Pi_2$ to zero, we get the expressions in (16.11) and (16.12). We assume that τ only needs to be in $(\underline{\tau}, \overline{\tau})$ when $(n_1, n_2) = (n_1^*, n_2^*)$, i.e., $\tau \in (\underline{\tau}(n_1^*), \overline{\tau}(n_2^*))$. Finally, conditions $n_1^* > 0$ and $n_2^* > 0$ need to be satisfied. □

Proof (Proposition 1).

(a) We begin with the case of imperfect competition. We first show that instituting climate policy regulation (i.e., either a emissions tax or cap-and-trade) decreases n_1 and increases n_2. It is straightforward to verify that for an interior solution, the expected profit of a firm in Region i, $E\Pi_i$, is strictly decreasing in n_1 and n_2 for $i \in \{1,2\}$. Further, for fixed n_1 and n_2, instituting climate policy regulation decreases the expected profit of a Region 1 firm

$$E\Pi_1|_{\mu>0,\ \sigma\geq 0} < E\Pi_1|_{\mu=0,\ \sigma=0}$$

and increases the expected profit of a Region 2 firm

$$E\Pi_2|_{\mu>0,\ \sigma\geq 0} > E\Pi_2|_{\mu=0,\ \sigma=0}.$$

We first establish that instituting climate policy regulation cannot either (1) increase both n_1 and n_2 or (2) decrease both n_1 and n_2. The proof is by contradiction. Let n_i^r denote the equilibrium number of firms under climate policy regulation and n_i^o denote the equilibrium number of firms under no climate policy regulation for $i \in \{1,2\}$. Suppose $n_1^r \geq n_1^o$ and $n_2^r \geq n_2^o$. Then,

$$\begin{aligned} 0 &= E\Pi_1|_{n_1=n_1^r,\ n_2=n_2^r,\ \mu>0,\ \sigma\geq 0} \\ &\leq E\Pi_1|_{n_1=n_1^o,\ n_2=n_2^o,\ \mu>0,\ \sigma\geq 0} < E\Pi_1|_{n_1=n_1^o,\ n_2=n_2^o,\ \mu=0,\ \sigma=0} = 0. \end{aligned}$$

a contradiction. So it cannot be that $n_1^r \geq n_1^o$ and $n_2^r \geq n_2^o$. Similarly, if $n_1^r \leq n_1^o$ and $n_2^r \leq n_2^o$, then

$$\begin{aligned} 0 &= E\Pi_2|_{n_1=n_1^r,\ n_2=n_2^r,\ \mu>0,\ \sigma\geq 0} \\ &\geq E\Pi_2|_{n_1=n_1^o,\ n_2=n_2^o,\ \mu>0,\ \sigma\geq 0} > E\Pi_2|_{n_1=n_1^o,\ n_2=n_2^o,\ \mu=0,\ \sigma=0} = 0. \end{aligned}$$

a contradiction. So it cannot be that $n_1^r \leq n_1^o$ and $n_2^r \leq n_2^o$. This implies that one of the following holds:

$$n_1^r \geq n_1^o \text{ and } n_2^r \leq n_2^o, \text{ where at least one of the equalities is strict,} \quad (16.23)$$

$$n_1^r \leq n_1^o \text{ and } n_2^r \geq n_2^o, \text{ where at least one of the equalities is strict.} \quad (16.24)$$

Observe from Eq. (16.12) that $n_1^r < n_2^r$ if and only if

$$\sigma^2 < \mu[2(d-c) - s - \mu]. \quad (16.25)$$

The condition for the interior solution, $x_1^* > 0$ holds for all τ, implies $\tau \leq d-c-s$. This implies that $\int_0^{d-c-s}(d-c-s-\tau)\phi(\tau)d\tau \geq 0$. This implies $E[\tau^2] - E[\tau]^2 \leq E[\tau](d-c-s) - E[\tau]^2$, or equivalently, $\sigma^2 \leq \mu(d-c-s-\mu)$. This implies (16.25). Therefore, $n_1^r - n_2^r < 0 = n_1^o - n_2^o$, which implies $n_1^o - n_1^r > n_2^o - n_2^r$. If (16.23) holds, then $0 \geq n_1^o - n_1^r > n_2^o - n_2^r \geq 0$, a contradiction. We conclude that (16.24) holds.

Second, we show that instituting climate policy regulation increases $n_1E[y_1]$ and $n_1E[x_1]$ and decreases $n_2E[y_2]$ and $n_2E[x_2]$. Equalities (16.5)–(16.8) denote the optimal sales quantities for each firm in Region 1 and Region 2, when there are n_1 firms in Region 1, n_2 firms in Region 2, and the realized permit price is τ. To make this dependence explicit, we write $y_1(n_1, n_2, \tau)$ to denote y_1^* in Eq. (16.5). Define $x_1(n_1, n_2, \tau)$, $y_2(n_1, n_2, \tau)$, and $x_1(n_1, n_2, \tau)$ analogously. Let x_i^o denote the export quantity of a firm in Region i under no climate policy regulation, and let x_i^r denote the export quantity of a firm in Region i under climate policy regulation and permit price $\tau \geq 0$, for $i \in \{1, 2\}$. Let y_i^o and y_i^r denote the analogous domestic production quantities for $i \in \{1, 2\}$. It is straightforward to show that $(\partial/\partial n_i)[n_i y_i(n_1, n_2, \tau)] > 0$, $(\partial/\partial n_i)[n_i x_i(n_1, n_2, \tau)] > 0$, $(\partial/\partial n_j) y_i(n_1, n_2, \tau) < 0$, and $(\partial/\partial n_j) x_i(n_1, n_2, \tau) < 0$ for $i \in \{1, 2\}$ and $j \neq i$. Then, because $n_1^r \leq n_1^o$ and $n_2^r \geq n_2^o$,

$$\begin{aligned} n_1^r x_1^r = n_1^r x_1(n_1^r, n_2^r, \tau) &\leq n_1^o x_1(n_1^o, n_2^r, \tau) \\ &\leq n_1^o x_1(n_1^o, n_2^o, \tau) \leq n_1^o x_1(n_1^o, n_2^o, 0) = n_1^o x_1^o, \end{aligned} \tag{16.26}$$

where the last inequality is strict if $\tau > 0$. Because (16.26) holds when x is replaced by y, it follows that $n_1^r y_1^r \leq n_1^o y_1^o$, where the equality is strict if $\tau > 0$. Similarly,

$$\begin{aligned} n_2^r x_2^r = n_2^r x_2(n_1^r, n_2^r, \tau) &\geq n_2^o x_2(n_1^r, n_2^o, \tau) \\ &\geq n_2^o x_2(n_1^o, n_2^o, \tau) \geq n_2^o x_2(n_1^o, n_2^o, 0) = n_2^o x_2^o, \end{aligned} \tag{16.27}$$

where the equality is strict if $\tau > 0$. By similar argument, $n_2^r y_2^r \geq n_2^o y_2^o$, where the equality is strict if $\tau > 0$. Because under climate policy regulation (i.e., $\mu > 0$ and $\sigma \geq 0$), $\tau > 0$ with positive probability, (16.26) implies that $n_1^r E[x_1^r] < n_1^o x_1^o$, where the expectation is taken over τ. Similarly, $n_1^r E[y_1^r] < n_1^o y_1^o$, $n_2^r E[x_2^r] > n_2^o x_2^o$, and $n_2^r E[y_2^r] > n_2^o y_2^o$. □

Proof (Proposition 2).

We first provide Lemma 2, which characterizes some properties of an interior solution under an emissions tax. The lemma is useful in the proof of Proposition 2.

Lemma 2. *Under $\sigma = 0$, an interior solution satisfies the following:*

$$\mu < (\sqrt{2} - 1)s, \tag{16.28}$$

$$f > (s^2 + \mu^2)^2/(s - \mu)^2, \tag{16.29}$$

$$D - c > s(s^2 - \mu^2)/(s^2 - 2t\mu - \mu^2). \tag{16.30}$$

Proof. Suppose $\sigma = 0$. Because an interior solution has $x_1 > 0$, it has

$$D - c - (1 + n_2)(s + \mu) > 0. \tag{16.31}$$

It follows from (16.11)–(16.12) that n_2 is decreasing in f and that (16.31) holds if and only if (16.28). An interior solution has $n_1 > 0$, which from (16.11), holds if and only if

$$f < \overline{f} = \frac{[2(D-c)(D-c-s)+s^2](s^2+\mu^2)^2}{([2(D-c)-s]\mu+s^2)^2}. \tag{16.32}$$

Together, (16.29) and (16.32) imply $(D-c-s)(s^2-\mu^2)-2(D-c)s\mu > 0$, which holds if and only if (16.28) and (16.30) hold. □

Next, we proceed with the proof of Proposition 2.

(a) First, we show that total shipments $n_1x_1 + n_2x_2$ are continuous and strictly convex in μ for an interior solution. Continuity follows from the fact that n_1, n_2, x_1 and x_2 are continuous in μ. With the change of variable $M = D - c$

$$\frac{\partial^2}{\partial \mu^2}[n_1x_1+n_2x_2] = f\frac{\beta(f,M,s,\mu)}{(2f-s^2-\mu^2)^{5/2}(s^2+\mu^2)^{7/2}}, \tag{16.33}$$

where

$$\begin{aligned}\beta(f,M,s,\mu) &= 2M\tau(f,s,\mu) - 4f^2s(s^4+6s^3\mu-10s^2\mu^2-9s\mu^3+4\mu^4)\\ &\quad + 2f(3s^7+15s^6\mu-20s^5\mu^2-5s^4\mu^3\\ &\quad - 13s^3\mu^4-19s^2\mu^5+10s\mu^6+\mu^7)-(s^2+\mu^2)^2\\ &\quad \times(2s^5+9s^4\mu-16s^3\mu^2-14s^2\mu^3+6s\mu^4+\mu^5) \qquad (16.34)\\ \tau(f,s,\mu) &= 4f^2(2s^4-11s^2\mu^2+4\mu^4)\\ &\quad - 2f(5s^6-21s^4\mu^2-21s^2\mu^4+5\mu^6)\\ &\quad + 3(s^2+\mu^2)^2(s^4-6s^2\mu^2+\mu^4). \qquad (16.35)\end{aligned}$$

We next observe that $\tau(f,s,\mu) > 0$ for (16.29) and (16.28); this follows because under (16.28), $\tau(f,s,\mu)$ is strictly convex in f,

$$\lim_{f\to(s^2+\mu^2)^2/(s^2-\mu^2)} \frac{\partial}{\partial\mu}\tau(f,s,\mu) > 0 \ \text{ and } \lim_{f\to(s^2+\mu^2)^2/(s^2-\mu^2)} \tau(f,s,\mu) > 0.$$

Therefore, $\beta(f,M,s,\mu)$ is increasing in M. Therefore, under (16.30),

$$\beta(f,M,s,\mu) > \beta\left(f, \frac{s(s^2-\mu^2)}{s^2-2s\mu-\mu^2}, s, \mu\right) = \frac{\psi(f,s,\mu)(s^2-\mu^2)}{s^2-2s\mu-\mu^2}, \tag{16.36}$$

where

$$\begin{aligned}\psi(f,s,\mu) &= 4f^2s^2(3s^3-4s^2\mu-6s\mu^2-\mu^3)\\ &\quad -2f(7s^7-9s^6\mu-6s^5\mu^2-11s^4\mu^3-11s^3\mu^4-s^2\mu^5+2s\mu^6+\mu^7)\\ &\quad +(s^2+\mu^2)^2(4s^5-5s^4\mu-10s^3\mu^2-4s^2\mu^3+2s\mu^4+\mu^5). \qquad (16.37)\end{aligned}$$

We next observe that

$$\psi(f,s,\mu) > 0 \tag{16.38}$$

for (16.28) and (16.29); this follows because under (16.28), $\psi(f, s, \mu)$ is strictly convex in f,

$$\lim_{f \to (s^2+\mu^2)^2/(s^2-\mu^2)} \frac{\partial}{\partial \mu}\psi(f, s, \mu) > 0 \quad \text{and} \quad \lim_{f \to (s^2+\mu^2)^2/(s^2-\mu^2)} \psi(f, s, \mu) > 0.$$

It follows from (16.33), (16.36), (16.38) and Lemma 2 that $n_1x_1 + n_2x_2$ is strictly convex in μ for an interior solution.

Second, we show that there exists $\overline{\mu} > 0$ such that the first inequality in (16.13) holds. Because an interior solution satisfies (16.28) and (16.29), it satisfies $f > s^2$. Observe that $\lim_{\mu \to 0}(\partial/\partial\mu)[n_1x_1 + n_2x_2] = (1/2)(s/\sqrt{2f - s^2} - 1) < 0$, where the inequality holds because $f > s^2$. This, together with the observation that $n_1x_1 + n_2x_2$ is continuous and strictly convex in μ, implies that there exists $\overline{\mu} > 0$ such that the first inequality in (16.13) holds.

Third, we show that total shipments are higher under a large emissions tax than they are under no emissions tax

$$(n_1x_1 + n_2x_2)|_{\mu=0} < (n_1x_1 + n_2x_2)|_{\mu \in [s/3, (\sqrt{2}-1)s)}. \tag{16.39}$$

From (16.39), Step One and Step Two, it follows that there exists $\overline{\mu} \in (0, (\sqrt{2} - 1)s)$ such that (16.13) holds.

(b) Let

$$\begin{aligned}\overline{e}_{s,1} = \max\Bigg\{0, &\frac{1}{[n_1x_1 + n_2x_2]|_{\mu=0} - [n_1x_1 + n_2x_2]|_{\mu=\varepsilon}} \\ &\times \left(\max_{\mu \in (\varepsilon, \mu_l)} [e_1n_1(x_1 + y_1) + e_2n_2(x_2 + y_2)]\right. \\ &\left.\quad - [e_1n_1(x_1 + y_1) + e_2[n_2(x_2 + y_2)]|_{\mu=0}\right)\Bigg\}.\end{aligned}$$

Because $\mu_l < \overline{\mu}$, by part (a),

$$(n_1x_1 + n_2x_2)|_{\mu \in (\varepsilon, \mu_l)} < (n_1x_1 + n_2x_2)|_{\mu=\varepsilon} < (n_1x_1 + n_2x_2)|_{\mu=0}.$$

Therefore, if $e_s > \overline{e}_{s,1}$, then $\mathcal{E}|_{\mu \in (\varepsilon, \mu_l)} < \mathcal{E}|_{\mu=0}$. Let

$$\begin{aligned}\overline{e}_{s,2} = \max\Bigg\{0, &\frac{1}{[n_1x_1 + n_2x_2]|_{\mu=\mu_h} - [n_1x_1 + n_2x_2]|_{\mu=0}} \\ &\times \left([e_1n_1(x_1 + y_1) + e_2n_2(x_2 + y_2)]|_{\mu=0}\right. \\ &\left.\quad - \min_{\mu \in (\mu_h, (\sqrt{2}-1)s)} [e_1n_1(x_1 + y_1) + e_2n_2(x_2 + y_2)]\right)\Bigg\}.\end{aligned}$$

Because $\mu_h \in (\overline{\mu}, (\sqrt{2}-1)s)$, by part (a),

$$(n_1x_1 + n_2x_2)|_{\mu=0} < (n_1x_1 + n_2x_2)|_{\mu=\mu_h} < (n_1x_1 + n_2x_2)|_{\mu\in(\mu_h,(\sqrt{2}-1)s)}$$

Therefore, if $e_s > \overline{e}_{s,2}$, then $\mathcal{E}|_{\mu=0} < \mathcal{E}|_{\mu\in(\mu_h,(\sqrt{2}-1)s)}$. The result holds with $\overline{e}_s = \max(\overline{e}_{s,1}, \overline{e}_{s,2})$.

(c) In the scenario with perfect competition, the total quantity shipped under an emissions tax ($T = \mu > 0$) or in the absence of climate policy ($T = \mu = 0$) is

$$[D_2 - c_1 - s - \mu]^+ 1\{c_1 + s + \mu < c_2\} + [D_1 - c_2 - s]^+ 1\{c_1 + \mu > c_2 + s\}, \tag{16.40}$$

wherein the first term represents Region 1 exports (to Region 2) and the second term represents Region 2 exports (to Region 1). When $\mu \in (0, \underline{\mu})$, $\underline{\mu} = c_2 - c_1 - s > 0$ which implies that Region 2 does not produce, and Region 1 exports the quantity $[D_2 - c_1 - s - \mu]^+$ which strictly decreases due to the emissions tax in the event that $D_2 - c_1 - s > 0$. Our assumption that consumption occurs in Region 2 with strictly positive probability implies that $D_2 - c_1 - s > 0$ with strictly positive probability, so $E[D_2 - c_1 - s - \mu]^+$ strictly decreases due to the emissions tax. A large emissions tax $\mu > \underline{\mu}$ prevents exports from Region 1, and it causes Region 2 to export to Region 1 if and only if $\mu > c_2 - c_1 + s$. Region 2 does not export in the absence of the emissions tax if and only if $c_2 - c_1 - s > 0$. When $c_2 - c_1 - s > 0$, the increase in total expected shipments caused by the large emissions tax is $E[D_1 - c_2 - s]^+ - E[D_2 - c_1 - s]^+$. Hence the large emissions tax $\mu > \underline{\mu}$ strictly increases total expected shipping if and only if $\mu > c_2 - c_1 + s$, $c_2 - c_1 - s > 0$, and $E[D_1 - c_2 - s]^+ > E[D_2 - c_1 - s]^+$. $\square$

Proof (Proposition 3).

Lemma 3. $n_1 + n_2$ *is strictly increasing in* σ.

Proof. We denote:

$$\begin{aligned} A &= n_1 + n_2 + 1 \\ &= \sqrt{\frac{4(D-c)[(D-c-s)(s^2+\sigma^2) - \mu s^2] + s^2[(\mu+s)^2 + 2\sigma^2]}{(2f - s^2 - \mu^2 - \sigma^2)(s^2 + \mu^2 + \sigma^2)}}. \end{aligned} \tag{16.41}$$

To prove the above lemma is equivalent to show that A is strictly increasing in σ. The sufficient conditions for $\partial A/\partial\sigma > 0$ to hold are:

$$\frac{\partial}{\partial\sigma}\left(\frac{4(D-c)[(D-c-s)(s^2+\sigma^2) - \mu s^2]}{(2f - s^2 - \mu^2 - \sigma^2)(s^2 + \mu^2 + \sigma^2)}\right) > 0, \tag{16.42}$$

and

$$\frac{\partial}{\partial \sigma}\left(\frac{s^2[(\mu+s)^2+2\sigma^2]}{(2f-s^2-\mu^2-\sigma^2)(s^2+\mu^2+\sigma^2)}\right) > 0. \tag{16.43}$$

We will first prove that (16.42) holds. Given the expression for x_1^* in (16.6) and the condition for an interior solution, $x_1^* > 0$ at $\tau = \mu$, imply that:

$$D - c - s - \mu > 0 \quad \Rightarrow \quad (D-c-s)(s^2+\sigma^2) - \mu s^2 > 0. \tag{16.44}$$

Formula (16.44) implies that for $A = n_1 + n_2 + 1$ in (16.41) to be positive at an interior solution, the following condition should hold:

$$2f - s^2 - \mu^2 - \sigma^2 > 0. \tag{16.45}$$

Combining (16.44) and (16.45) with the facts:

$$\frac{\partial}{\partial \sigma}(2f - s^2 - \mu^2 - \sigma^2) < 0$$

and

$$\frac{\partial}{\partial \sigma}\frac{[(D-c-s)(s^2+\sigma^2)-\mu s^2]}{(s^2+\mu^2+\sigma^2)} = \frac{2\mu\sigma[(D-c-s)\mu+s^2]}{(s^2+\mu^2+\sigma^2)^2} > 0$$

shows that (16.42) holds.

Inequality (16.43) is equivalent to:

$$\frac{2s^2[(s-\mu)^2 f + (2\mu s+\sigma^2)(2f-s^2-\mu^2-\sigma^2)]}{(2f-s^2-\mu^2-\sigma^2)^2(s^2+\mu^2+\sigma^2)^2} > 0.$$

Given (16.45), the above inequality holds. □

Lemma 4. *$n_1 - n_2$ is strictly increasing in σ.*

Proof. By the expression for n_1 and n_2 in (16.11) and (16.12):

$$n_1 - n_2 = \frac{\mu^2+\sigma^2-\mu[2(D-c)-s]}{s^2+\mu^2+\sigma^2}.$$

Thus, the derivative of $n_1 - n_2$ with respect to σ is:

$$\begin{aligned}\frac{\partial}{\partial \sigma}(n_1-n_2) &= \frac{\partial}{\partial \sigma}\frac{\mu^2+\sigma^2-\mu[2(D-c)-s]}{s^2+\mu^2+\sigma^2}\\ &= \frac{2\sigma(s^2+\mu[2(D-c)-s])}{s^2+\mu^2+\sigma^2} > 0\end{aligned}$$

where the inequality follows as $D - c - s > 0$ holds at an interior solution. □

Proposition 3 follows directly from Lemmata 3 and 4. □

Proof (Proposition 4). We first show that there exists $\overline{\sigma} > 0$ such that as σ increases on $\sigma \in (0, \overline{\sigma}]$, $n_2 E[x_2 + y_2]$ strictly decreases. Note that

$$\frac{d}{d\sigma} n_2 E[x_2 + y_2] = \frac{\sigma}{2(t^2 + \mu^2 + \sigma^2)^3 A} B, \tag{16.46}$$

where A is given by (16.41) and B is a lengthy expression satisfying

$$\lim_{\sigma \to 0} B = -\frac{2C}{(2f - s^2 - \mu^2)^2 (2[D - c] - s - \mu)},$$

where

$$\begin{aligned}
C = {} & 8(D-c)^3 f\mu[2f(2s^2 - \mu^2) - 3s^4 - 2s^2\mu^2 + \mu^4] \\
& + 2(D-c)^2[4f^2(s-\mu)(2s^3 - 4s^2\mu - 7s\mu^2 - 4\mu^3) \\
& - 2f(s^2+\mu^2)(5s^4 - 9s^3\mu + 3s\mu^3 + 7\mu^4) + 3(s^2+\mu^2)^4] \\
& - 2(D-c)[2f^2(4s^5 - 3s^4\mu - 6s^3\mu^2 + s^2\mu^3 + 8s\mu^4 + 4\mu^5) \\
& - 2f(s^2+\mu^2)(5s^5 - s^4\mu + 3s^3\mu^2 + 7s\mu^4 + 4\mu^5) + (3s + 2\mu)(s^2+\mu^2)^4] \\
& + s[2f^2(s-\mu)(s^4 + 2s^3\mu - 3s^2\mu^2 - 4s\mu^3 - 4\mu^4) \\
& - f(s^2+\mu^2)(3s^5 + 4s^4\mu - 4s^3\mu^2 + 4s^2\mu^3 + s\mu^4 + 8\mu^5) \\
& + (s + 2\mu)(s^2+\mu^2)^4].
\end{aligned} \tag{16.47}$$

Because an interior solution satisfies (16.29), to show that $C > 0$, it is sufficient to show that C is convex in f for an interior solution, $\lim_{f \to (s^2+\mu^2)^2/(s-\mu)^2} (d/df)C > 0$ and $C|_{f=(s^2+\mu^2)^2/(s-\mu)^2} > 0$. Note that $(d^2/df^2)C = G$, where

$$\begin{aligned}
G = {} & 32(D-c)^3\mu(2s^2 - \mu^2) \\
& + 16(D-c)^2(s-\mu)(2s^3 - 4s^2\mu - 7s\mu^2 - 4\mu^3) \\
& - 8(D-c)(4s^5 - 3s^4\mu - 6s^3\mu^2 + s^2\mu^3 + 8s\mu^4 + 4\mu^5) \\
& + 4s(s-\mu)(s^4 + 2s^3\mu - 3s^2\mu^2 - 4s\mu^3 - 4\mu^4).
\end{aligned} \tag{16.48}$$

With the change of variable $M = D - c$, and using the fact that an interior solution satisfies (16.28) and (16.30), it is straightforward to show that G is convex in M on $M \geq s(s^2 - \mu^2)/(s^2 - 2s\mu - \mu^2)$, $\lim_{M \to s(s^2-\mu^2)/(s^2-2s\mu-\mu^2)} (d/dM)G > 0$ and $G|_{M=s(s^2-\mu^2)/(s^2-2s\mu-\mu^2)} > 0$. Because an interior solution satisfies (16.28), this implies that $G > 0$, which implies that C is convex in f for an interior solution. A parallel argument establishes that $\lim_{f \to (s^2+\mu^2)^2/(s-\mu)^2} (d/df)C > 0$ and $C|_{f=(s^2+\mu^2)^2/(s-\mu)^2} > 0$. We conclude that for an interior solution, $C > 0$. Because the constraints for an interior solution are continuous in σ, from (16.46), $C > 0$ implies that there exists $\overline{\sigma} > 0$ such that as σ increases on $\sigma \in (0, \overline{\sigma}]$, $n_2 E[x_2 + y_2]$ strictly decreases. This in conjunction with part (a) of Proposition 6 implies that as σ increases on $\sigma \in (0, \overline{\sigma}]$, $n_1 E[x_1 + y_1]$ strictly increases. $\square$

Proof (Proposition 5). In the scenario with perfect competition, domestic production is

$$[D_1-c_1-T]^{+}1\{c_1+T \le c_2+s\}+[D_2-c_1-T-s]^{+}1\{c_1+T+s < c_2\} \quad (16.49)$$

where the first term represents production for the domestic market and the second term represents exports. Under an emissions tax $T = \mu > s+c_2-c_1$, (16.49) is zero. It is strictly positive for realizations of the emissions cost $T < \min(s+c_2-c_1, D_1-c_1)$ and zero for $T \ge \min(s+c_2-c_1, D_1-c_1)$, so domestic expected production is greater under the cap & trade system. A similar argument establishes the result regarding foreign expected production. □

Proof (Proposition 6).

(a) First, observe that because an interior solution has $n_1 > 0$, an interior solution has

$$f < \frac{[2(D-c)(D-c-s)+s^2](s^2+\mu^2+\sigma^2)^2}{[(2(D-c)-s)\mu+s^2]^2}. \quad (16.50)$$

Note that

$$\frac{\partial}{\partial\sigma}(n_1E[x_1+y_1]+n_2E[x_2+y_2]) = \frac{\sigma B(f)}{(2f-s^2-\mu^2-\sigma^2)^2(s^2+\mu^2+\sigma^2)^3A^3}, \quad (16.51)$$

where

$$\begin{aligned} B(f) &= (s^2+\mu^2+\sigma^2)([2(D-c)-s-\mu]s^2 \\ &\quad + [2(D-c)-s]\sigma^2)(4(D-c)[(D2-c-s)(s^2+\sigma^2)-\mu s^2] \\ &\quad + s^2[(\mu+s)^2+2\sigma^2]) + (2f-s^2-\mu^2-\sigma^2)[(2(D-c)-s)\mu+s^2]G, \\ G &= [2(D-c)-s](s^2+\sigma^2)s^2-\mu([2(D-c)-s]^2(s^2+\sigma^2) \\ &\quad - s^2[6(D-c)\mu-2\mu^2-2\sigma^2-3s\mu-s^2]). \end{aligned}$$

and A is given by (16.41). If $G \ge 0$, then the result holds. Suppose $G < 0$. Then, because $B(f)$ is decreasing in f and inequality (16.50) holds, for an interior solution,

$$\begin{aligned} B(f) &> B\left(\frac{[2(D-c)(D-c-s)+s^2](s^2+\mu^2+\sigma^2)^2}{[(2(D-c)-s)\mu+s^2]^2}\right) \\ &= 2s^2[2(D-c)-s-\mu](s^2+\mu^2+\sigma^2)^2 \\ &\quad \times \frac{4(D-c)[(D-c-s)(s^2+\sigma^2)-\mu s^2]+s^2[(\mu+s)^2+2\sigma^2]}{[2(D-c)-s]\mu+s^2} \\ &> 0. \end{aligned}$$

This, together with (16.51) implies the result.

(b) The claim that corresponds to the imperfect competition case is a direct consequence of part (a). For the case of perfect competition, we proceed with the following argument. In the scenario with perfect competition, production to serve Region 1 is

$$[D_1-c_1-T]^+1\{c_1+T \le c_2+s\}+[D_1-c_2-s]^+1\{c_1+T > c_2+s\}, \quad (16.52)$$

where the first term represents local production and the second term represents exports from Region 2. This is a convex function of T for $T \geq 0$, so by Jensen's inequality, changing the cost of emissions T from a constant μ (an emissions tax) to a random variable with mean μ (a mean-equivalent cap-and-trade system) increases the expected value of (16.52). The same arguments hold regarding production to serve Region 2,

$$[D_2-c_2]^+1\{c_1+T+s \ge c_2\}+[D_2-c_1-T-s]^+1\{c_1+T+s < c_2\}. \quad (16.53)$$

Therefore, total industry production, the sum of (16.52) and (16.53), is greater in expectation under a cap-and-trade system than a mean-equivalent emissions tax. □

Proof (Proposition 7). We define the expected consumer surplus for Region 1 as:

$$E[(D-p_1)(n_1y_1+n_2x_2)/2]$$

or given the demand function in (16.1) and the supply-demand equation in (16.2),

$$E[(n_1y_1+n_2x_2)^2/2].$$

Using the expressions for y_1 and x_2 in (16.5) and (16.8):

$$\begin{aligned}
E[(n_1y_1+n_2x_2)^2] &= \frac{[(n_1+n_2)(D-c)-n_1\mu-n_2s]^2+n_1^2\sigma^2}{(1+n_1+n_2)^2};\\
\frac{dE[(n_1y_1+n_2x_2)^2]}{d\sigma} &= \frac{2[(D-c)(n_1+n_2)-n_1\mu-n_2s]}{n_1+n_2+1}\\
&\quad \cdot\frac{d}{d\sigma}\left[(D-c)-\frac{D-c}{n_1+n_2+1}-n_1\mu-n_2s\right]\\
&\quad +\frac{d}{d\sigma}\left[\frac{n_1^2\sigma^2}{(n_1+n_2+1)^2}\right]. \qquad (16.54)
\end{aligned}$$

As $x_1 > 0$ at an interior solution, $D-c-\mu-s>0$ holds, and by Lemma 1, n_1+n_2 is increasing in σ. Therefore,

$$\frac{dE[(n_1y_1+n_2x_2)^2]}{d\sigma} > \frac{d}{d\sigma}\left[\frac{[(\mu+s)(n_1+n_2)-n_1\mu-n_2s]^2+n_1^2\sigma^2}{(n_1+n_2+1)^2}\right]. \quad (16.55)$$

Note that $(\mu+s)(n_1+n_2)-n_1\mu-n_2 s = n_1 s + n_2\mu$. Then, the right hand side of (16.55):

$$\frac{d}{d\sigma}\left[\frac{(n_1 s+n_2\mu)^2+n_1^2\sigma^2}{(n_1+n_2+1)^2}\right] = 2\left(\frac{n_1 s+n_2\mu}{n_1+n_2+1}\right)\cdot\frac{d}{d\sigma}\left(\frac{n_1 s+n_2\mu}{n_1+n_2+1}\right) + \frac{d}{d\sigma}\frac{n_1^2\sigma^2}{(n_1+n_2+1)^2}.$$

Note that

$$\frac{n_1}{n_1+n_2+1} = \frac{1}{2A}\left(A-\frac{s^2+[2(D-c)-s]\mu}{s^2+\mu^2+\sigma^2}\right) = \frac{1}{2}-\frac{1}{2}\frac{s^2+[2(D-c)-s]\mu}{(s^2+\mu^2+\sigma^2)A}.$$

Then, $(d/d\sigma)(n_1/(n_1+n_2+1))>0$, as $s^2+\mu^2+\sigma^2$ and A are both increasing in σ. Therefore, given $s\geq\mu$,

$$\frac{d}{d\sigma}\left[\frac{(n_1 s+n_2\mu)^2+n_1^2\sigma^2}{(n_1+n_2+1)^2}\right] \geq \frac{d}{d\sigma}\left[\frac{\mu^2(n_1+n_2)^2+n_1^2\sigma^2}{(1+n_1+n_2)^2}\right]. \tag{16.56}$$

We now prove that the RHS of (16.56) is greater than zero. We split the expression into two terms.

Term 1:

$$\begin{aligned}
&\frac{d}{d\sigma}\left\{(1+n_1+n_2)^{-2}(\mu^2(n_1+n_2)^2)\right\}\\
&=\frac{d}{d(n_1+n_2)}\left\{(1+n_1+n_2)^{-2}\mu^2(n_1+n_2)^2\right\}\frac{d(n_1+n_2)}{d\sigma}\\
&=\frac{\mu^2[2(n_1+n_2)(1+n_1+n_2)^2-2(n_1+n_2+1)(n_1+n_2)^2]}{(n_1+n_2+1)^4}\frac{d(n_1+n_2)}{d\sigma}\\
&=\frac{2\mu^2(n_1+n_2)(n_1+n_2+1)}{(n_1+n_2+1)^4}\frac{d(n_1+n_2)}{d\sigma}>0.
\end{aligned} \tag{16.57}$$

Term 2:

$$\begin{aligned}
&\frac{d}{d\sigma}\left\{(1+n_1+n_2)^{-2}n_1^2\sigma^2\right\}\\
&=\frac{\left(2n_1\frac{dn_1}{d\sigma}\sigma^2+2\sigma n_1^2\right)(1+n_1+n_2)^2-2(n_1+n_2+1)\left(\frac{dn_1}{d\sigma}+\frac{dn_2}{d\sigma}\right)\sigma^2 n_1}{(n_1+n_2+1)^4}\\
&=\frac{2(n_1+n_2+1)\sigma n_1}{(n_1+n_2+1)^4}\left[\left(\sigma\frac{dn_1}{d\sigma}+n_1\right)(1+n_1+n_2)-\left(\frac{dn_1}{d\sigma}+\frac{dn_2}{d\sigma}\right)\sigma n_1\right]\\
&=\frac{2\sigma n_1}{(n_1+n_2+1)^3}\left[\sigma(n_2+1)\frac{dn_1}{d\sigma}-\sigma n_1\frac{dn_2}{d\sigma}+n_1(1+n_1+n_2)\right]\\
&=\frac{2\sigma n_1}{(n_1+n_2+1)^3}\left[\frac{d}{d\sigma}\left(\frac{n_1}{n_2+1}\right)(n_2+1)^2+n_1(1+n_1+n_2)\right],
\end{aligned} \tag{16.58}$$

where the last equality follows from the fact that $dn_2/d\sigma = d(n_2+1)/d\sigma$. To prove the above expression for term 2 is strictly greater than zero, we need to show that $(d/d\sigma)(n_1/(n_2+1)) > 0$. By (16.12), $n_2 = n_1 + f(\sigma)$ where $f'(\sigma) < 0$,

$$\frac{d}{d\sigma}\left(\frac{n_1}{1+n_1+f(\sigma)}\right) = \frac{\frac{dn_1}{d\sigma}(1+n_1+f(\sigma)) - \frac{dn_1}{d\sigma}n_1 - f'(\sigma)n_1}{(1+n_1+f(\sigma))^2}$$
$$= \frac{\frac{dn_1}{d\sigma}(1+f(\sigma)) - f'(\sigma)n_1}{(1+n_1+f(\sigma))^2} > 0, \tag{16.59}$$

where the last inequality follows from Proposition 3 (that n_1 is increasing in σ) and $1+f(\sigma) = [\mu(2(D-c)-s)+s^2]/[s^2+\mu^2+\sigma^2] > 0$, given $D-c-s > 0$ holds at an interior solution.

As given $s \geq \mu$, the first and second terms of the right hand side of (16.56) are both strictly greater than zero, then the right hand side of (16.55) is strictly greater than zero. Hence, given $s \geq \mu$, the expected consumer surplus in market 1 is increasing in σ. □

The Calibration of Parameters for the Numerical Analysis We fit a linear demand function for each region i, $Q_i = D_i - a_i p_i$ for $i = 1, 2$. For this, we need the demand and price data for cement. We will use the shipment of Portland cement to a region as a proxy for that region's demand for Portland cement. We will also assume that the demand function did not shift in years 2010 and 2011.

The Portland cement shipments to the final customers in California were 6,218,000 metric tons in 2010 and 6,890,000 metric tons in 2011 (Van Oss 2013, Table 9). The average value[8] per metric ton of Portland cement reported by California-based entities (not necessarily the location of sales)[9] is \$79 in 2010 and \$75.5 in 2011 (Van Oss 2013, Table 11). \$79 in 2010 corresponds to \$81.5 in 2011.[10]

The Portland cement shipments to the final customers in Arizona and Nevada were 2,374,000 metric tons in 2010 and 2,403,000 metric tons in 2011 (Van Oss 2013, Table 9). The weighted average mill net value per metric ton of Portland cement sold in the regions including Idaho, Montana, Nevada,

[8] Values are mill net or ex-plant (free on board) valuations of total sales to final customers, including sales from plants' external distribution terminals. The data are ex-terminal for independently reporting terminals. Data include all varieties of Portland cement and both bulk and bag shipments.

[9] The mill net values are better viewed as price indices for cement, suitable for crude comparisons among regions and during time.

[10] 2010 and 2011 annual average consumer price indices as given by U.S. Department of Labor, Bureau of Labor Statistics (2013) are 218.056 and 224.939, respectively.

Utah, Arizona and New Mexico is \$102 in 2010 and \$94 in 2011. \$102 in 2010 corresponds to \$104.71 in 2011.[11]

We have two (Q_i, p_i) pairs for each region $i = 1, 2$ as above. We assume a linear demand function $Q_i = D_i - a_i p_i$ for each region i. Then, in Region 1 (California), D_1 is calculated as 15,354,948 and a_1 is 112,118.5. In Region 2 (Arizona and Nevada), D_2 is 2,657,528, and a_2 is 2707.75.

Building a new state-of-the-art conventional plant for a production capacity of 2 and 1 million metric tons per year of clinker costs €130 and €170 per metric ton in 2007 Euros. Assuming a linear relation between the production capacity and unit capacity building cost, for a production capacity of 1,104,167 metric tons, the investment cost is €165.83 per metric ton, or approximately \$236.7 per metric ton in 2011 dollars,[12] then the fixed capacity investment is $F_1 = F_2 =$ \$261,378,850.

References

Australian Government Clean Energy Regulator (2014) About the carbon pricing mechanism. http://www.cleanenergyregulator.gov.au/Carbon-Pricing-Mechanism/About-the-Mechanism/Pages/default.aspx. Accessed 15 Mar 2015

Benjaafar S, Li Y, Daskin M (2013) Carbon footprint and the management of supply chains: insights from simple models. IEEE Tran Autom Sci Eng 10(1):99–116

Bernstein L, Roy J, Delhotal KC, Harnisch J, Matsuhashi R, Price L, Tanaka K, Worrell E, Yamba F, Fengqi Z (2007) Industry. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, New York

Chen L, Olhager J, Tang O (2014) Manufacturing facility location and sustainability: a literature review. Int J Prod Econ 149:154–163

Condon M, Ignaciuk A (2013) Border carbon adjustment and international trade: a literature review. OECD trade and environment working papers

Demailly D, Quirion P (2008) Leakage from climate policies and border tax adjustment: lessons from a geographic model of the cement industry. In: Guesnerie R, Tulkens H (eds) The design of climate policy. MIT, Cambridge, pp 333–358

Diabat A, Simchi-Levi D (2010) A carbon-capped supply chain network problem. In: Proceedings of the IEEE international conference on industrial engineering and engineering management, 2009

Drake DF (2015) Carbon tariffs: effects in settings with technology choice and foreign production cost advantage. Harvard Business School Working Paper No. 13-021 (revised November 2015)

Drake DF, Kleindorfer PR, Van Wassenhove LN (2015, forthcoming) Technology choice and capacity portfolios under emissions regulation. Prod Oper Manag

[11] 2010 and 2011 annual average consumer price indices as given by U.S. Department of Labor, Bureau of Labor Statistics (2013) are 218.056 and 224.939, respectively.

[12] The 2007 average exchange rate of Euro and U.S. dollar was \$1 =€0.760 (Internal Revenue Service, 2013). 2007 and 2011 annual average consumer price indices as given by U.S. Department of Labor, Bureau of Labor Statistics (2013) are 207.342 and 224.939, respectively.

Ellerman AD, Joskow PL, Harrison D Jr (2003) Emissions trading: experience, lessons, and considerations for greenhouse gases. Pew Center on Global Climate Change, Washington, DC

Fowlie M, Reguant M, Ryan SP (2016) Market-based emissions regulation and industry dynamics. J Polit Econ 124(1):249–302

Goulder L (2013) Markets for pollution allowances: what are the (new) lessons? J Econ Perspect 27(1):87–102

Goulder LH, Schein A (2013) Carbon taxes versus cap and trade: a critical review. Climate Change Econ 4(3) 1350010 (28pp)

Hannam P (2014) Carbon price helped curb emissions, ANU study finds. The Guardian. http://www.theguardian.com.au/story/2423463/carbon-price-helped-curb-emissions-anu-study-finds/?cs=8. Accessed 15 Mar 2015

International Energy Agency Energy Technology Systems Analysis Programme (2010) Technology brief I03: cement production. IEA Technical Report http://www.iea-etsap.org/web/E-TechDS/PDF/I03_cement_June/202010_GS-gct.pdf

Jin M, Granda-Marulanda NA, Down I (2014) The impact of carbon policies on supply chain design and logistics of a major retailer. J Clean Prod 85:453–461

Jornsten K, Bjorndal M (1994) Dynamic location under uncertainty. Stud Reg Urban Plan 3:163–184

Lanz B, Rutherford T, Tilton J (2013) Subglobal climate agreements and energy-intensive activities: an evaluation of carbon leakage in the copper industry. World Econ 36(3):254–279

Mathiesen L, Maestad O (2004) Climate policy and the steel industry: achieving global emission reductions by an incomplete climate agreement. Energy J 25(4):91–114

McKinnon A (2008) The potential of economic incentives to reduce CO_2 emissions from goods transport. Paper prepared for the 1st international transport forum on "Transport and energy: the challenge of climate change" Leipzig, 28–30 May 2008

Melo MT, Nickel S, da Gama FS (2009) Facility location and supply chain management—a review. Eur J Oper Res 196:401–412

Miller NH, Osborne M (2014) Spatial differentiation and price discrimination in the cement industry: evidence from a structural model. RAND J Econ 45(2):221–247

Milne JE (2008) A carbon tax may look better when considering the current economic climate. Technical Report, Bull. At. Sci. Roundtable: Carbon tax vs cap-and-trade. October 7, 2008. http://www.thebulletin.org/web-edition/roundtables/carbon-tax-vs-cap-and-trade

Nordhaus WD (2007) To tax or not to tax: alternative approaches to slowing global warming. Rev Environ Econ Policy 1(1):26–44

Nordhaus WD (2009) Economic issues in designing a global agreement on global warming. Keynote address prepared for an international meeting. Climate change: global risks, challenges, and decisions, Copenhagen (2009)

Schipper L, Saenger C, Sudardshan A (2011) Transport and carbon emissions in the United States: the long view. Energies 4:563–581

Shapiro RJ (2009) Is cap and trade a dead policy walking? http://ndn.org/blog/2009/04/cap-and-trade-dead-policy-walking

Snyder LV (2006) Facility location under uncertainty: a review. IIE Trans 38:537–554

The Guardian (2013) EU carbon price crashes to record low. http://www.theguardian.com/environment/2013/jan/24/eu-carbon-price-crash-record-low

US Department of Labor, Bureau of Labor Statistics (2013) Consumer price index: all urban consumers – (CPI-U) U.S. city average. ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt. Accessed 19 Jun 2013

Van Oss HG (2004) U.S. Geological Survey 2004 minerals yearbook: cement. Technical Report, U.S. Department of the Interior, U.S. Geological Survey. http://minerals.usgs.gov/minerals/pubs/commodity/cement/cemenmyb04.pdf. Accessed 22 Jun 2013

Van Oss HG (2012) U.S. Geological Survey 2010 minerals yearbook: cement. Technical Report, U.S. Department of the Interior, U.S. Geological Survey. http://minerals.usgs.gov/minerals/pubs/commodity/cement/myb1-2010-cemen.pdf. Accessed 8 Mar 2013

Van Oss HG (2013) U.S. Geological Survey 2011 minerals yearbook: cement. Technical Report, U.S. Department of the Interior, U.S. Geological Survey. http://minerals.er.usgs.gov/minerals/pubs/commodity/cement/myb1-2011-cemen.pdf Accessed 18 Jun 2013

Venables A (1985) Trade and trade policy with imperfect competition: the case of identical products and free entry. J Int Econ 19:1–19

Weber TA, Neuhoff K (2010) Carbon markets and technological innovation. J Environ Econ Manag 60:115–132

Weitzman ML (1974) Prices vs quantities. Rev Econ Stud 41:477–491

Chapter 17
Managing the Chemicals and Substances in Products and Supply Chains

Tim Kraft, Özgen Karaer, and Kathryn Sharpe

Abstract This chapter explores the challenges that companies face in managing the chemicals and substances found in their products and supply chains. The topic is presented from both a practice and an academic perspective. Based on the authors' work with an environmental nonprofit, a model is presented that examines levers available to both companies and nonprofits for improving the environmental performance of suppliers. The chapter concludes by discussing potential future research directions with respect to chemicals management and sustainable supply chains.

17.1 Introduction

Today there are almost 84,000 known chemicals in commercial use in the United States, with over 500 new chemicals introduced each year (U.S. Environmental Protection Agency 2014). We are still unsure of the health and environmental impacts for an alarming number of these substances (Layton 2010; Rizzuto 2013). In the United States, even as public awareness of environmental hazards increases, proper regulations for monitoring and controlling chemical usage are still not in place. As Dr. Richard Denison, senior scientist at the Environmental Defense Fund, noted, "By failing to identify, let alone control, the long and growing list of chemicals in everyday products

T. Kraft (✉) • K. Sharpe
Darden School of Business, University of Virginia, Charlottesville, VA 22903, USA
e-mail: kraftt@darden.virginia.edu; sharpek@darden.virginia.edu

Ö. Karaer
Industrial Engineering Department, Middle East Technical University, Ankara, Turkey
e-mail: okaraer@metu.edu.tr

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_17

that we now know can harm people and the environment, [the U.S. Toxic Substances and Control Act] has forced states, businesses, workers and consumers to try to act on their own to address what should be a national priority" (Safer Chemicals Healthy Families 2010). Due to this lack of regulatory guidance, an opportunity exists for nonprofits and companies to play an influential role in shaping the chemical management policies of industries.

This chapter is based on the authors' work with GreenBlue, an environmental nonprofit that develops science-based decision tools for industry. Recently, in an effort to increase the transparency of the chemicals and substances used in products and supply chains, GreenBlue created Material IQ (MiQ), a new tool with which suppliers can safely share sensitive chemical toxicity data with their customers without divulging intellectual property secrets.[1] Due to its ability to act as a marketplace where a buyer can compare the product information of different suppliers, MiQ has the potential to introduce competition between suppliers to improve their environmental performance. As GreenBlue takes MiQ to market, it must determine when to promote the use of MiQ and whether to recommend that buyers use it as a platform to encourage competition amongst suppliers or to collaborate with suppliers.

Buyers (i.e., manufacturers and retailers) have long used *competition* as a lever with which to improve the quality and price performance of suppliers (Laseter and Stasior 1998). More recently, buyers have used competition to also improve suppliers' environmental performance. For example, in an effort to "green" the products it sells and set standards in the retail industry, Walmart requested that over 100,000 of its suppliers answer questions regarding their sustainability practices. Walmart warned that suppliers who chose not to participate would "probably (be) less relevant (to Walmart)" (Rosenbloom 2009). This strategy implicitly promotes competition amongst suppliers to abide by Walmart's sustainability objectives. Conversely, buyers are increasingly *collaborating* with suppliers to improve their sustainability performance. For example, in 2009, Nike began to integrate sustainability into its preliminary design and manufacturing decisions. As part of this initiative, Nike implemented a demanding but collaborative environmental program at over 40 of its footwear suppliers in Asia (Plambeck et al. 2012).

The goals of this chapter are to (1) introduce the operations management community to the topic of chemicals management in supply chains and (2) examine when competition or collaboration can be used by buyers or nonprofits to incentivize suppliers to improve their environmental performance. Our discussion is organized as follows. First, we review some of the challenges that industries face managing the chemicals and substances found in their products and supply chains. We then discuss the literature relevant to our problem setting. Next, we consider the specific case of GreenBlue and examine ways in which buyers and nonprofits can improve the environmental

[1] The chemical composition information shared between supplier and buyer is collected and entered into MiQ by SciVera, a third-party chemical safety assessment provider.

performance of suppliers. We divide this discussion into two parts: (1) first, we investigate when a buyer can use either competition or cost sharing to improve a supplier's environmental performance; (2) second, we develop insights into when and how GreenBlue should promote the use of MiQ. Finally, based on an industry survey conducted with GreenBlue, we highlight potential future research directions with respect to chemicals management and sustainable supply chains.

17.2 Challenges to Chemicals Management in Supply Chains

The Toxic Substances Control Act (TSCA) is a United States law that regulates the manufacture, distribution, and importation of new and existing chemicals in the United States. Established in 1976, TSCA is administered by the Environmental Protection Agency (EPA). In recent years, TSCA has been heavily criticized for not mandating stronger chemicals-management practices by industries and not properly protecting consumers' safety (Environmental Defense Fund 2015; Hamblin 2014; Koch 2014). In particular, two common criticisms of TSCA are (1) it does not provide the EPA with the proper authority to regulate the use of chemicals[2] and (2) when put into place, it grandfathered in (i.e., considered safe) over 62,000 chemicals already in commercial use. Consequently, calls for TSCA reform have increased and states have begun to enact their own legislation, such as California's Safer Consumer Products Regulation. These new state laws have made regulatory compliance more complex for companies producing and selling products in the U.S. who must now manage and abide by not only national and international laws, but also state requirements (Murray 2010; Westervelt 2012). The European Union equivalent to TSCA is the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) directive. When it was established in 2007, REACH was considered ground-breaking legislation because it required manufacturers to register the chemicals and substances found in their products, before selling or distributing them. Due to these stricter requirements, REACH has forced manufacturers to identify all of the chemicals and substances being used in their products and to increase the transparency in their supply chains (Westervelt 2012). Although critics have noted the additional costs and trade restrictions companies have incurred due to REACH (European Commission 2013; Moritz 2014), the directive has inspired similar regulation in countries outside of the EU (Lin 2013).

[2] Under TSCA, the EPA has successfully restricted the use of only four chemicals. The ban on the use of a fifth chemical, asbestos, was overturned in 1991.

The advent of REACH has also increased consumer and industry awareness of substances of concern. A substance of concern is an unregulated chemical or substance that could potentially cause harm to the environment or human health. In recent years, substances of concern contained in widely used consumer products have become regular topics in the mainstream media. For example, reports have been published on the potential hazards of triclosan in toothpastes (Kary 2014), brominated flame retardants (BFRs) in electronics and furniture (Callahan and Roe 2012), and phthalates in fashion goods (Pous 2012). While these substances have generated consumer fears and scientific debate, they remain unregulated and can still be found in everyday consumer products. As a result, manufacturers face difficult tradeoffs when deciding whether to replace a substance in their products. On the one hand, replacing a substance can be very costly. For example, the Consumer Electronics Association estimates that the initial compliance requirements for the EU's Restriction of Hazardous Substances (RoHS) directive, which restricts the use of only six substances, cost the global electronics industry \$32 billion (Carbone 2008). On the other hand, not all substances of concern are proven to be harmful (e.g., aspartame in diet soft drinks; see Brody 1983 and Halliday 2008) and a replacement substance may introduce new potential risks (e.g., scientists are questioning whether bisphenol-S (BPS) is a safe replacement for bisphenol-A (BPA); see Bilbrey 2014).

The debate over the true environmental or health risk of a substance of concern can create tension between science and industry. Often the discussion focuses on the toxicity of the substance versus individuals' level of exposure (Dale-Harris 2014). Whereas proponents for banning a substance will argue that if a chemical in a product is potentially hazardous, then it should be banned, opponents will counter that consumers are not at risk if their level of exposure is extremely low. Companies will often lobby against potential regulation if they do not believe that consumers or the environment are at risk from a substance found in their product. For example, the leading producers of BFRs in the U.S. mounted both consumer campaigns and political lobbying in an attempt to highlight the safety benefits of BFRs (Callahan and Roe 2012). Furthermore, due in part to industry lobbying and inconclusive scientific evidence, the regulation of a substance can take many years and create a lengthy time frame over which companies must manage all of the potential safety, financial, and brand risks of a substance. For example, the length of time from the first popular press warning regarding BPA in baby bottles until regulation in the U.S. was over a decade (Consumers Union 1999; Tavernise 2012). Interestingly, the eventual regulation of BPA in baby bottles in the U.S. was a mere formality as the six largest baby bottle producers in the U.S. had already removed BPA from their products 2 years earlier due to consumer demands (Layton 2009).

Given these complexities regarding the regulation of and science behind chemicals and substances, opportunities exist for both nonprofits and companies to influence the chemicals being used in products and supply chains.

For example, the EU's REACH directive has been criticized for not being aggressive enough in identifying substances of high concern. As a result, a nonprofit called ChemSec established the SIN (Substitute It Now!) List to "[accelerate] the REACH legislative process" and to identify additional substances of concern (The SIN List 2015). The SIN List is often used as a predictive tool by companies to forecast future regulations (ChemSec 2009). Similarly, examples exist of large retailers such as Walmart banning the sale of products containing substances of concern such as BFRs (Koch 2013). Given Walmart's extensive purchasing power, a ban by the retailer is almost as powerful as regulation in terms of restricting the use of a substance of concern in industries.

17.3 A Review of the Relevant Literature

Within the operations management (OM) literature, the transportation of hazardous materials is a well-studied problem (e.g., Bianco et al, 2015; Carotenuto et al, 2007; Erkut and Verter, 1998; Kara and Verter, 2004; for a review, see Erkut et al. 2007). The main focus has been on the design of networks that minimize the risk associated with the transportation and storage of hazardous materials. Outside of this stream of literature, relatively few papers have studied the topic of chemicals management, with the existing works addressing a broad range of topics. For example, Corbett and DeCroix (2001) examine the effectiveness of shared-savings contracts used for chemicals purchasing. King and Lenox (2001) empirically test the relationship between lean production and environmental performance using the EPA's Toxic Release Inventory. This paper is related to the author's well-known work on industry self- regulation that examines the chemical industry's Responsible Care Program (King and Lenox 2000). Kraft et al. (2013a,b) examine firm and non-governmental organization (NGO) decisions regarding the replacement of a substance of concern in a product. Although all of these works examine interesting and relevant topics, the lack of consistent themes within the literature further highlights the research opportunity with respect to chemicals management.

Next, we discuss two additional streams of literature relevant to GreenBlue's problem: levers for improving suppliers' nonprice performance and the analytical modeling of a nonprofit problem.

Levers for Improving Suppliers' Nonprice Performance We compare two methods for improving suppliers' nonprice performance: supplier competition and cost sharing. Models that examine how supplier competition can impact a supplier's nonprice performance have been applied to a broad range of OM topics such as supply disruption risk (e.g., Babich 2006; Babich et al. 2007), yield uncertainty (e.g., Federgruen and Yang 2009; Tang and

Kouvelis 2011), service (e.g., Cachon and Zhang 2007; Ha et al. 2003), and quality (e.g., Elahi et al. 2007; Gans 2002).[3] For example, Elahi et al. (2007) use supplier competition to elicit a supplier's service quality, comparing the supplier's performance under multi-supplier and single-supplier settings. The allocation of demand is used as the incentive with which to improve supplier quality. Outside of the contracting literature, there are relatively few papers (e.g., Babich 2010; Friedl and Wagner 2012; Liu et al. 2010; Talluri et al. 2010; Wang et al. 2010) that apply theoretical modeling to examine the impact of a firm sharing costs to develop a supplier's capabilities. For example, Wang et al. (2010) study a setting in which a firm can either source from multiple suppliers or exert effort to improve supplier reliability. They model both random yield and random capacity cases.

There is an emerging stream of supply chain literature that investigates corporate social responsibility (CSR). One aspect that makes CSR a challenging topic to study is that CSR activities are often nonverifiable (Norman and MacDonald 2004) and therefore difficult to enforce with contracts. As a result, papers have emerged that examine the impact that supply chain structure can have on a supplier's CSR performance (Agrawal and Lee 2015; Guo et al. 2015; Hendrikse and Letizia 2015; Mendoza and Clemen 2013). For example, Guo et al. (2015) consider the sourcing decisions of a buyer choosing between responsible and risky suppliers. The authors examine how supplier concentration influences a firm's responsible sourcing decisions. They show that efforts to improve social responsibility practices in supply chains that focus on consumers or increasing transparency may lead to negative consequences such as an increase in risky sourcing. Mendoza and Clemen (2013) examine a setting with two competing firms who can source from separate suppliers or a shared supplier. The authors find that firms have more incentives to share a supplier when consumer demand for sustainability is high, firms are more efficient at helping suppliers, and suppliers receive a lower benefit for their efforts.

Analytical Modeling of Nonprofit Problems There is a growing body of work that examines nonprofit issues from an OM perspective (e.g., DeVericourt and Lobo 2009, Lien et al 2014, Privett and Erhun 2011; for a review, see Berenguer et al. 2014). However, relatively few of these works examine or consider a nonprofit's activism towards firms (e.g., Kraft et al. 2013b). Instead, most of the papers that theoretically examine activism can be found in either the strategy or political economy literatures (e.g., Baron 2001; Calveras et al. 2007; Lenox and Eesley 2009). Within the environmental

[3] Within the supply chain contracting literature, a number of papers analyze how a buyer can incentivize a supplier to improve her quality or process through supplier competition (e.g., Deng and Elmaghraby 2005; Li and Debo 2009), supplier development (e.g., Corbett and DeCroix 2001; Kim and Netessine 2013; Zhu et al. 2007), or a combination of the two (e.g., Li 2013; Li et al. 2013). However, as a nonprofit, GreenBlue is not in a position to coordinate the supply chain. Therefore, we focus our discussion on how the structure of the buyer-supplier dynamic impacts a supplier's environmental performance.

literature, there exists a division between activists on whether to confront or to work with firms to improve their environmental performance (Dowie 1996; Schwartz and Paul 1992; Speth 2008). Conner and Epstein (2007) divide nonprofits into two broad categories: purists, who typically seek change through confrontation, and pragmatists, who instead prefer to work with firms to solve environmental problems. GreenBlue regularly works with industry to find solutions to environmental problems. As noted by James Ewell, Sustainable Materials Director at GreenBlue, “GreenBlue has always been ‘industry-facing’ in its work [and worked to provide] the practical guidance that is necessary for companies to fully engage and implement best practices [in sustainable design]” (Ewell 2014). Therefore, we classify GreenBlue as a pragmatic nonprofit.

Defining a nonprofit’s objective can be difficult since nonprofits often have multiple goals (Steinberg 1986; Weisbrod 1998). Within the nonprofit literature, a nonprofit’s objective function is often modeled as a linear combination of different goals (e.g., Harrison and Lybecker 2005; Liu et al. 2010; Steinberg 1986). For example, Harrison and Lybecker (2005) model a nonprofit hospital’s objective function as a linear combination of the hospital’s profit and quality of care. Conversely, within the political economy and strategy literatures, activists’ objective functions are often modeled around a single goal (e.g., Baron 2001; Baron and Diermeier 2007; Lenox and Eesley 2009). For example, Baron (2001) model an activist’s objective function to minimize a firm’s pollution levels. GreenBlue is a pragmatic nonprofit. Thus, although GreenBlue’s objective function is to maximize environmental quality, when formulating GreenBlue’s problem we incorporate constraints to ensure that both the buyer and the supplier do not incur a decrease in profits from using MiQ.

17.4 GreenBlue and Material IQ

In this section, we examine how GreenBlue should recommend buyers use MiQ. We present GreenBlue’s problem in two parts. First, we examine under what market and economic conditions supplier competition or cost sharing can improve a supplier’s environmental performance. Based on these findings, we then develop insights into GreenBlue’s strategy for promoting how buyers should use MiQ.[4]

[4] The model presented in Sect. 17.4 is based on the working paper “Buyer and Nonprofit Levers to Improve Suppliers’ Environmental Performance” by Karaer et al. (2015).

17.4.1 Model Overview

First, we review our model formulation and assumptions. We consider a supply chain in which a buyer (he) attempts to increase the environmental quality of the product his supplier (she) provides. We first describe our base case and then discuss two additional methods for improving a supplier's environmental quality: (1) the buyer introduces a second supplier and, thus, supplier competition; and (2) the buyer and his existing supplier share the investment cost to improve quality. From GreenBlue's perspective, understanding the impact that these levers can have on a supplier's environmental performance is critical since MiQ can be used to facilitate either competition between suppliers or collaboration between a buyer and a supplier. Although our research is motivated by an environmental issue, the model we present can be applied to a broad set of problems where the quality in question is an "attribute [that consumers] prefer more to less" (see Kaya and Özer 2009, p. 669).[5]

The *base case* (BC), analyzes a single-buyer, single-supplier setting. The buyer sells a product with demand driven by both price and environmental quality. The supplier produces the product and, thus, determines its quality. Based on market trends, we assume that consumers demand a higher-quality product, but not at a higher price (Hyatt and Spicer 2012). Therefore, we fix the price of the product, but allow demand to vary based on the supplier's quality. The base case sequence of events is as follows: (1) The profit-maximizing buyer offers the supplier a premium that he is willing to pay to entice investment in environmental quality. (2) Based on the premium, the supplier sets her quality level, with the level impacting the end demand for the product. In the base case, the per-unit premium is the only option available to the buyer to incentivize the supplier to improve quality.

The consumer demand for the product is given by

$$D = K - ap + dq, \tag{17.1}$$

where K is the base market potential, a is consumers' price awareness, and d is consumers' environmental quality awareness. Price, p, is fixed with only environmental quality, q, being a decision variable for the supplier. We model the buyer's demand as linear in both price and quality. The linear demand form has been widely used to study demand functions composed of more than one attribute (e.g., Banker et al. 1998; Kaya and Özer 2009; Tsay and Agrawal. 2000). The structure is suitable for our purposes since our goal is to

[5] There exists an extensive literature that examines conformance quality. For example, Baiman et al. (2000), Chao et al. (2009), Lim (2001), and Zhu et al. (2007) study supplier-buyer interactions in the context of conformance quality. Similar to Kaya and Özer (2009), we instead consider environmental quality or performance as a "demand-enhancing" attribute. We refer the interested reader to Banker et al. (1998), Karaer and Erhun (2015), Karmarkar and Pitbladdo (1997), and Moorthy (1988) for examples of a firm facing quality decisions under competition.

capture the general demand effect of quality on the buyer's and the supplier's decisions.

The buyer's (B) profit function for the base case (BC) is given by

$$\begin{aligned}\pi^B_{BC} &= D[(p-\omega)-r] \\ &= (K-ap+dq)[(p-\omega)-r]. \end{aligned} \tag{17.2}$$

Here $p-\omega$ represents the buyer's existing margin and r is the per-unit premium the buyer offers the supplier in order to increase her environmental quality level.

After the buyer decides on the premium, the supplier (S) sets the quality level, q, to maximize her own profit function below

$$\begin{aligned}\Pi^S_{BC} &= D[(\omega-m)+(r-cq)]-yq^2 \\ &= (K-ap+dq)[(\omega-m)+(r-cq)]-yq^2. \end{aligned} \tag{17.3}$$

Here $\omega - m$ represents the supplier's existing margin, cq is the supplier's additional unit cost of quality, and yq^2 is the supplier's investment cost to build quality, q. We model the investment cost as a quadratic function. Thus, our assumption is that the effort to improve environmental quality has diminishing returns (see Savaskan and Wassenhove 2006, p. 242).

For the *cost-sharing dynamic* (CS) the buyer shares the supplier's investment cost to build quality, yq^2, in order to improve her environmental quality level. Specifically, the buyer's profit function is

$$\pi^B_{CS} = (K-ap+dq)[(p-\omega)-r]-(1-\gamma)yq^2,$$

with $0 \le \gamma < 1$ and $1-\gamma$ representing the portion of the supplier's investment cost the buyer is willing to incur. If $\gamma = 1$, then the model setup for cost sharing and the base case are identical. The supplier's profit function is given by

$$\Pi^S_{CS} = (K-ap+dq)[(\omega-m)+(r-cq)]-\gamma yq^2.$$

Under cost sharing, the change to the base case sequence of events is that the buyer determines the portion of the supplier's investment cost that he is willing to share, $1-\gamma$, before determining the per-unit premium that he is willing to pay the supplier.

For the *quality competition dynamic* (C), a second supplier is introduced to the base case. The supplier is identical to the existing supplier except that her process to produce a higher-quality product is more costly than the existing supplier. To capture this difference, we define her unit cost factor as $\bar{c}$ with $\bar{c} > c$. We model the supplier competition similar to Jiang and Wang (2010) in that (1) we consider the suppliers' cost difference, $\bar{c}-c$, as the measure of competitive intensity, with the competition strengthening as the difference decreases and (2) the competitor is only used to incentivize the existing supplier to increase her effort. Therefore, our focus is not on which supplier wins the competition, but, instead, on how the threat of competition impacts the existing supplier's quality decision.

Supplier 2's profit function is given by

$$\Pi_C^{S_2} = (K - ap + dq_2)[(\omega - m) + (r - \bar{c}q_2)] - yq_2^2. \qquad (17.4)$$

The base case sequence of events change as follows under competition. After the buyer determines the premium that he is willing to offer, the two suppliers compete in a static game of complete information; i.e., they make their quality proposals simultaneously without observing the other's action. Supplier i's strategy is to set environmental quality level q_i. After the two suppliers compete, the buyer then sources from the supplier with the maximum quality level. Since the existing supplier always wins the competition, Eq. (17.4) represents supplier 2's *potential* profit.

To simplify notation, we define $\theta \equiv K - ap$, $\hat{p} \equiv p - \omega$ (buyer's existing margin), and $\hat{\omega} \equiv \omega - m$ (supplier's existing margin). To clearly show how the division of the supply chain margin between the buyer and the supplier impacts our results, in our numerical examples we fix the total supply chain margin to 1; i.e., $p = 1$ and $m = 0$. Hereafter, any references to the buyer's or the supplier's margins are with respect to their existing margins, $\hat{p}$ and $\hat{\omega}$, before a premium or quality investment is made. Any references to the buyer's choice of premium or the supplier's choice of quality are with respect to equilibrium levels unless stated otherwise. For comparison, we define the *do-nothing case (DN)* as when both the buyer and the supplier do not invest; i.e., $r = 0$ and $q = 0$.

17.4.2 Buyer's Perspective

Next, we examine the levers available to the buyer for improving the supplier's quality. First, we compare the buyer's premium decision and the supplier's quality decision under the base case and supplier competition. Second, we examine when opportunities exist for the buyer to share costs to improve the supplier's quality.

17.4.2.1 Base Case and Supplier Competition

Figure 17.1 illustrates the supplier's quality levels for the base case, q_{BC}^*, and supplier competition, q_C^*, with respect to her margin, $\hat{\omega}$. To show how consumer demand can influence quality, we consider cases for both a low (Fig. 17.1a) and a high (Fig. 17.1b) consumer environmental quality awareness, d. To provide a frame of reference, we include the optimal quality level for the centralized solution, q_{Cent}^*.

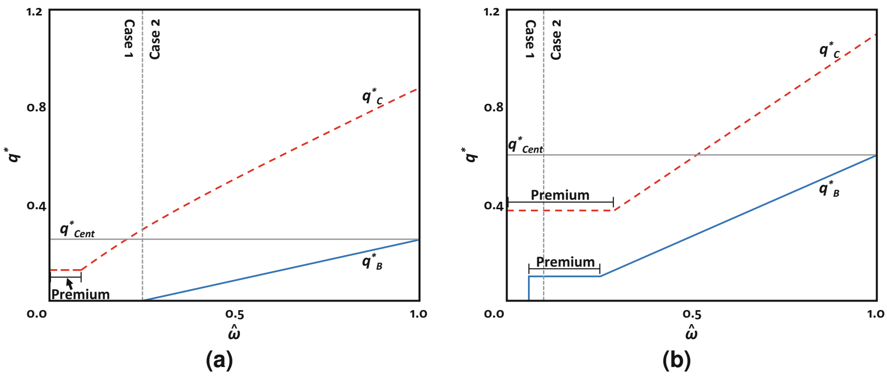

Fig. 17.1 Environmental quality (q^*) with respect to the supplier's existing margin ($\hat{\omega}$): base case and supplier competition. (Note: The following values were used to generate this figure, $K = 1.00$, $a = 0.60$, $p = 1.00$, $y = 0.50$, $c = 0.25$, and $\bar{c} = 0.55$, $d = 0.4$ (**a**), and $d = 1.0$ (**b**). The cases represent when the supplier does (Case 1) and does not (Case 2) require a premium to invest in environmental quality under the base case)

First, we analyze the buyer's use of a premium and the supplier's need for a premium under the base case and supplier competition. By providing a premium, the buyer can offset the supplier's unit cost of quality. We find that when the buyer provides a premium, the supplier's quality level, q^*, remains constant in her margin, $\hat{\omega}$, while the size of the buyer's premium, r^*, is decreasing in $\hat{\omega}$. Graphically this implies that the buyer offers the supplier a premium for any range of the supplier's margin in which $q^* > 0$ and constant in $\hat{\omega}$ (see Fig. 17.1).

For the base case, whether the supplier requires a premium to invest in quality depends on the tradeoff between the relative market awareness of quality (i.e., d/θ) and the supplier's unit cost impact of quality (i.e., $c/\hat{\omega}$). If $d/\theta < c/\hat{\omega}$ (i.e., Case 1 in Fig. 17.1), then the supplier does not invest in quality unless the buyer offers her a premium to increase her margin. This occurs whenever the supplier's margin and/or consumers' awareness to quality are low. Conversely, if $d/\theta \geq c/\hat{\omega}$ (i.e., Case 2 in Fig. 17.1), then the supplier always invests in quality, even if the buyer does not offer her a premium. When suppliers compete, the supplier does not require a premium to invest in quality. As long as the buyer introduces a comparable second supplier (i.e., the second supplier's unit cost, $\bar{c}$, is not too high), the existing supplier is forced to compete and $q^*_C > 0$.[6]

When deciding whether or not to offer a premium, the buyer faces a trade-off between a potential market opportunity and reducing his margin. First,

[6] For extreme cases, supplier competition may not always increase quality. Specifically, if there is a large difference between $\bar{c}$ and c, then cases may occur in which competition does not influence the existing supplier's quality performance. To ensure that competition produces nontrivial results, we assume throughout our analysis that $d(2c - \bar{c}) + y \geq 0$.

consider the base case and Case 1, when the supplier does not invest in quality unless the buyer offers a premium. Although the supplier's margin is low under Case 1, this does not guarantee that the buyer will offer her a premium. We find that as the supplier's margin, $\hat{\omega}$, decreases, the size of the premium, r^*_{BC}, that the buyer must offer the supplier to incentivize her to invest in quality is increasing. Hence, when the supplier's margin is very low, there can be a misalignment of incentives as the buyer may not find it profitable to support the supplier when she needs it most and as shown in Fig. 17.1, $q^*_{BC} = 0$.

Second, consider Case 2, when the supplier invests in quality with or without a premium from the buyer. For this case, the buyer weighs further encouraging investment versus leaving the supplier to invest on her own. The conditions under which the buyer and the supplier invest are misaligned. The supplier's willingness to invest in quality is increasing in $\hat{\omega}$ but the buyer is more likely to offer a premium when his own share of the supply chain margin, $1 - \hat{\omega}$, increases. While the buyer may find it profitable to further encourage the supplier with a premium, his willingness to invest is limited to cases in which his margin is sufficiently larger than the supplier's and a market opportunity exists (i.e., d is high). Therefore, as shown in Fig. 17.1, the buyer offers the supplier a premium only when $\hat{\omega}$ is low under Case 2.

Under supplier competition, although $q^*_C > 0$ always holds, the buyer may still offer the supplier a premium to encourage further investment. However, similar to the base case, he only does so when his margin is sufficiently larger than the supplier's and a market opportunity exists (i.e., d is high).

Finally, we examine how the supplier's quality level changes with respect to model parameters. As shown in Fig. 17.1, the supplier's quality is nondecreasing in both her margin and consumers' environmental quality awareness. First, consider the base case. The gap between q^*_{Cent} and q^*_{BC} (see Fig. 17.1) represents the double marginalization effect and the resulting inefficiency that can occur when a buyer and a supplier make decentralized decisions. When the buyer captures the majority of the supply chain margin (i.e., $\hat{\omega}$ is low), the inefficiency is exacerbated. The buyer, as the downstream partner, prefers not to help a low-margin supplier if it is too costly for him to entice her to invest. The double marginalization effect begins to dissipate as the supplier's margin increases. When $\hat{\omega}$ is high, the supplier acts as if she is the single decision maker in the supply chain. Consequently, the supplier's environmental quality level is increasing in her share of the supply chain margin.

When we compare supplier competition to the base case, we find that the additional buyer-supplier dynamic always produces a higher quality than the base case. While a quality level greater than the centralized solution is not achievable under the base case, it is under competition when the supplier has a high margin. As $\hat{\omega}$ increases, the supplier has more flexibility to increase her unit cost to improve quality. Competition forces her to deplete her margin in order to produce a high q^*_C and retain the buyer as a customer. Note, however, that cases in which $q^*_C > q^*_{\text{Cent}}$ do not necessarily benefit the financial health of the supply chain. Instead, the supply chain profit is maximized when the supplier's quality level is equal to the centralized quality level. Our focus in Sect. 17.4.2 is on how to increase environmental quality; in Sect. 17.4.3 we address the impact that cost sharing and competition can have on the buyer's and the supplier's profits.

17.4.2.2 Cost Sharing

Next, we examine the buyer's and the supplier's decisions under cost sharing. Recall that under cost sharing, the buyer shares portion $1-\gamma$ of the supplier's investment cost to build quality (i.e., yq^2) and he determines γ before deciding the per-unit premium that he is willing to offer the supplier. Figure 17.2 adds to Fig. 17.1b the buyer's choice of γ^* and the resulting cost-sharing quality level, $q^*_{CS}(\gamma^*)$. Similar to the base case and supplier competition, under cost sharing, we find that when the buyer offers the supplier a premium, her quality, $q^*_{CS}(\gamma^*)$, remains constant in her margin, $\hat{\omega}$, while the size of r^*_{CS} is decreasing in $\hat{\omega}$.

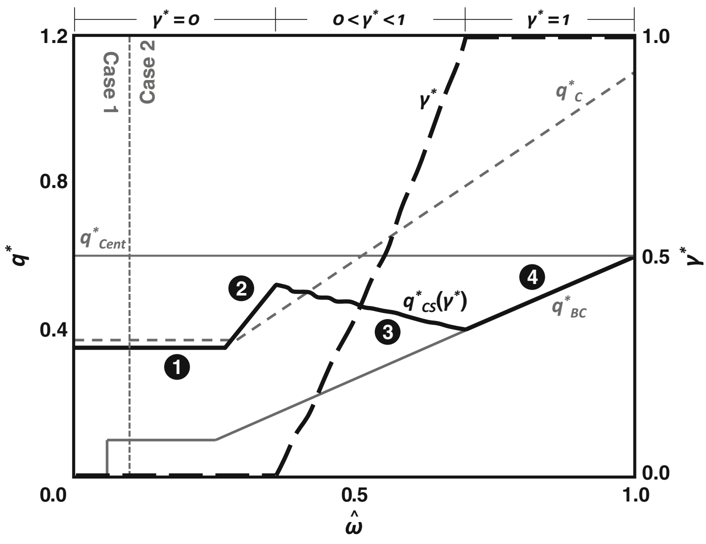

Fig. 17.2 Environmental quality (q^*) with respect to the supplier's existing margin ($\hat{\omega}$): cost sharing. (Note: This figure adds the buyer's choice of γ^* and the supplier's quality level $q^*_{CS}(\gamma^*)$ to Fig. 17.1b)

The supplier's need for a premium and the buyer's use of a premium under the base case and cost sharing are similar. The key difference is the extent to which the buyer is willing to utilize a premium under cost sharing. As shown in Fig. 17.2, the buyer is willing to offer the supplier a premium for a lower

$\hat{\omega}$ under cost sharing than under the base case. This result highlights the potential benefits a buyer can incur by developing his supplier's capabilities. By sharing costs, the buyer reduces the supplier's investment cost, increases her ability to generate a high quality level, and, thus, increases the impact of his premium investment. Cost sharing helps the buyer discover opportunities to increase demand with a low-margin supplier that do not exist under the base case.

Intuition would suggest that the buyer should use cost sharing and the premium as substitutes for one another. However, we find that when the supplier's margin is low and a market opportunity exists, the buyer's profit-maximizing strategy is to instead use them in a complementary manner. First, consider Case 1. Although not shown in Fig. 17.2, consistent with our findings for the base case, we find that when $\hat{\omega}$ and d are very low, the size of the premium the buyer must offer the supplier to incentivize her to invest in quality is very high. Therefore, he does not offer a premium and, similarly, he does not subsidize the supplier's investment cost; i.e., $\gamma^* = 1$. As a result, the supplier does not invest in quality; i.e., $q^*_{CS}(\gamma^*) = 0$. Interestingly, for higher values of either $\hat{\omega}$ or d (under Case 1), if the buyer is willing to offer the supplier a premium, then the buyer's optimal strategy is to fully subsidize the supplier's investment cost with $\gamma^* = 0$. By fully assuming the supplier's investment cost, the buyer increases the effectiveness of his premium investment in the supplier and, thus, the supplier's quality level.

The buyer's optimal cost-sharing investment is less straightforward under Case 2. The buyer's premium strategy depends on the cost-sharing investment cost, γ. In addition, the buyer's profit is decreasing in γ when he offers a premium but is unimodal in γ when he does not offer a premium. Therefore, under Case 2, the buyer's optimal cost-sharing investment may be to fully (i.e., $\gamma^* = 0$), partially (i.e., $0 < \gamma^* < 1$), or not (i.e., $\gamma^* = 1$) subsidize the supplier's quality investment, potentially coupled with a premium or no premium offered to the supplier. Consider the four ranges of the supplier's margin, $\hat{\omega}$, labeled in Fig. 17.2 for Case 2. (1) For low $\hat{\omega}$ values, the buyer continues to fully subsidize the supplier's investment cost and to offer her a premium. (2) As the supplier's margin increases, however, the buyer no longer offers her a premium. Still, the supplier's higher margin (relative to the previous case) along with $\gamma^* = 0$ ensure that $q^*_{CS}(\gamma^*)$ is nondecreasing in $\hat{\omega}$. (3) For higher values of $\hat{\omega}$, the supplier's larger margin causes the buyer to decrease his portion of the shared investment cost; i.e., γ^* is increasing in $\hat{\omega}$. As a result, $q^*_{CS}(\gamma^*)$ is nonincreasing in $\hat{\omega}$. (4) Finally, when $\hat{\omega}$ is very high, the supplier captures most of the supply chain margin and thus, the buyer does not subsidize her investment cost as $\gamma^* = 1$ and $q^*_{CS}(\gamma^*) = q^*_{BC}$.

The quality level under cost sharing is never greater than the centralized solution as the buyer sets γ^* and the premium to maximize his profit, not necessarily quality. Furthermore, we find that only when $\hat{\omega}$ is low and $q^*_{CS}(\gamma^*)$ is increasing in $\hat{\omega}$ do select cases in which $q^*_{CS}(\gamma^*) > q^*_C$ occur.[7]

[7] For 8.0 % of a sample of 868,660 cases tested, $q^*_{CS}(\gamma^*) > q^*_C$. For these cases, $\bar{c}/c$ and d/θ are both high and the median $\hat{\omega} = 0.21$.

17.4.3 GreenBlue's Perspective

Next, we develop insights into when and how GreenBlue should promote the use of MiQ. To formulate GreenBlue's strategy, we cannot focus solely on environmental quality. Instead, since we classify GreenBlue as a pragmatic nonprofit, we also must consider the buyer's and the supplier's profits. Figure 17.3 illustrates the median buyer profit, supplier profit, and environmental quality for each dynamic. Notice that while supplier competition can induce a high median quality level, large potential differences in median profits may occur between the buyer and the supplier. Since competition forces the existing supplier to reduce her margin to generate a high quality, it also produces the lowest supplier profit. This suggests that while recommending MiQ as a tool to create competition between suppliers may help to improve quality, this often may not be a feasible strategy for GreenBlue, which is also concerned with buyers' and suppliers' financial health.

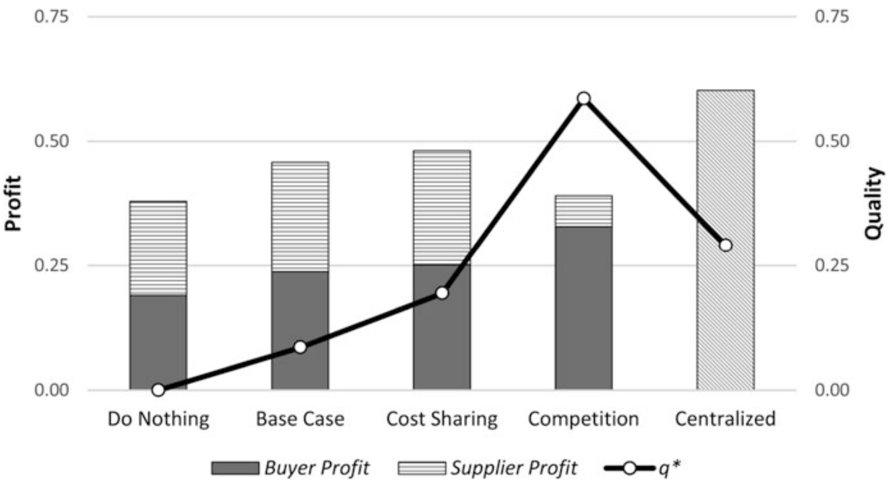

Fig. 17.3 Median buyer profit, supplier profit, and environmental quality (Note: For each dynamic, the median values of 868,660 cases tested are presented)

To analyze GreenBlue's strategy, we first define GreenBlue's objective function. GreenBlue is a pragmatic nonprofit that prefers to work with buyers to solve environmental problems. Therefore, although GreenBlue's objective as an activist is to improve the environmental quality of products, it will only do so if the buyer and the supplier do not incur losses in profits. To determine when and how GreenBlue should promote the use of MiQ, we define GreenBlue's objective function as the maximum quality level between the potential buyer-supplier dynamics. We add constraints to our model to ensure that both the buyer and the supplier earn profits greater than or equal to their profits under the do-nothing case. If under the parameter set tested, either the buyer or the supplier earns a profit for a dynamic less than their profit for the do-nothing case, then we consider that dynamic infeasible. If instead the constraints hold and quality is maximized under either the base case, competition, or cost sharing, then an opportunity exists for GreenBlue to promote the buyer's use of MiQ with the quality-maximizing dynamic.

We define GreenBlue's optimization problem as follows.

$$\begin{aligned} \max_{D\in\{BC,C,CS\}} \quad & z_D \\ \text{s.t.} \quad \pi_D^B(r_D^*, q_D^*) &\geq \pi_{BC}^B(r=0, q=0)x_D \\ \varPi_D^S(r_D^*, q_D^*) &\geq \varPi_{BC}^S(r=0, q=0)x_D \\ q_D^* x_D &\geq z_D \\ x_D \in \{0,1\} \ \& \ z_D &\geq 0 \end{aligned}$$

Figure 17.4 illustrates GreenBlue's quality-maximizing strategy when we compare the performance of each dynamic with respect to the supplier's margin, $\hat{\omega}$, and the relative market awareness of environmental quality, d/θ. Comparing $\hat{\omega}$ with respect to d/θ helps us show how GreenBlue's strategy changes as both the supplier's influence and consumers' sensitivity to quality change. To present a complete picture, we delineate when the buyer does or does not offer the supplier a premium.

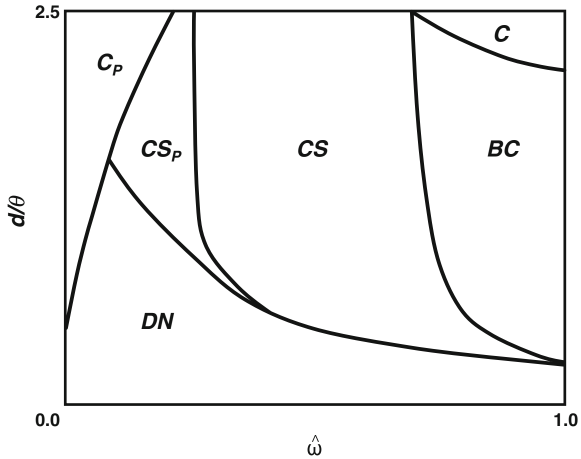

Fig. 17.4 GreenBlue's equilibrium strategy with respect to the relative market awareness of environmental quality (d/θ) and the supplier's existing margin ($\hat{\omega}$). (Note: The values used to generate this figure are identical to those used for Fig. 17.2 but with d taking values from $[0.00, 1.00]$. The abbreviations represent Base Case (BC), Cost Sharing with (CS_P) and without (CS) a premium, Competition with (C_P) and without (C) a premium, and Do Nothing (DN))

As shown in Fig. 17.4, promoting MiQ as a platform for creating competition between suppliers is GreenBlue's preferred strategy only when the relative market awareness of quality is very high and there exists a dominant entity in the supply chain. For these cases, the existing supplier does not incur a loss in profit due to competition since d/θ is high. When the buyer captures most of the supply chain margin (i.e., $\hat{\omega}$ is very low), the buyer offers a premium to offset the supplier's unit cost of quality. When instead, the supplier captures most of the supply chain margin (i.e., $\hat{\omega}$ is very high), the supplier acts as if she is the single decision maker in the supply chain and her incentive to improve quality and, thus, demand increases. Therefore, the buyer does not offer a premium.

For a wide range of $\hat{\omega}$ values, GreenBlue's preferred strategy is to encourage the buyer to share costs with his existing supplier and create an incentive for her to invest in quality. Although cost sharing can increase environmental quality while ensuring that the buyer and the supplier do not lose profits, it typically does not generate a higher environmental quality than supplier competition. For example, numerically we find that for cases in which GreenBlue's preferred strategy is cost sharing, the supplier's median quality level is 0.25 for cost sharing and 0.28 for cost sharing with a premium. For these same cases, median quality levels of 0.58 and 0.39 are achievable under supplier competition. However, competition is an infeasible strategy for these cases since the supplier incurs profits less than she would under the do-nothing case. Furthermore, alignment between GreenBlue's objective to maximize quality and the buyer's objective to maximize his profit rarely occurs under cost sharing. Only when d/θ is very high and the supplier's margin is low (in the CS region) do we find that cost sharing maximizes both quality and the buyer's profits. In contrast, when supplier competition is GreenBlue's preferred strategy, it always aligns GreenBlue's and the buyer's objectives.

When the supplier's margin is very high, cost sharing is not an effective strategy since the buyer is unwilling to share costs due to the supplier capturing most of the supply chain margin. As previously shown in Fig. 17.2, the buyer sets $\gamma^* = 1$, and as a result, $q^*_{CS}(\gamma^*) = q^*_{BC}$. Supplier competition can be an effective strategy, but only when there exists a market opportunity (i.e., d/θ is high) that helps the supplier offset her cost due to competition. Instead, for a majority of the cases, GreenBlue's preferred strategy when $\hat{\omega}$ is high is to recommend the base case (without a premium) and let the existing market incentives drive the supplier's quality decision and use of MiQ. Finally, if both the supplier's margin and the relative market awareness of quality are low, then GreenBlue's strategy is to not promote MiQ; i.e., the do-nothing case. Under these conditions, GreenBlue cannot influence quality since competition decreases the supplier's profits, and investments made by the buyer or the supplier under the base case or cost sharing decrease their profits.

17.4.4 Model Summary

We find that the buyer can use cost sharing and competition to improve the supplier's quality, but with some limitations. For example, under *cost sharing*, intuition would suggest that the buyer should use the shared investment cost and the premium as substitutes for one another. However, if the buyer captures more of the supply chain margin than the supplier and a market opportunity exists, then his optimal strategy is often to offer the supplier a premium *and* fully subsidize her investment cost in quality. By aggressively investing in the supplier, the buyer develops her capabilities, and as a result, increases the effectiveness of the premium he offers. Cost sharing is less effective as the supplier's margin increases—the buyer's strategy is either to decrease his portion of the shared investment cost or, if the supplier captures a larger portion of the supply chain margin, to not share costs. Conversely, under *supplier competition*, the supplier's quality level is nondecreasing in her portion of the supply chain margin and, in general, higher than her quality level under cost sharing. When existing incentives are in place such that the supplier is willing to invest on her own in quality and the buyer does not find it beneficial to offer a premium, cases can even occur in which her quality level is higher under competition than the centralized solution.[8] The key risk to competition is the negative impact that it can have on suppliers' margins and, thus, financial health.

As a nonprofit, GreenBlue is in a unique position in that it has an opportunity to influence the dynamic between buyers and suppliers with MiQ. Recommending MiQ as a platform for creating competition between suppliers is rarely feasible since competition often hurts suppliers' profits. Instead, we find that GreenBlue should focus on the more modest improvements that can occur when buyers and suppliers work together in a collaborative relationship. For example, if the buyer captures enough of the supply chain margin such that he is willing to share costs with the supplier, then GreenBlue should recommend the buyer use MiQ as a tool for collaborating with an existing supplier to improve quality. Conversely, if the buyer is unwilling to share costs with the supplier due to her high margin, then GreenBlue should not recommend a new buyer-supplier dynamic, but instead let the existing market incentives drive the supplier's quality decision and use of MiQ.

---

[8] We emphasize that for all three dynamics, it is never optimal for the buyer to use a premium to induce the supplier to produce a quality level greater than the centralized solution. Either the size of the premium needed is too large or the supplier captures too much of the supply chain margin for the buyer to financially justify offering a premium to achieve a quality level that high.

17.5 Future Research Directions

As part of our work with GreenBlue, we conducted an industry survey to better understand the environmental performance and practices of companies. In particular, we were interested in identifying ways to improve the transparency of the chemicals and substances used in supply chains. A total of 45 companies participated in the survey, 28 of which were public. In general, the companies surveyed were large, with 29 of them having revenues in 2013 greater than $1 billion (U.S.). The participating companies represented a wide range of industries, with the two largest groups being Chemicals (14) and Furniture (5). On average, participants taking the survey had been with their company for 15.9 years, had 13.7 years of experience in an operational role, and had 11.4 years of experience in an environmental role. Based on our survey results, we highlight three potential future research topics with respect to chemicals management and sustainable supply chains.

Barriers to Improved Transparency Figure 17.5 lists the top four barriers to improved transparency in supply chains according to our survey participants. As shown, intellectual property, product complexity, and supplier resources are critical barriers. Furthermore, intellectual property and product complexity were listed as top barriers for upstream suppliers, public companies, and global companies (i.e., greater than 50 % of sales occurring outside of the U.S.). These concerns highlight the need for tools, such as MiQ, that are specifically designed to help suppliers safely share complex and potentially sensitive data with customers, in a standardized method. From a research perspective, they also illustrate how the quality and safety of information is a critical aspect to consider when studying environmental issues in supply chain management. Examining a buyer's alternatives for improving the information asymmetry that may exist between himself and suppliers regarding environmental issues could provide valuable insights.

Chemicals-Management Practices of Small, Private Suppliers Figure 17.5 also lists suppliers' lack of resources as a concern for improved transparency. As noted by James Ewell, "small suppliers are at a distinct disadvantage when it comes to chemical management and chemical transparency initiatives. Commonly, they lack the resources required to manage the processes that are required to be responsive to their customers" (Ewell 2014). Our findings illustrate the hurdles that small, private suppliers face in improving their environmental performance. For example, we define a company's use of a Restricted Substances List (RSL)[9] as a proxy, representative of whether a company follows good chemicals-management practices. Although 60 % of participants use RSLs, our results suggest that small, private suppliers are less likely to use them. We find that public companies are 5.2 times more likely to

[9] A Restricted Substances List is a voluntary list a company creates and publishes to either prevent or restrict the use of nonregulated substances and chemicals in its supply chain.

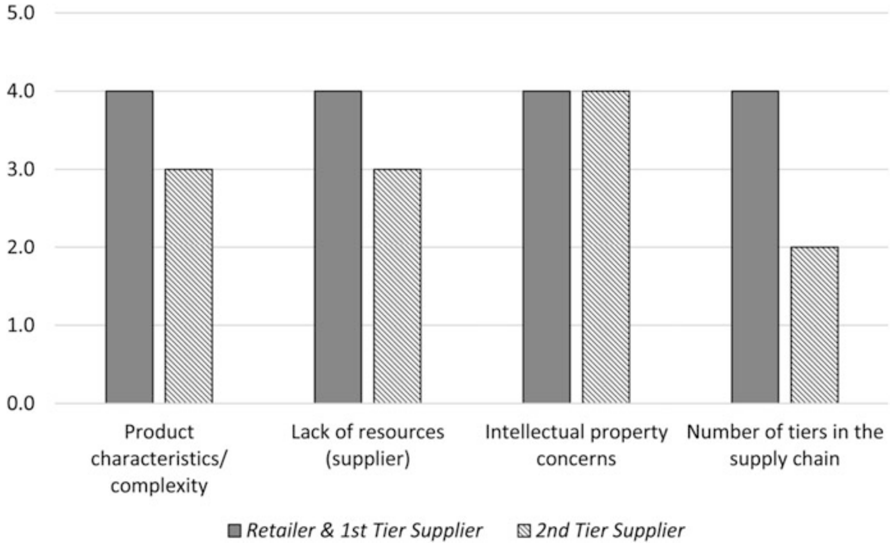

Fig. 17.5 Barriers to improved transparency. (Note: Median values for the top 4 of 16 possible responses are shown. A value of 5.0 (1.0) represents "Strongly Agree" ("Strongly Disagree"). A total of 26 retailer/first-tier suppliers and 19 second-tier suppliers were surveyed)

use RSLs than private companies. In addition, 72.4 % (37.5 %) of companies with 2013 revenues greater (less) than $1B were found to use RSLs and 65.4 % (52.6 %) of retailers/first-tier suppliers (second-tier suppliers) were found to use them.[10]

Investigating how a supplier's lack of resources limits her ability to improve her environmental performance would be a valuable extension to the model presented in Sect. 17.4. Another interesting topic would be to examine how the public versus private status of a company impacts its environmental performance; specifically, focusing on the impact that different stakeholders can have on a company's decisions.

The Influence of Regulation on Collaboration Industries are increasingly collaborating to improve their sustainability performance. For example, the members of the Business and Institutional Furniture Manufacturers Association (BIFMA) recently implemented new, self-imposed standards on sustainability issues. These included strict regulation on the chemicals and substances used in products within the industry (BIFMA 2014). Similarly, competitors Target and Walmart are working together to encourage cosmetic suppliers to be more transparent regarding the chemicals they put into their

[10] Results regarding public versus private companies were found using a logistic regression model. Surveyed participants included 29 (16) companies with 2013 revenues greater (less) than $1B; 26 retailer/first-tier suppliers and 19 second-tier suppliers.

products (Kumar 2014). Despite this, Nidumolu et al. (2014) state that "when it comes to developing collaborative solutions to systematic [environmental] problems, very little progress has been made," even though there is a "growing awareness of the critical need for improved collaboration" (pp. 77–78). Too often, efforts have failed due in large part to competitive self-interests and a lack of shared purpose between collaborators.

Our survey results suggest that a potentially interesting topic of study is the intersection between regulatory requirements and industry collaborations. We find that companies are more likely to be part of an industry-wide chemical composition information-sharing program when there exists a higher threat of regulatory costs. The degree of sharing, however, is not dependent on the company's position (i.e., tier) in the supply chain.[11] Collaboration primarily occurs between large companies: only 1 out of 16 companies with 2013 revenues less than $1 billion (U.S.) was found to participate in an information-sharing program; 13 out of 29 companies with 2013 revenues greater than $1 billion participated in a program.

Note that a higher threat of regulation was also found to be associated with more concentrated markets; i.e., fewer companies capturing a larger portion of the total market share. As regulations with respect to chemicals usage and monitoring continue to strengthen, particularly here in the United States, this finding has potential competitive implications. Stronger regulation will put even more pressure on small, private suppliers to improve their practices, making it difficult for them to meet industry requirements. An analogous situation occurred in the 1990s, when strict regulations for nutrition labels were put into effect. The cost of complying with these regulations pushed a number of smaller companies, who lacked the resources to compete, out of business (Moorman et al. 2005). Our survey results suggest that GreenBlue may face a similar situation as it promotes the use of MiQ.

17.6 Conclusion

We hope that this overview has informed the reader of some of the challenges that companies face when managing chemicals in their supply chains. From an academic perspective, this is a rich field of study. In particular, the regulatory and scientific uncertainty surrounding chemical usage, as well as intellectual property concerns between supply chain partners, all lend themselves to a number of interesting potential research topics. These problems can then take the perspective of a number of different stakeholders, including companies, regulators, nonprofits, or consumers.

[11] These results were found using a logistic regression model.

Acknowledgements The authors thank James Ewell, Minal Mistry (GreenBlue), and Joseph Donlan (University of Virginia) for their helpful contributions to this chapter; Atalay Atasu, Basak Kalkanci, Beril Toktay, and the participants at the 2015 Sustainable Operations Workshop (Georgia Institute of Technology) for their constructive feedback; and Mirko Janc (INFORMS) for his editorial support and helpful feedback.

References

Agrawal V, Lee D (2015) The effect of sourcing policies on a supplier's sustainable practices. Working paper, Georgetown University, Washington, DC

Babich V (2006) Vulnerable options in supply chains: Effects of supplier competition. Naval Res Logist 53:656–673

Babich V (2010) Independence of capacity ordering and financial subsidies to risky suppliers. Manufact Service Oper Manag 12(4):583–607

Babich V, Burnetas A, Ritchken P (2007) Competition and diversification effects in supply chains with supplier default risk. Manufact Service Oper Manag 9(2):123–146

Baiman S, Fischer P, Rajan M (2000) Information, contracting, and quality costs. Manag Sci 46(6):776–789

Banker R, Khosla I, Sinha K (1998) Quality and competition. Manag Sci 44(9):1179–1192

Baron D (2001) Private politics, corporate social responsibility, and integrated strategy. J Econ Manag Strateg 10(1):7–45

Baron D, Diermeier D (2007) Strategic activism and nonmarket strategy. J Econ Manag Strateg 16(3):599–634

Berenguer G, Righter A, Shen M (2014) Challenges and strategies in managing nonprofit operations: an OR/MS perspective. Working paper, Purdue University, West Lafayette, IN

Bianco L, Caramia M, Giordani S, Piccialli V (2015) A game-theoretic approach for regulating Hazmat transportation. Transp Sci. doi:10.1287/trsc.2015.0592

BIFMA (2014) ANSI/BIFMA e3 furniture sustainability standard and tools. www.bifma.org. Accessed 8 Jan 2015

Bilbrey J (2014) BPA-free plastic containers may be just as hazardous. ScientificAmerican.com (Aug 11). Accessed 10 Jan 2015

Brody J (1983) Personal health: judging safety of aspartame in soft drinks. NYTimes.com (July 13). Accessed 21 Apr 2008

Cachon G, Zhang F (2007) Obtaining fast service in a queueing system via performance-based allocation of demand. Manag Sci 53(3):408–420

Callahan P, Roe S (2012) Fear fans flames for chemical makers. ChicagoTribune.com (May 6). Accessed 6 May 2012

Calveras A, Ganuza J, Llobet G (2007) Regulation, corporate social responsibility and activism. J Econ Manag Strateg 16(3):719–740

Carbone J (2008) RoHS cost: $32 billion and counting. Purchasing.com (June 12). Accessed 21 Sept 2009

Carotenuto P, Giordani S, Ricciardelli S (2007) Finding minimum and equitable risk routes for Hazmat shipments. Comput Oper Res 34(5):1304–1327

Chao G, Iravani S, Savaskan R (2009) Quality improvement incentives and product recall cost sharing contracts. Manag Sci 55(7):1122–1138

ChemSec (2009) Dell: The SIN List provides advance warning of restrictions to come. www.chemsec.org (Oct 15). Accessed 2 Oct 2010

Conner A, Epstein K (2007) Harnessing purity and pragmatism. Stanf Soc Innov Rev (Fall):61–65

Consumers Union (1999) Baby alert: new findings about plastics. Consum Rep (May):28–29

Corbett C, DeCroix G (2001) Shared-savings contracts for indirect materials in supply chains: channel profits and environmental impacts. Manag Sci 47(7):881–893

Dale-Harris L (2014) Calls to ban toxic chemicals fall on deaf ears around the world. Newsweek.com (Oct 30), Accessed 8 Jan 2014

Deng S, Elmaghraby W (2005) Supplier selection via tournaments. Prod Oper Manag 14(2):252–267

DeVericourt F, Lobo M (2009) Resource and revenue management in nonprofit operations. Oper Res 57(5):1114–1128

Dowie M (1996) Losing ground. The MIT Press, Cambridge, MA

Elahi E, Benjaafar S, Donohue K (2007) Outsourcing via service competition. Manag Sci 53(2):241–259

Environmental Defense Fund (2015) Chemicals policy reform. www.edf.org. Accessed 8 Jan 2015

Erkut E, Verter V (1998) Modeling of transport risk for hazardous materials. Oper Res 46(5):625–642

Erkut E, Tjandra S, Verter V (2007) Hazardous materials transportation, Chap 9 In: Barnhart C, Laporte G (eds) Transportation. Handbooks in Operations Research and Management Science, vol 14. Elsevier, Amsterdam, pp 539–621

European Commission (2013) Top 10 most burdensome EU laws for small and medium-sized enterprises: how the commission is helping SMEs. Europa.eu (Mar 7). Accessed 10 Jan 2015

Ewell J (2014) Interview by the authors. Sustainable Materials Director, GreenBlue (Feb 3)

Federgruen A, Yang N (2009) Competition under generalized attraction models: applications to quality competition under yield uncertainty. Manag Sci 55(12):2028–2043

Friedl G, Wagner S (2012) Supplier development or supplier switching? Int J Prod Res 50(11):3066–3079

Gans N (2002) Customer loyalty and supplier quality competition. Manag Sci 48(2):207–221

Guo R, Lee H, Swinney R (2015) Responsible sourcing in supply chains. Forthcoming in Management Science

Ha A, Li L, Ng S (2003) Price and delivery logistics competition in a supply chain. Manag Sci 49(9):1139–1153

Halliday J (2008) Gap is closing on Aspartame's lead over Sucralose: Mintel data. www.foodnavigator.com (July 24). Accessed 18 Feb 2010

Hamblin J (2014) The toxins that threaten our brains. TheAtlantic.com (Mar 8). Accessed 8 Jan 2015

Harrison T, Lybecker K (2005) The effect of the nonprofit motive on hospital competitive behavior. Contrib Econ Anal Policy 4(1):1–15

Hendrikse G, Letizia P (2015) Incentives for corporate social responsibility: The role of supply chain structure. Working paper, Erasmus University, Rotterdam, The Netherlands

Hyatt D, Spicer A (2012) Walmart's sustainability journey: defining sustainable products (A). sustainabilitycases.kenexcloud.org (Dec 4). Accessed 12 Oct 2013

Jiang L, Wang Y (2010) Supplier competition in decentralized assembly systems with price-sensitive and uncertain demand. Manufact Service Oper Manag 12(1):93–101

Kara B, Verter V (2004) Designing a road network for hazardous materials transportation. Transp Sci 38(2):188–196

Karaer Ö, Erhun F (2015) Quality and entry deterrence. Eur J Oper Res 240(1):292–303

Karaer Ö, Kraft T, Khawam J (2015) Buyer and nonprofit levers to improve suppliers' environmental performance. Working paper, Middle East Technical University, Ankara, Turkey

Karmarkar U, Pitbladdo R (1997) Quality, class, and competition. Manag Sci 43(1):27–39

Kary T (2014) Colgate Total ingredient linked to hormones, cancer spotlights FDA process. Bloomberg.com (Aug 11). Accessed 14 Aug 2014

Kaya M, Özer Ö (2009) Quality risk in outsourcing: noncontractible quality and private quality cost information. Naval Res Logist 56:669–685

Kim S, Netessine S (2013) Collaborative cost reduction and component procurement under information asymmetry. Manag Sci 59(1):189–206

King A, Lenox M (2000) Industry self-regulation without sanctions: The chemical industry's responsible care program. Acad Manag J 43(4):698–716

King A, Lenox M (2001) Lean and green? An empirical examination of the relationship between lean production and environmental performance. Prod Oper Manag 10(3):244–256

Koch W (2013) Walmart announces phase-out of hazardous chemicals. USAToday.com (Sept 12). Accessed 13 Sept 2013

Koch W (2014) Fatal chemicals accidents expose weak federal laws. USAToday.com (Jan 29). Accessed 8 Jan 2015

Kraft T, Erhun F, Carlson R, Rafinejad D (2013a) Replacement decisions for potentially hazardous substances. Prod Oper Manag 22(4):958–975

Kraft T, Zheng Y, Erhun F (2013b) The NGO's dilemma: How to influence firms to replace a potentially hazardous substance. Manufact Service Oper Manag 15(4):649–669

Kumar K (2014) Target, Walmart team up on sustainability. StarTribune.com (Sept 5). Accessed 11 Sept 2014

Laseter T, Stasior W (1998) Balanced sourcing: cooperation and competition in supplier relationships. Jossey-Bass Publishers, San Francisco, CA

Layton L (2009) No BPA for baby bottles in U.S. WashingtonPost.com (Mar 6). Accessed 14 Sept 2009

Layton L (2010) Law allows companies to hide risks of chemicals. WashingtonPost.com (Jan 4). Accessed 7 Aug 2013

Lenox M, Eesley C (2009) Private environmental activism and the selection and response of firm targets. J Econ Manag Strateg 18(1):45–73

Li C (2013) Sourcing for supplier effort and competition: design of the supply base and pricing mechanism. Manag Sci 59(6):1389–1406

Li C, Debo L (2009) Second sourcing vs. sole sourcing with capacity investment and asymmetric information. Manufact Service Oper Manag 11(3):448–470

Li H, Zhang H, Fine C (2013) Dynamic business share allocation in a supply chain with competing suppliers. Oper Res 61(2):280–297

Lien R, Iravani S, Smilowitz K (2014) Sequential resource allocation for nonprofit operations. Oper Res 62(2):301–317

Lim W (2001) Producer-supplier contracts with incomplete information. Manag Sci 47(5):709–715

Lin J (2013) South Korea REACH legislation signed into law; registration starts January 2015. BNA.com (May 24). Accessed 10 Jan 2015

Liu S, So K, Zhang F (2010) Effect of supply reliability in a retail setting with joint marketing and inventory decisions. Manufact Service Oper Manag 12(1):19–32

Mendoza A, Clemen R (2013) Outsourcing sustainability: a game-theoretic approach. Env Syst Decis 33(2):224–236

Moorman C, Du R, Mela C (2005) The effect of standardized information on firm survival and marketing strategies. Mark Sci 24(2):263–274

Moorthy K (1988) Product and price competition in a duopoly. Mark Sci 7(2):141–168

Moritz J (2014) U.S. trade deal might loosen Europe's chemical safety rules. MiamiHerald.com (Aug 16). Accessed 10 Jan 2015

Murray S (2010) Green chemistry: Companies see benefits of 'friendlier' formulas. FT.com (Oct 1). Accessed 10 Jan 2015

Nidumolu R, Ellison J, Whalen J, Billman E (2014) The collaboration imperative. Harv Bus Rev (April):76–84

Norman W, MacDonald C (2004) Getting to the bottom of "triple bottom line." Bus Ethics Quart 14(2):243–262

Plambeck E, Lee H, Yatsko P (2012) Improving environmental performance in your Chinese supply chain. MIT Sloan Manag Rev 53(2):43–52

Pous T (2012) 'Toxic threads' study finds high levels of dangerous chemicals in popular brands. Time.com (Nov 21). Accessed 12 Dec 2012

Privett N, Erhun F (2011) Efficient funding: Auditing in the nonprofit sector. Manufact Service Oper Manag 13(4):471–488

Rizzuto P (2013) TSCA reform bill seen as promising but road to enactment is uncertain. BNA.com (June 3). Accessed 6 Sept 2013

Rosenbloom S (2009) At Walmart, labeling to reflect green intent. NYTimes.com (July 15). Accessed 3 Aug 2013

Safer Chemicals Healthy Families (2010) The business case for comprehensive TSCA reform. SaferChemicals.org. Accessed 20 May 2011

Savaskan R, Wassenhove LV (2006) Reverse channel design: the case of competing retailers. Manag Sci 52(1):1–14

Schwartz M, Paul S (1992) Resource mobilization versus the mobilization of people: why consensus movements cannot be instruments of change. In: Morris A, McClurg C (eds) Frontiers in Social Movement Theory, Yale University Press, New Haven, CT, pp 205–223

Speth G (2008) Environmental failure: a case for a new green politics. e360.yale.edu (Oct 20). Accessed 21 May 2011

Steinberg R (1986) The revealed objective functions of nonprofit firms. The Rand J Econ 17(4):508–526

Talluri S, Narasimhan R, Chung W (2010) Manufacturer cooperation in supplier development under risk. Eur J Oper Res 207(1):165–173

Tang S, Kouvelis P (2011) Supplier diversification strategies in the presence of yield uncertainty and buyer competition. Manufact Service Oper Manag 13(4):439–451

Tavernise S (2012) F.D.A. makes it official: BPA can't be used in baby bottles and cups. NYTimes.com (July 17). Accessed 17 July 2012

The SIN List (2015) The SIN (Substitute It Now!) List. www.chemsec.org. Accessed 9 Jan 2015

Tsay A, Agrawal N (2000) Channel dynamics under price and service competition. Manufact Service Oper Manag 2(4):372–391

US Environmental Protection Agency (2014) TSCA chemical substance inventory. www.epa.gov. Accessed 7 Aug 2014

Wang Y, Gilland W, Tomlin B (2010) Mitigating supply risk: dual sourcing or process improvement? Manufact Service Oper Manag 12(3):489–510

Weisbrod B (1998) Modeling the nonprofit organization as a multiproduct firm: A framework for choice. In: Weisbrod B (ed) To profit or not to profit: the commercial transformation of the nonprofit sector, Cambridge University Press, Cambridge, pp 47–64

Westervelt A (2012) How international regulations are changing American supply chains. Forbes.com (May 12). Accessed 10 Jan 2015

Zhu K, Zhang R, Tsung F (2007) Pushing quality improvement along supply chains. Manag Sci 53(3):421–436

Chapter 18
Design Implications of Extended Producer Responsibility Legislation

Luyi Gui, Ximin (Natalie) Huang, Atalay Atasu, and L. Beril Toktay

Abstract Take-back legislation based on Extended Producer Responsibility (EPR) holds producers responsible for proper end-of-life treatment of their products. In addition to diverting waste products from landfills, EPR legislation has the potential advantage of incentivizing eco-design of products. However, evidence suggests that product design outcomes of EPR legislation can be significantly influenced by its implementation. In this chapter, we survey the research on this topic, focusing on design impacts associated with several key operational considerations in supply chains. We show that intended design incentives under EPR legislation may be weakened, muted, or even negated as a result of operational factors such as design trade-off, market competition, and recycling resource sharing. Accordingly, we develop insights as to how the design potential of EPR legislation may be realized.

18.1 Introduction

In recent years, product eco-designs (i.e., designs based on enhanced considerations of ecological impacts) have been highly emphasized as public awareness of environmental problems has grown. In particular, there is growing concern about electronic waste (e-waste) disposal, due to its exponentially

L. Gui (✉)
Paul Merage School of Business, University of California, Irvine, Irvine, CA, USA
e-mail: luyig@uci.edu

X. (Natalie) Huang • A. Atasu • L.B. Toktay
Scheller College of Business, Georgia Institute of Technology, Atlanta, GA, USA
e-mail: ximin.huang@scheller.gatech.edu; atalay.atasu@scheller.gatech.edu; beril.toktay@scheller.gatech.edu

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8_18

growing volume. In 2014, countries worldwide generated as much as 41.8 million tons of e-waste, and it is expected to increase at an annual rate of 4–5 % in the coming years (Balde et al. 2014). Moreover, many e-waste products contain hazardous materials (e.g., lead and mercury), which can pose serious threats to the environment and public health if they are not handled properly. Eco-design, one response to this waste management problem, is considered a proactive and sustainable approach: Product designs that minimize toxic materials and/or contain more recyclable attributes can alleviate environmental hazards at the source and facilitate easier and cheaper end-of-life waste management.

In this context, Extended Producer Responsibility (EPR) is a policy instrument that is widely adopted due to its potential to incentivize eco-designs. EPR holds producers financially and/or physically responsible for the proper end-of-life treatment of their products. In the past two decades, product take-back legislation based on EPR has gained momentum over the world. Examples of EPR legislation include: the Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU) established by the European Commission; the Specified Household Appliance Recycling (SHAR) Law in Japan, and the e-waste legislation adopted in 25 states across the United States. EPR legislation has producers internalize the externalities of waste products into their cost considerations. This is expected to incentivize producers to incorporate eco-friendly attributes into their product designs. Generating such design incentives is one of the main objectives pursued by regulators. For example, the e-waste legislation in Washington State specifies that a collection and recycling system "must encourage the design of electronic products that are less toxic and more recyclable" (Washington State Senate 2006).

Design implications associated with environmental legislation have been a major research topic in the environmental economics. This research stream takes a social planner's perspective and explores design for environment based on economic models. One of the pioneering papers is Fullerton and Wu (1998). The paper shows that a deposit-refund system motivates firms to choose socially optimal recyclability levels for their product designs. Calcott and Walls (2005) studied a similar problem, taking into account the influence of the recycling market. The authors show that socially optimal product designs can be induced by combining a product tax and recycling subsidies with modest disposal fees. Along this line, Walls (2006) reviewed real-life applications of a number of policy tools (e.g., take-back mandates, advanced recycling fees, subsidies, deposit-refunds, and unit-based policies) and examined their potential impacts on producers' product design decisions.

While economic studies indicate that environmental legislation can promote design incentives, the legislation's impact on design seems not to have fully materialized in practice. Although eco-design improvements have been documented [e.g., in Japan after the launch of the SHAR Law (Tojo 2004)], such activities in a global scale are scarce, especially in comparison to the prevalence of EPR legislation. In particular, current EPR legislation associated with e-waste has been criticized for failing to realize the design potential of the policy concept in several aspects. For example, most EPR legislation is implemented in a collective way (i.e., a statewide reverse supply chain is established to collect, transport, and process a mixture of products manufactured by different producers). The total cost is then allocated to each participating producer using uniform weight-based metrics such as return share (i.e., the percentage of a producer's own products in the total volume returned by weight). While collective implementations bring about overall cost benefits due to economies of scale, the typical associated cost allocation models often lead to free-riding on eco-design efforts: Some producers have indicated a loss of design improvement incentive because one producer's relatively high recycling costs (from a bad design) will be jointly absorbed by all participants in the collective system (Atasu and Subramanian 2012; IPR Working Group 2012). This indicates that implementation of EPR legislation exerts a critical impact that can lead to design outcomes that vary from policy-level projections.

In practice, EPR implementation is the process of managing products and their associated financial and information flows in complex reverse supply chains. This process is driven by multiple economic, environmental, political, and operational concerns; thus the legislative outcome represents a high-level balancing act between these concerns. For instance, while the WEEE Directive mandates a uniform take-back policy across the 27 European states, it also grants discretion to each member state for its own transposition and implementation of the legislation. This results in considerable variations across member states in diverse aspects, such as layout of the collection and recycling infrastructure, commodity market dynamics, and the collaboration and competition in reverse supply chain activities. All these operational factors influence how WEEE takes effect (as similarly discussed in the context of implementing the E-Cycle program in Washington State in Gui et al. 2013).

In this chapter, we examine how design incentives intended by EPR legislation filter through the operational factors and stakeholder incentives at the implementation stage. In particular, we focus on the design impacts of operations in the reverse supply chain that involve the collection and recycling of end-of-life products. The interaction between supply chain considerations and product design strategies is a fundamental issue studied in traditional operations management literature (Simchi-Levi et al. 1999). This same issue has been recognized in the context of eco-design and reverse supply chains, especially in the presence of EPR legislation (Renssen 2015). We survey this research stream and highlight three issues emerging from e-waste management: (1) trade-offs between different eco-design attributes (e.g., durability vs. recyclability), (2) design implications of competition in primary markets, and (3) interactions between product design and capacity configurations in the recycling reverse supply chain. We then provide insights as to how policy implementation choices associated with EPR legislation can help attain more effective design incentives.

The rest of the chapter is organized as follows. In Sect. 18.2, we describe how a reverse supply chain is established and operated to execute the EPR principle. We then analyze the design implications of EPR by introducing a benchmark case with minimum operational complexity in EPR implementation in Sect. 18.3. In the subsequent three sections (i.e., Sect. 18.4–18.6), we extend the benchmark case to study each of the three issues mentioned at the end of last paragraph and compare the resulting product design outcomes. Finally, we summarize the findings and discuss insights in Sect. 18.7.

18.2 An Overview of EPR Implementations

Implementation of EPR legislation involves developing a set of operational guidelines that embody EPR principles and translating these guidelines into a working system. This typically involves addressing two major implementation problems: (1) how to develop a reverse supply chain and manage its product, financial, and information flows, and (2) how to establish effective regulatory standards and monitor the compliance of entities involved in the process.

To address the first problem, two major operational frameworks have been developed: an individual and a collective form of EPR implementation. In an individual implementation, every producer is responsible for developing its own collection and recycling resources to process its products, and paying for costs incurred. For example, the recycling legislation in Japan for personal computers (e.g., desktop personal computers and laptops with CPT or LCD displays) requires individual producers to take back their products separately by brand and process the products in their own recycling plants (Dempsey et al. 2010).

A collective implementation, on the other hand, involves establishing a large-scale reverse supply chain that combines available collection and recycling resources and processes a mixture of electronics manufactured by different producers in an aggregate manner. As of now, collective EPR implementations are prevalent in practice due to the following economic concern:

> The proper handling of e-waste is costly for most products, and EPR introduces a significant cost burden on the electronics industry, the main stakeholder group it affects. Hence, in the phase where EPR is operationalized, the focus - of not only producers, but also of the architects, enforcers and operators of these systems - typically turns to establishing a well-functioning system and minimizing the implementation cost (subject to the regulatory standards). (Gui et al. 2015b)

A similar cost concern is shared by many involved entities. The European Recycling Platform, a producer-operated nonprofit, aims to ensure cost-efficient implementation of the WEEE Directive for its members (European Recycling Platform 2012). The UK Minister of State for Business of Enterprise, in introducing a proposed set of new guidelines regarding WEEE implementation (developed by the Department of Business, Innovation and Skills), stated that the aim is to "reduce the cost of compliance for producers" (Department for Business Innovation & Skills 2013, p. 4). The Washington Materials Management and Financing Authority (WMMFA), an authority created by Washington State law to establish a collection and recycling network (CRN) that participating manufacturers finance, aims to operate "in the most cost effective manner" (WMMFA 2012). Many other state implementations across the United States take the same perspective. In this context, a collective implementation is preferred because of the associated cost benefits obtained by synergies, which enable economies of scale and the sharing of cheap resources (i.e., system-wide cost reductions by more efficient product routing).

In order to achieve such synergies under a collective EPR implementation, a statewide reverse supply chain is often centrally managed by a system operator, which routes returned products from collection points to processing facilities (i.e., processors) in the most cost-effective manner. This operator also manages the CRN's capacity and cost information, pays all service providers for the volumes handled, and allocates the total costs among all participating producers based on a predetermined allocation mechanism. In practice, many implementations adopt weight-based proportional allocations such as return share or market share (i.e., each producer pays the portion of total cost that equals the percentage of its products among the total volume returned or sold by weight). These percentages are often calculated based on product sampling at processing facilities or via physical product separation (by brand) at collection points.

The other major problem associated with EPR implementation (as mentioned earlier) is establishing a mechanism to monitor the legal compliance of producers. To this end, many EPR implementations impose a recycling target on producers (i.e., a minimum percentage by weight per appliance that needs to be recycled). The WEEE Directive mandated a recycling target that varied from 50–80 %, depending on the product category (Europa-Environment 2003); and the target was later raised by 5 % by the Recast of WEEE Directive in 2012 (Europa-Environment 2012). For another example, starting from 2007, EPR legislation for electronics in Minnesota has required producers to collect and recycle a specified scope of products that equals at least 80 % of the weight of products they put into market in the current year (MPCA 2011). Moreover, in order to ensure proper e-waste treatment throughout the reverse supply chain, a typical EPR legislation also imposes environmental standards on associated collection and processing facilities involved, and reinforces these standards via certification, auditing, and/or inspection (WMMFA 2012). Other examples of regulatory standards include a convenience measure for collection networks (e.g., at least one collection point should be established for a region with a certain population) that was adopted by Washington and Oregon legislation, and the Product toxicity standards (such as the Restriction of Hazardous Substances Directive (RoHS)) that were incorporated into EPR legislation in Illinois, Indiana, New Jersey, New York, and Wisconsin (API 2015).

18.3 A Benchmark Case

EPR legislation is believed to create design incentives as it introduces additional costs for producers that can be reduced by improving designs. To illustrate such economic incentives, we introduce a benchmark case in this section with minimum operational complexity. Consider a monopolist producing and selling a single type of product in the market. In the absence of legislation, the profit of the producer equals the sales revenue net of the production cost. When EPR legislation is enacted, the producer also needs to pay for the end-of-life cost of its product. This motivates the producer to design products that can be recycled at lower costs (e.g., via the incorporation of features that facilitate easy disassembly or use more recyclable materials). Note that such design improvements incur additional costs (e.g., increased production costs); thus, the optimal recyclability level of the product is achieved when the marginal benefit of reducing recycling costs equals the marginal investment required.

The following numerical example illustrates this idea. Note that the numerical examples we use are rather stylized to illustrate our point of view and are by no means general (or even realistic); however, they represent the trade-offs emphasized here and allow us to generate and replicate insights produced by more realistic models in the literature.

Example 1. In this example, we denote the monopolist's product by π. Assume that the recyclability attributes and the associated production cost have a negligible impact on sales. For simplicity, we normalize the sales volume to 1 in this example. We measure the recyclability of the products by a λ_π metric. The larger λ_π is, the more recyclable π is.

To highlight the impact of EPR legislation, we restrict our attention to compliance-related costs, which include recycling and incremental production costs due to improved product recyclability (i.e., a higher λ_π value). For ease of demonstration, we assume that under legislation, the unit recycling cost of the product equals $10 - 2\lambda_\pi$, where 10 is the base unit recycling cost given the stringency of legislation (represented by a certain recycling target) in the absence of any design improvement. As λ_π becomes larger, this unit recycling cost decreases. We also assume that the incremental production cost equals $(\lambda_\pi)^2$ per unit of product. This quadratic functional form is chosen simply to represent the idea that in general, the incremental production cost increases faster as the product becomes more recyclable.

From a cost minimization perspective, when there is no end-of-life product responsibility, the producer prefers not to increase the recyclability level of its product (i.e., $\lambda_\pi = 0$), as doing so only leads to a higher production cost. However, under EPR, the producer is motivated to choose the λ_π value that minimizes its total compliance-related cost $10 - 2\lambda_\pi + (\lambda_\pi)^2$, which can be calculated to be $\lambda_\pi = 1$.

The economic intuition behind this benchmark case is straightforward; however, in the next three sections, we show that the predicted design outcome can be significantly altered when supply chain considerations are also taken into account for this illustrative example.

18.4 Trade-offs Between Design Alternatives

In the benchmark case, the producer increases product recyclability to cope with the economic burden imposed by EPR legislation, which coincides with some observations in practice. For example, after the enactment of the SHAR Law in Japan, there were some documented recyclability design improvements in electronics (Tojo 2004). Therefore, raising the stringency of recycling legislation may be expected to incentivize more recyclable product designs. This logic underpins the more stringent recycling targets in the 2012 Recast of the WEEE Directive (2012/19/EU). At the operational level, however, producers are not restricted to designing for recycling (which will reduce unit costs of recycling). Specifically, a producer can also achieve lower total recycling costs by enhancing the durability of products. The underlying rationale is that when products are made more durable, they provide a higher overall utility to consumers. Accordingly, producers can set a higher new product price and sell a smaller volume, resulting in fewer end-of-life items and hence a lower cost of compliance.

Therefore, a stringent recycling target can potentially lead to improvements in both recyclability and durability. One can indeed expect this favorable outcome if the two product attributes go hand-in-hand (e.g., for desktop computers, recyclability and durability increase simultaneously by the same design change that replaces the plastic by matel as main material for the cases, HP 2009). However, the two attributes can be conflicting for some products, in which case design changes that enhance one attribute may compromise the other attribute. An example is the Photovoltaic Panels (PVPs) that were recently added to the regulated product categories by the 2012 Recast of the WEEE Directive (2012/19/EU). For PVPs, a frameless design implies easier disassembly (i.e., higher recyclability) but renders the products more fragile (i.e., with reduced durability). In the presence of such design trade-off, an important question arises: *How does the relation between product recyclability and durability influence the design implications of EPR legislation?*

Huang et al. (2015) shed light on this problem by explicitly modeling the synergistic or conflicting relation between recyclability and durability. The paper suggests that when recyclability and durability are synergistic, a more stringent recycling target leads to improvements in both product attributes, which coincides with intuition. However, analysis of the case where the two attributes are conflicting reveals surprising results: An increase in recycling targets may in fact backfire and incentivize product designs with lower durability or recyclability. We demonstrate the underlying rationale with the following example that builds upon Example 1.

Example 2. Recall that in Example 1, under a given stringency of the recycling targets, the total compliance-related cost of the product π (accounting for design for recyclability alone) is $10 - 2\lambda_\pi + (\lambda_\pi)^2$. When product durability is considered, which we measure in this example by μ_π ($\mu_\pi \in [0, 1]$, with a higher μ_π corresponding to a more durable product), it changes the recycling cost in two ways. First, it reduces the volume of sold products that will enter the waste stream at the end-of-life. We capture this by assuming the sales volume to be $(1 - \mu_\pi)$ (recall that the sales volume is normalized to 1 in Example 1). Second, when products are designed to be more durable, an incremental production cost will be incurred. In particular, when recyclability and durability are conflicting, increasing μ_π should be more expensive when λ_π is higher. We model this interaction by including an additional term $10\lambda_\pi\mu_\pi$ in the incremental production cost. Accordingly, the producer's total unit compliance-related cost in the example becomes $10 - 2\lambda_\pi + (\lambda_\pi)^2 + 10\lambda_\pi\mu_\pi$. Multiplying this unit cost by the reduced sales volume yields the total compliance-related cost incurred to the producer: $[10 - 2\lambda_\pi + (\lambda_\pi)^2 + 10\lambda_\pi\mu_\pi] \cdot (1 - \mu_\pi)$.

Then the optimal design choices that minimize the total cost can be calculated to be $\lambda_\pi = 0.927$ and $\mu_\pi = 0.0145$. Notably, the optimal λ_π in this case is lower than that in Example 1. This is exactly because of the conflicting relation between recyclability and durability. This discussion shows how the design trade-off weakens the effectiveness of EPR legislation to motivate producers to improve their eco-designs of products.

Next, we evaluate how the design trade-off may change the way that legislative stringency affects the design outcome. To this end, we further experiment with the case where the recycling target has increased and resulted in a unit base recycling cost that is higher than the original value of 10. Specifically, we assume now the unit recycling cost equals $11 - 2\lambda_\pi$, with which the total cost becomes $[11 - 2\lambda_\pi + (\lambda_\pi)^2 + 10\lambda_\pi\mu_\pi] \cdot (1 - \mu_\pi)$. In this case, the optimal λ_π increases to 0.964, while the optimal μ_π decreases to 0.0072.

This numerical example demonstrates some key findings in Huang et al. (2015) on a more stylized model: Due to the link between the return volume in the reverse supply chain and the sales volume in the forward supply chain, a producer has alternative options in different dimensions of product design to reduce compliance costs associated with end-of-life products. The trade-off between these design options can weaken or even negate the effectiveness of recycling targets in terms of motivating more environmentally-friendly product designs.

Huang et al. (2015) show that in the presence of design trade-off between recyclability and durability, relatively low recycling targets incentivize producers to design more recyclable yet less durable products. This can consequently lead to greater total consumption, which demands more raw materials and energy for production, and also creates a heavier burden for recycling. According to the well-established Waste Management Hierarchy, consumption reduction should be prioritized over recycling. When promoting recycling activities (by inducing higher recyclability) is achieved at the cost of increasing production and consumption (due to lower durability), the priority is negated and legislation may fail to fulfill its goal of improving overall environmental performance. Huang et al. (2015) further show that, in the presence of the design trade-offs, high recycling targets may induce the producer to improve product durability while decreasing recyclability. This result is counter-intuitive because one expects the recycling target to have a direct effect on recyclability and thereby guarantee designs that enhance recyclability. We summarize the above discussions below.

> When a design trade-off exists between product recyclability and durability improvements, relatively low recycling targets may imply more recyclable yet less durable designs, whereas high recycling targets imply more durable yet less recyclable designs. Thus, stringent recycling targets may not necessarily lead to higher recyclability in products.

To conclude, this section demonstrates that the trade-off between different design attributes can result in counter-intuitive outcomes under EPR legislation. As a result, EPR legislation may fail to promote superior waste management practices (e.g., consumption reduction). The key to avoid these unintended consequences is to carefully factor in the existences and influences of possible trade-offs between relevant design options that can lower producers' end-of-life costs at different stages of the reverse supply chain. Specifically, the trade-off between durability and recyclability warrants special attention, given that durable products (e.g., electronics) make up a significant portion of the total waste stream.

18.5 Design Incentives Under Collective EPR Implementations: The Impact of Market Competition

In the next two sections, we turn our attention to another implementation choice that critically affects the design outcomes of EPR legislation: the choice between a collective vs. an individual form of the reverse supply chain system. In this study, we focus on a single design option and analyze design incentives for recyclability.

In the benchmark case, we considered the design impact of EPR legislation on a single firm. This essentially illustrates the design incentives under an individual implementation (e.g., each producer only bears the cost of its own products). It is commonly believed that an individual implementation provides the best design incentives for recyclability as no free-riding in cost sharing can occur. However, as mentioned in Sect. 18.2, the practice of EPR implementation has converged into a collective one.

Despite their cost-efficiency advantage, collective implementations are generally believed to undermine design incentives due to the potential free-riding problem under cost sharing pertaining to the shared end-of-life financial responsibilities of producers. This problem is particularly evident under the weight-based proportional cost allocation schemes commonly used in practice (e.g., return or market share). Such cost allocations charge producers a uniform cost per pound and do not penalize or reward producers according to their product designs for recycling. In this case, the cost savings from one producer's design effort will be uniformly shared by all participants, causing a free-riding problem.

While this economic perspective provides valuable intuition into the design implications of collective EPR implementations, we observe that additional complexities may exist in this context due to interactions among producers within the supply chain, for example, when take-back legislation is imposed on a set of competing producers. The competition dynamics in the forward chain critically hinge on producers' cost structures, including those incurred in the reverse chain that are influenced by their design choices. On the other hand, competition determines producers' market shares and influences the associated cost allocations under collective implementations. In this case, competition has a direct impact on producers' design incentives. Hence, in the rest of this section, we re-examine the design outcomes of collective and individual EPR implementations under market competition.

Our analysis in this section is based on a two-producer setting. Specifically, we consider a Bertrand duopoly with a high-end and a low-end producer with vertically differentiated products. We assume that the producers select their product designs and sales prices to maximize their own total profits. They compete on price, which determines their market shares in the consumer market. At product end-of-life, if an individual EPR implementation is adopted, each producer recycles its own products independently. The unit recycling costs may be different between the two producers, depending on the recyclability attributes of their designs. If a collective implementation is adopted, the two products are processed collectively and we consider an allocation scheme under which each producer is charged the same unit per pound price (that equals some weighted average of the unit processing costs of the two products). This approach mimics the uniform weight-based cost allocations widely adopted in practice (based on arbitrary assumptions about product mix before actual product recovery takes place) (Atasu and Subramanian 2012).

Given this stylized model setup, the following example demonstrates that the design outcome in a collective implementation is worse than that of an individual one, and the discrepancy depends on the level of brand differentiation and the calculation method of the average unit cost charged.

Example 3. In this example, we consider a high-end producer h and a low-end one l. They produce product $\pi(h)$ and $\pi(l)$, respectively. For each producer, we assume the same compliance-related cost structure as in Example 1. That is, the unit recycling costs of $\pi(h)$ and $\pi(l)$ are $10 - 2\lambda_{\pi(h)}$ and $10 - 2\lambda_{\pi(l)}$ respectively, and producer h and l incur an incremental production cost of $(\lambda_{\pi(h)})^2$ and $(\lambda_{\pi(l)})^2$, respectively.

As before, we assume that the market size is normalized to 1. The market competition between the two producers depends on their brand differentiation, quantified by the difference between consumers' valuations of their products. In this example, we assume that consumers' valuation of the low-end product is φ $(0 < \varphi < 1)$ fraction of that of the high-end one. A lower φ indicates a higher level of brand differentiation for consumers. Let q_h and q_l denote the resulting sales quantities in a Bertrand duopoly. Note that these quantities are functions of the sales prices of the two products (denoted as p_h and p_l) and the brand differentiation parameter φ (see Atasu and Subramanian 2012 for details of these functions).

We assume the following sequence of decisions. In the first stage, the producers simultaneously choose product recyclabilities $\lambda_{\pi(h)}$ and $\lambda_{\pi(l)}$. In the second stage, the producers simultaneously choose prices p_h and p_l. We deduce the equilibrium prices and recyclability levels that maximize producers' net profits by backward induction (see Atasu and Subramanian 2012 for a detailed description of the backward induction procedure). Note that depending on the form of EPR implementation, the producers incur different recycling costs and thus obtain different unit profits, which induce different pricing and product design decisions.

In an Individual System Each producer i recycles its own product independently in an individual system, and incurs the unit recycling cost $\lambda_{\pi(i)}$. Hence, the producers' objectives in an individual system are:

$$\Pi^h_{\text{Ind}} = \max_{p_h, \lambda_{\pi(h)}} q_h \cdot [p_h - (10 - 2\lambda_{\pi(h)} + \lambda^2_{\pi(h)})], \tag{18.1}$$

$$\Pi^l_{\text{Ind}} = \max_{p_l, \lambda_{\pi(l)}} q_l \cdot [p_l - (10 - 2\lambda_{\pi(l)} + \lambda^2_{\pi(l)})]. \tag{18.2}$$

We calculate that the equilibrium design solution to (18.1) and (18.2) is $\lambda_{\pi(h)} = \lambda_{\pi(l)} = 1$, which is identical to the monopolist's design choice in the benchmark case shown in Example 1. Note that in this case, although φ affects the sales quantities q_h and q_l and thus affects producers' profits, producers' equilibrium design choices are independent of φ. This indicates that the design incentives induced by an individual EPR implementation are not influenced by market competition.

In a Collective System In this example, we assume that the average cost charged in the collective system is based on a 50/50 estimate of the product mix of the entire volume processed. That is, both producers are charged the average unit cost $\frac{1}{2}(10 - 2\lambda_{\pi(h)} + 10 - 2\lambda_{\pi(l)}) = 10 - \lambda_{\pi(h)} - \lambda_{\pi(l)}$. Hence, the total profits of the two producers in the collective system equal

$$\Pi^h_{\mathrm{col}} = \max_{p_h, \lambda_{\pi(h)}} q_h \cdot [p_h - (10 - \lambda_{\pi(h)} - \lambda_{\pi(l)} + \lambda^2_{\pi(h)})], \tag{18.3}$$

$$\Pi^l_{\mathrm{col}} = \max_{p_l, \lambda_{\pi(l)}} q_l \cdot [p_l - (10 - \lambda_{\pi(h)} - \lambda_{\pi(l)} + \lambda^2_{\pi(l)})]. \tag{18.4}$$

Figure 18.1(a) plots the equilibrium design solution to (18.3) and (18.4). It can be observed that both producers' equilibrium design choices under a collective implementation are worse than those in the individual system (i.e., $\lambda_{\pi(h)} = \lambda_{\pi(l)} = 1$). Moreover, the collective implementation leads to a worse design outcome as φ increases, i.e., as the level of brand differentiation decreases.

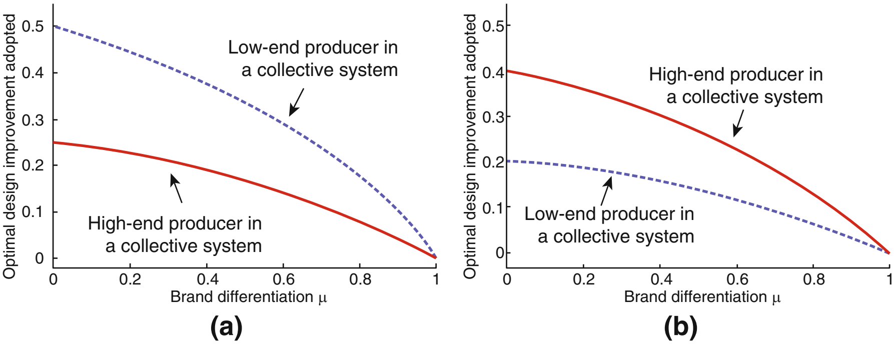

Fig. 18.1 The equilibrium design solutions in a collective implementation under a uniform weight-based cost allocation (**a**) when the unit cost charged is calculated based on a 50/50 product mix estimate; (**b**) when the unit cost charged is calculated based on an 80/20 product mix estimate

Another interesting observation in Fig. 18.1(a) is that the low-end producer chooses a design with a higher recyclability level than the high-end producer. In other words, in a collective system, it may be the high-end producer who free-rides over the low-end one on its eco-design effort. We show that this result may flip if the cost allocation is calculated differently. To see this, we calculate the optimal design choices when the average cost charged in the collective system is based on an 80/20 estimate of the product mix (i.e., 80 % of the high-end product $\pi(h)$ and 20 % of the low-end product $\pi(l)$). The results are shown in Fig. 18.1(b). Note that the producers' design choices in Fig. 18.1(b) continue to be worse than those in an individual system.

Example 3 illustrates that the design outcome of a collective EPR implementation depends on the competitive dynamics among the participating producers in the collective system, which can be summarized as follows.

Under a collective EPR implementation with a uniform weight-based cost allocation:

1. the design outcome is worse than that in an individual system due to free-riding on the design efforts among producers;
2. the identity of the free-rider depends on how the cost allocation is calculated;

3. both producers have less incentives to design for recycling as φ increases, i.e., the level of brand differentiation decreases.

The first observation is aligned with the environmental economics perspective associated with design implications of collective EPR, i.e., uniform cost sharing leads to free-riding and mutes design incentives. However, the second observation indicates that the form of free-riding on design efforts can be shaped by operational details. In particular, it depends on whether a recycling cost advantage in the reverse supply chain can yield additional leverage to compete in the primary market (e.g., beyond pricing). For example, Atasu and Subramanian (2012) indicated that when the low-end products account for a significant portion of the uniform average recycling cost charged in the collective system, "the low-end producer, being at a disadvantage with respect to its brand position, finds it more attractive to focus on recycling cost reduction to compete. The high-end producer, on the other hand, can utilize its brand advantage to benefit from the low-end producer's design improvements." The situation is reversed when the high-end products become dominant in the return volume. In this case, competing by recycling cost reduction is more effective for the high-end producer despite its market advantage.

The third observation further argues that under a collective implementation, greater brand differentiation results in better design incentives. Intuitively, this is due to the competitive dynamics in the primary market: As the customer valuation of the low-end product decreases, the low-end producer has a weaker branding position and is thus more willing to focus on improving design and competing by recycling cost reductions. Given the better design of the low-end product, the high-end producer is motivated to improve its product design accordingly to maintain its competitive ground. This result implies that, in practice, "a collective implementation would be more efficient with respect to driving design for recycling in markets where there is greater differentiation between the high- and low-end brands" (Atasu and Subramanian 2012).

Note also that Example 3 illustrates a case when cost allocation is calculated ex-ante based on an assumption about the product mix in the return volume. In practice, the advancement of real-time brand identification and product separation techniques (e.g., RFID) enables more accurate evaluations of the return shares of producers ex-post. For example, in Example 3, the return shares of the high-end and the low-end producer equal $q_h/(q_h + q_l)$ and $q_l/(q_h + q_l)$, respectively. Hence, the actual average unit recycling cost incurred in the collective system equals $(q_h/(q_h + q_l)) \cdot (10 - 2\lambda_{\pi(h)}) + (q_l/(q_h + q_l)) \cdot (10 - 2\lambda_{\pi(l)})$. This motivates us to consider the design implication of a collective implementation with producers being charged based on this actual recovery cost. Atasu and Subramanian (2012) studied this problem and showed that adopting such a cost allocation influences producers' competitive behaviors. In particular, the low-end producer is more likely to free-ride on the high-end producer's design efforts. Because of this, greater brand differentiation leads to worse design incentives for the low-end producer.

The main take-away from this section is that the competitive structure in the primary markets is a critical driver behind the specific form of free-riding on design for recyclability efforts when EPR implementation is based on a collective reverse supply chain. This is because the reverse chain yields additional competitive lever for producers, and they may prefer different levers (e.g., recycling cost reduction vs. pricing strategies) depending on their brand positions. Hence, it is important to take into account the competitive dynamics associated with producers when evaluating design outcomes of a collective implementation. In addition, the discussion also illustrates the design impact of the cost allocation adopted, which we further explore in the next section.

18.6 Design Incentives Under Collective EPR Implementations: Cost Allocation and Network Effects

In this section, we analyze the following question: Given a reverse supply chain infrastructure, is there a cost allocation mechanism under which a collective implementation achieves the same design incentives as in an individual system? This is one of the central issues associated with design implications under collective EPR implementation. Generally, it is believed that the problem of free-riding on eco-design efforts in a collective system is rooted in the uniform cost allocations used in practice. Hence, by differentiating between the unit recycling cost charged to the producers, the free-riding problem can be eliminated and design incentives can be restored under a collective implementation. In particular, a set of papers in the literature argue that the principle underlying an individual system (i.e., each producer only bears the cost for its own products) "can be realized in practice in collectively organized compliance systems" by financing mechanisms based on the "actual costs associated with managing individual producers" (Sander et al. 2007; IPR Working Group 2012; Dempsey et al. 2010). However, developing cost allocation mechanisms that provably promote design incentives remains an open problem.

Gui et al. (2015a) analyzed the above problem and showed that the infrastructural properties of the reverse supply chain determine whether cost allocation adjustments can restore design incentives in a collective implementation. In particular, a collective reverse supply chain often consists of heterogeneous collection and recycling resources that are different in cost efficiency and capacity levels. This supply chain system is centrally managed by a system operator that routes the return volume of all participating producers to minimize the total cost. In other words, producers share capacity in this collective system. It is shown in Gui et al. (2015a) that, depending on the capacity configuration of the reverse supply chain, capacity sharing leads to network effects that can either promote or dilute the design incentives under a collective implementation. The following example demonstrates how the former case occurs.

Example 4. Consider two producers a and b, who produce products $\pi(a)$ and $\pi(b)$. Their return volumes are 2 units and 4 units, respectively. When operating independently in an individual system, producer a has access to 3 units of capacity at a processor, denoted as $r(a)$. Producer b has 5 units of capacity at another processor, denoted as $r(b)$. Among the two processors, $r(a)$ is more cost efficient (due to the more advanced recycling technology used) such that for each product $\pi(i)$, $i = a, b$, the unit processing cost at $r(a)$ is half of that at $r(b)$. Specifically, we assume that at processor $r(b)$, the unit recycling cost of either product is the same as that in Example 1 (i.e., equals $10 - 2\lambda_{\pi(i)}$, $i = a, b$). The unit recycling cost at $r(a)$ then equals $5 - \lambda_{\pi(i)}$, $i = a, b$. Moreover, producer a and b also incur an incremental production cost of $\lambda^2_{\pi(a)}$ and $3\lambda^2_{\pi(b)}$, respectively.

In this example, we do not consider the pricing decision of producers and assume that the producers choose product recyclabilities $\lambda_{\pi(a)}$ and $\lambda_{\pi(b)}$ simultaneously, aiming at minimizing their own compliance-related costs. We solve for the optimal design choices in an individual and a collective system as follows.

In an Individual System In this example, the design outcome in an individual system can be calculated in the same way as in Example 1 (as there is no operational interaction between the producers). Specifically, producers a and b incur total compliance-related costs of $2 \cdot [5 - \lambda_{\pi(a)} + \lambda^2_{\pi(a)}]$ and $4 \cdot [10 - 2\lambda_{\pi(b)} + 3\lambda^2_{\pi(b)}]$, respectively. Then the design solution that minimizes these costs is $\lambda_{\pi(a)} = 0.5$ and $\lambda_{\pi(b)} = \frac{1}{3}$.

In a Collective System In this example, a collective system involves a central authority that pools the capacity of producer a and b and processes their volumes in the most cost-efficient manner. This can be captured by a minimum cost transportation problem; the optimal routing is as shown in Fig. 18.2. Intuitively, under the optimal routing, any product that is less recyclable (i.e., the one with a smaller λ value) has the priority to use the more efficient capacity. Accordingly, the minimum total recycling cost in the collective system, denoted by $Z(f^*)$, equals

$$Z(f^*) = \begin{cases} 2(10 - 2\lambda_{\pi(a)}) + 3(5 - \lambda_{\pi(b)}) + (10 - 2\lambda_{\pi(b)}) & \\ \quad = 45 - 4\lambda_{\pi(a)} - 5\lambda_{\pi(b)} & \text{if } \lambda_{\pi(a)} > \lambda_{\pi(b)}, \\ 2(5 - \lambda_{\pi(a)}) + 3(10 - 2\lambda_{\pi(b)}) + (5 - \lambda_{\pi(b)}) & \\ \quad = 45 - 2\lambda_{\pi(a)} - 7\lambda_{\pi(b)} & \text{if } \lambda_{\pi(a)} \le \lambda_{\pi(b)}. \end{cases} \tag{18.5}$$

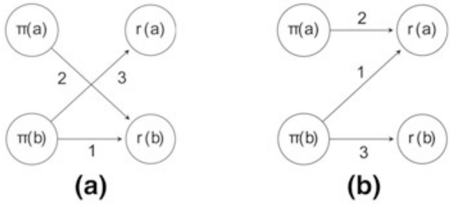

Fig. 18.2 The optimal routing in the collective system in Example 4 (**a**) when $\lambda_{\pi(a)} > \lambda_{\pi(b)}$; (**b**) when $\lambda_{\pi(a)} \leq \lambda_{\pi(b)}$

Consider the following cost allocation mechanism x: Producer b is allocated the same unit recycling cost for its product $\pi(b)$ as what it incurs in an individual system. Hence, the total recycling cost allocated to producer b equals $x_b = 4(10 - 2\lambda_{\pi(b)})$. The remaining cost is allocated to producer a, i.e., $x_a = Z(f^*) - x_b$ and can be calculated as follows:

$$x_a = \begin{cases} 5 - 4\lambda_{\pi(a)} + 3\lambda_{\pi(b)} & \text{if } \lambda_{\pi(a)} > \lambda_{\pi(b)}, \\ 5 - 2\lambda_{\pi(a)} + \lambda_{\pi(b)} & \text{if } \lambda_{\pi(a)} \leq \lambda_{\pi(b)}. \end{cases} \tag{18.6}$$

Given the above cost allocation, we can calculate that the best design choice for producer b is the same as that in an individual system, since its recycling cost remains unchanged. That is, producer b chooses $\lambda_{\pi(b)} = \frac{1}{3}$. For producer a, its best design choice under the above cost allocation is the value of $\lambda_{\pi(a)}$ that minimizes $x_a + 2\lambda^2_{\pi(a)}$. We can calculate that it is either $\lambda_{\pi(a)} = 1$ if $\lambda_{\pi(a)} > \lambda_{\pi(b)}$, or $\lambda_{\pi(a)} = 0.5$ otherwise. Since $\lambda_{\pi(b)} = \frac{1}{3}$ is producer b's best design choice, producer a will choose $\lambda_{\pi(a)} = 1$ accordingly under the equilibrium. Comparing the design outcomes induced by the two implementation systems, it can be observed that, while producer b chooses the same recyclability level under both systems, producer a is motivated to adopt a strictly better product design under a collective implementation.

Example 4 indicates that a collective implementation may have the potential to induce better design incentives (vs. an individual system). This is contrary to the general economic assumption that an individual system yields superior design incentives under EPR. To see why this is the case in Example 4, note that in a collective system, producer a's product may be routed to a processor where improvement in recyclability generates higher cost savings (vs. at its own facility). By reflecting this routing selection in the costs allocated to producer a, a collective implementation achieves a better design outcome. Hence, we conclude that network effects in the reverse supply chain, derived from capacity sharing in a heterogeneous collective system, can be beneficial for realizing the design potential associated with EPR.

Another advantage of the cost allocation mechanism in Example 4 is that both producers are allocated an equal or lower cost in the collective system (vs. what they would incur in an individual system). This provides participation incentives for the producers to voluntarily join the collective system and guarantees the stability of a collective implementation. In practice, such a stability problem is one of the major challenges faced by legislators, as producers' actions to defect from collective systems can be observed in several implementations (Gui et al. 2015b). Example 4 demonstrates that this problem can also be solved by improving the cost allocation used.

To summarize, Example 4 presents an ideal situation with a cost allocation that ensures (1) better design incentives (vs. those achieved in individual systems) and (2) a stable collective system with producers participating voluntarily. However, whether this situation is generally achievable remains a question. Gui et al. (2015a) studied this problem and identified two deciding factors, both of which are related to the capacity configuration of reverse supply chain. The first is the level of cost benefits derived from resource sharing, which we term as the *network synergy*. As is demonstrated in Example 4, such synergy is derived from re-routing a product to capacities cheaper than those used to process this product in an individual system. Accordingly, we define a collection and recycling infrastructure as a *low-synergy* one if no producer could have its products entirely recycled using cheaper capacities in the collective system. The second factor is the correlation between the product and the process technologies in reducing recycling costs. We can summarize the main findings in Gui et al. (2015a) as follows.

> Given a reverse supply chain infrastructure, assume that recyclability improvements in product design result in higher cost savings at less efficient processors. Under certain functional assumptions of compliance-related costs, there exists a cost allocation that ensures (i) a design outcome in the collective system no worse than that in an individual system and (ii) a stable collective implementation, if and only if the collection and recycling infrastructure is a low-synergy one.

The above summary indicates that the synergy level in a reverse supply chain infrastructure is a key determinant of whether a voluntarily operated collective implementation can provide better design incentives than an individual system. When the conditions specified in the above summary are satisfied, Gui et al. (2015a) also proposed a cost allocation that will help achieve the superior design potential of a collective implementation. The mechanism, called the *marginal-contribution-based* allocation, is a generalization of the simple cost allocation illustrated in Example 4.

To conclude, by taking into account network-based operations in the reverse supply chain under a collective implementation, we obtain insights that challenge prevalent perspectives about design implications of collective EPR implementations. In particular, a collective implementation may not achieve the same design outcomes as an individual system unless under stringent conditions of capacity configurations associated with the reverse supply chain infrastructure. This implies that modifying cost allocation mechanisms may not fully resolve weak design incentives within practical EPR implementations as advocated. In these cases, a collective implementation promotes cost efficiencies at the expense of design incentives. However, a collective (vs. individual) implementation may still have the potential to induce better design incentives with certain reverse supply chain structures. The key is adopting cost allocation mechanisms that properly account for network effects derived from optimizing the routing selection in the collective reverse supply chain.

18.7 Conclusion

EPR legislation has long been regarded as an effective waste management tool mainly due to its potential to incentivize product eco-designs. However, while EPR legislation has been enacted worldwide over the past two decades, evidence of legislation-induced product design improvements is lacking. This chapter attempts to provide insights into the drivers of such discrepancies. In particular, we examine how EPR legislation is implemented through reverse supply chain operations and demonstrate the critical impact of these operations on the design outcome of the policy.

We show that specific reverse supply chain considerations can hinder design incentives (associated with EPR legislation) at the implementation level. We demonstrate three significant ones based on stylized examples. The first barrier emerges from possible trade-offs between relevant design options. Although EPR legislation is developed to ensure proper waste management, its influence can reach other phases of product lifecycles (due to interactions between the forward and the reverse supply chain operations). In the context of durable goods, EPR legislation can affect a producer's design choices of recyclability and durability. When the two alternative design options are conflicting, EPR legislation incentivizes design improvements in one attribute at the expense of the other. We conclude that in the presence of such trade-offs, it is important for regulators to prioritize among the possible design alternatives, and define "better" designs (relative to the environment) based on the nature of each product, prior to making legislative choices (e.g., setting the stringency of recycling or collection targets).

The second barrier faced by regulators is the free-riding issue that can arise if the reverse supply chain is operated in a collective manner, which is prevalent in practice for its cost efficiency. We demonstrate that the way this free-riding problem occurs critically depends on the competition dynamics in the primary markets. Thus, to fully understand the design implications of EPR legislation, regulators should consider not only the interactions among producers in the reverse supply chain, but also those in the forward chain as well.

We further consider cost allocation issues in collective reverse supply chains. We develop a cost allocation mechanism to overcome the free-riding problem and promote design incentives. We show that the effectiveness of this approach critically hinges on the network-based operations of the collective systems, which are determined by the capacity configuration of the reverse chain. In particular, limited amounts of collection and recycling resources can yield trade-offs between design incentives and the stability of the collective system, and may hinder the adoption of technologies with design improvements that lead to significant cost savings. Thus, improving design incentives may come at a cost in terms of other legislative objectives. Hence, understandings of the underlying tension and how trade-offs are related to the infrastructural properties of the reverse chain are critical when making informed policy decisions.

To summarize, the three issues that we discussed in this chapter share the same spirit: they all boil down to how the design outcome of EPR legislation is influenced by operational considerations in the reverse supply chain through which policy is implemented. Therefore, the high-level take-away from this chapter is that although EPR legislation builds on a principle that provides effective design incentives in theory, the realization of such design incentives hinges on implementation details (e.g., properly taking into account related supply chain issues during the policy design phase to avoid unintended and inefficient design outcomes). This insight can be applied to dealing with not only the three barriers discussed in this chapter but also other design challenges encountered during EPR implementations. For example, while the majority of current EPR legislation mandates that waste products be processed by certified recycling facilities, this may lead to an increased waste volume that is exported and processed inappropriately. To solve this problem, a monitoring mechanism needs to be established. However, only when on-the-ground operational factors and associated supply chain implications are fully understood can we determine specifications of the mechanism that restore the design incentives that have been lost due to the export of waste. Lastly, the incorporation of product reuse has been proposed as a promising future step for EPR legislation. This results in multi-tier service differentiation in the reverse supply chain, which can bring about significant complexities at the operational front. Hence, in order to properly include reuse options in the legislation and generate effective design incentives out of these options, an operational perspective will also be critical.

References

API (2015) Why should I care about RoHS and lead-free initiatives? http://apitech.com/product-classes/why-should-i-care-about-rohs-and-lead-free-initiatives

Atasu A, Subramanian R (2012) Extended producer responsibility for e-waste: Individual or collective producer responsibility? Prod Oper Manag 21(6):1042–1059

Balde C, Wang F, Kuehr R, Huisman J (2014) The Global E-Waste Monitor 2014. http://i.unu.edu/media/unu.edu/news/52624/UNU-1stGlobal-E-Waste-Monitor-2014-small.pdf

Calcott P, Walls M (2005) Waste, recycling, and "design for environment": Roles for markets and policy instruments. Resour Energy Econ 27(4):287–305

Dempsey M, Van Rossem C, Lifset R, Linnell J, Gregory J, Atasu A, Perry J, Sverkman A, Van Wassenhove LN, Therkelsen M, Sunberg V, Mayers K, Kalimo H (2010) Individual producer responsibility: a review of practical approaches to implementing individual producer responsibility for the WEEE directive. INSEAD, Working paper

Department for Business Innovation & Skills (2013) Implementation of the WEEE recast directive 2012/19/EU and changes to the UK WEEE system. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/190207/bis-13-762-implementation-of-weee-recast-directive-and-changes-to-the-uk-weee-system-consultation.pdf

Europa-Environment (2003) On waste electrical and electronic equipment (WEEE). http://eur-lex.europa.eu/resource.html?uri=cellar:ac89e64f-a4a5-4c13-8d96-1fd1d6bcaa49.0004.02/DOC_1&format=PDF

Europa-Environment (2012) On waste electrical and electronic equipment (WEEE) (recast). http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:197:0038:0071:en:PDF

European Recycling Platform (2012) The European recycling platform. http://www.erp-recycling.org/index.php?content=12

Fullerton D, Wu W (1998) Policies for Green Design. J Environ Econ Manag 36(2):131–148

Gui L, Atasu A, Ergun Ö, Toktay LB (2013) implementing extended producer responsibility legislation. J Ind Ecol 17(2):262–276

Gui L, Atasu A, Ergun Ö, Toktay L (2015a) Design incentives under collective extended producer responsibility: a network perspective. Georgia Institute of Technology, Working paper

Gui L, Atasu A, Ergun Ö, Toktay L (2015b) Efficient implementation of collective extended producer responsibility legislation. Manag. Sci. Published Online: September 3, 2015

HP (2009) HP introduces Z Line of efficient PC's. http://cleantechauthority.com/hp-introduces-z-line-of-efficient-pcs/

Huang X, Atasu A, Toktay LB (2015) Design implications of extended producer responsibility for durable products. Georgia Institute of Technology, Working paper

IPR Working Group (2012) Waste Electrical and Electronic Equipment (WEEE) Regulations: Individual Producer Responsibility (IPR) in a UK Context. https://www.gov.uk/government/publications/waste-electrical-and-electronic-equipment-weee-regulations-individual-producer-responsibility-ipr-in-a-uk-context

MPCA (2011) Evaluation report on the Minnesota electronics recycling act. http://www.pca.state.mn.us/index.php/view-document.html?gid=17092

Renssen S (2015) New waste law proposal to cover product design. http://www.endseurope.com/article/38887/new-waste-law-proposal-to-cover-product-design

Sander K, Tojo N, Vernon J (2007) The producer responsibility principle of the WEEE directive. www.weee-forum.org/system/files/documents/2007_producer_responsibility_principle_okopol1.pdf

Simchi-Levi D, Simchi-Levi E, Kaminsky P (1999) Designing and managing the supply chain: concepts, strategies, and cases. McGraw-Hill, New York

Tojo N (2004) Extended producer responsibility as a driver for design change - Utopia or reality? IIIEE Dissertations 2004:2, Lund University

Walls M (2006) Extended producer responsibility and product design: Economic theory and selected case studies. Resources for the Future discussion paper 03-11

Washington State Senate (2006) Engrossed Substitute Senate Bill 6428: Electronic product recycling. http://www.dnr.mo.gov/env/hwp/escrap/docs/sb6428final.pdf

WMMFA (2012) http://www.wmmfa.net/

Index

A. Atasu (ed.), *Environmentally Responsible Supply Chains*, Springer Series in Supply Chain Management 3, DOI 10.1007/978-3-319-30094-8