MODELS FOR MANAGING GREEN PRODUCT AND PROCESS INNOVATIONS

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THESIS

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Business Administration
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2000

Urbana, Illinois

UMI Number: 9989956

UMI

UMI Microform 9989956

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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

THE GRADUATE COLLEGE

JUNE 2000
(date)

WE HEREBY RECOMMEND THAT THE THESIS BY

CHIALIN CHEN

ENTITLED MODELS FOR MANAGING GREEN PRODUCT AND PROCESS INNOVATIONS

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF DOCTOR OF PHILOSOPHY

Director of Thesis Research

Head of Department

Committee on Final Examination†

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† Required for doctor's degree but not for master's.

O-517

Abstract

The focus of the dissertation is to integrate Operations Management and Environmental Management, the two functional fields that are of crucial importance for the prosperity and welfare of the human society in the twenty-first century. The current trend of production and operations management, which emphasizes the management of the entire supply chain from raw materials extraction, to manufacturing, to the delivery of final products to customers, presents new opportunities in preventing and resolving the problems of environmental pollution through product and process innovations. In the dissertation, we develop decision and simulation models to investigate the roles of product and process innovations in integrating operations and environmental management. In the model of green product development, we analyze a firm's strategies regarding the number of products introduced and their respective prices and quality levels, and compare the economic and environmental impacts of these strategies. The analytical results show that green product development and stricter environmental standards do not necessarily benefit the environment. In the model of green process management, we analyze a firm's decisions of production planning and inventory control under an uncertain environmental limit. The analytical results show that the firm will use an optimal policy that leads to higher planned production in order to deal with both demand and environmental uncertainties. In addition, we use simulation analysis to develop a decision support system for analyzing the quantitative properties of green process management. The simulation results show that the optimal policy that requires higher production may also result in higher stock levels throughout the entire planning horizon, which increases the environmental

risks associated with the storage of certain toxic semi or final products. Based on the analytical results derived from the models of green product development and process management, we propose guidelines that can be used by both operations managers and environmental policy makers. The objective of the research is twofold. For the private sector, the analytical results can be used to guide today's managers in dealing with the increasingly important environmental issues in supply chain management. For the public sector, the research can provide critical insights that can be used to manage and regulate industries on environment-related issues.

Acknowledgments

First and foremost, I would like to express my sincere thanks to my dissertation advisor, Professor George Monahan, who has inspired me to set lofty research and teaching goals, and helped me develop the skills and confidence to achieve them. I am also grateful to the other members of my dissertation committee, Professors Dilip Chhajed, Jim Hess, and Mike Shaw, for their advice and support. Finally, I give special thanks to my parents for supporting my decision to pursue the doctoral degree. This dissertation would not be possible without their love and encouragement over the years.

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Chapter 1

Introduction

1.1 Motivation: The Future Is Now

Almost twenty years ago, in his opening statement for the *Journal of Operations Management*, Buffa (1980) identified energy and environmental issues as two major areas for future research in Operations Management. Today environment-related issues are still largely on the list of potential or future research for most operations researchers and practitioners (refer to Chase and Aquilano 1995, Stevenson 1996, Handfield and Nichols, Jr. 1999). The purpose of this research is to integrate Operations Management and Environmental Management, the two critical areas that will bring productivity and welfare to society in the twenty-first century. I will show that the best way to preserve the natural environment is through green product and process innovations, and that the best time to do it is not in the future but now.

Integration is the main theme of this research. From an interdisciplinary perspective, the research bridges Operations Management and Environmental Management in order to balance a variety of corporate objectives, such as profitability, productivity, and waste management. From a cross-functional perspective, the research brings together different functional fields in business administration that are related to product and process innovations, including Production, Marketing, Finance, Cost Accounting, Business Law, and

Information Systems. It is believed that only from an interdisciplinary, cross-functional perspective can we develop effective strategies that balance the economic and environmental costs and benefits to both the industry and society as a whole.

The objective of the research is twofold. For the private sector, it is expected that the results from the research can be used to guide today's managers in dealing with the increasingly important environmental issues in supply chain management. For the public sector, the research can provide important insights that can be used to manage and regulate industries on environment-related issues. A unique feature of the research is the integrative analysis of the interactions between the private sector's strategic decisions and public sector's environmental policies, an analysis which differs from most economic or operations models that focus merely on either the public or private viewpoint on an environmental problem. Preserving the environment while retaining competitiveness requires joint efforts from both the industry and the government. Only through an integrative analysis of both private strategy and public policy can we develop effective solutions that achieve both economic growth and environmental protection, two of the most important objectives for society in the twenty-first century.

1.2 Problem Overview

It has been long recognized that humankind, and indeed the whole planet and future generations, are facing a severe environmental crisis, aspects of which include such problems as global warming, acid rain, ozone depletion, loss of biodiversity, topsoil erosion, tropical deforestation, and groundwater depletion and pollution (Welford and Starkey 1996). Polls taken in the United States in recent years, for example, consistently indicate that the state of the environment is among the top public concerns. The public has also shown substantial support for imposing regulations on business to ensure environmental improvement over time (Portney 1990).

As an essential part of industrial activities, the production or operations process is usually held responsible for most environmental damage that has occurred and continues to take place. From an environmental point of view, what production does is to turn resources into products that will eventually enter the natural environment as wastes. Similarly, the energy used in production must eventually end up as waste heat. As a result, the more intensive the production process, the more resources and wastes are depleted and generated, respectively. The close causal relationship between the operations process and environmental degradation, however, also presents the industry with both challenges and opportunities in integrating operations and environmental management for achieving sustainable development of the human society, which requires continuously pursuing productivity and efficiency in industrial processes without sacrificing the health of our natural environment. In the subsections that follow, we will discuss why we should integrate Operations Management and Environmental Management, how it can be accomplished, and what the major tasks are in order to integrate the two functional fields that are critical to the prosperity and welfare of human society.

1.2.1 Why Should Manufacturers Care about the Environment?

The process of integrating environmental concerns into production and operations activities can be described as pushed by the economic and regulatory pressure and pulled by the competitive and ethical concerns.

Most environmental regulations implemented by governments around the world, regardless of their various forms such as standards, taxes, and pollution permits, are intended to impose legal and especially economic pressure on industries. The necessity to comply with environmental regulations often becomes a major financial burden to most companies. For example, according to an estimate by the U.S. Environmental Protection Agency (EPA), the cost of complying with federal air and water pollution-control regulations was $52 billion in 1981 alone. Between 1981 and 1990, the nation spent more than $640 billion in pursuit of clean air and water (Portney 1990). Integrating environmental considerations into production and operations processes can lessen the financial burden faced by most companies in complying with environmental regulations. The 3M Company, for example, estimates that its "Pollution Prevention Pays" program has saved $482 million since 1975, while eliminating more than 500,000 tons of wastes and pollutants from its production processes, and has saved another $650 million by conserving energy (Bringer and Benforado 1993).

Turning environmental concerns into a competitive advantage has become one of the most important business strategies in today's global marketplace (Porter 1996). In addition to the huge potential saving in compliance cost described previously, many manufacturers have been trying to explore the first-mover advantage by introducing environmentally-friendly products to the so-called green consumers, such as the electric vehicles introduced by most major automobile manufacturers around the world. It is estimated that about 700,000 companies are already committed to some form of environmental commerce that competes with businesses that are not willing to adapt (Hawken 1996). Some people even suggest that the recent trend of adopting international environmental standards, such as *ISO 14000*, may become a potential trade barrier in the near future. As a result, incorporating environmental considerations into the production and operations processes may become a necessity for those companies who intend to compete and succeed in the global market (Kuhre 1997).

Perhaps the most important justification for integrating environmental protection with production and operations management is just a simple ethical reason: it is a good thing to do. Production and operations activities have been having a severely damaging impact on the global environment since the age of industrialization, and such an impact must be reduced to a level which is environmentally sustainable (Welford 1996). Sustainable production, which refers to the production process where the throughput of materials and energy is reduced to a level where the regenerative and assimilative capacities of environmental sources and sinks are maintained, is now practiced by major companies in various industries, such as 3M, Du Pont, AT&T, McDonald, Chevron, The Big Three, and Toyota (Gladwin 1991). The credibility and significance of these companies' actions have been confirmed by support from the general public and applause from the media and the government. All of these components combined create a new attitude toward corporate responsibility and performance that requires the integration of Operations Management and Environmental Management.

1.2.2 How to Integrate Operations and Environmental Management?

The current trend of production and operations management, which emphasizes the management of the entire supply chain from raw materials extraction, to manufacturing, to the delivery of final products to customers (Handfield and Nichols, Jr. 1999), presents new opportunities in preventing and resolving the problems of environmental pollution. Supply chain managers are the primary agents of change in making decisions about the procurement and disposition of materials and are responsible for the entire flow of materials throughout the supply chain. Design decisions, cost control, technology acquisition, process management, and supply-base strategy all have a major effect on the environmental performance of an organization. With innovative products, processes, and technologies along every stage of a supply chain, an enterprise is able to address its environmental problems from a life-cycle framework under which environmental hazards are identified and then treated at every stage of a product's life cycle.

Figure 3-1 illustrates the importance of supply chain management in environmental protection and pollution prevention. The traditional end-of-pipe control strategy merely focuses on remedying environmental damages caused by industrial wastes downstream of a product's life cycle where the production process is completed (Ehrenfeld 1995). On the same basis as the concept of Total Quality Management, remedying environmental damages is usually more expensive and less effective than attacking or preventing the causes of environmental damages in the first place, upstream of the product's life cycle (Lifset 1993). An environmentally-unfriendly product or a pollution-intensive manufacturing process is bound to result in a huge amount of wastes or pollutants downstream of the life cycle, which will cause tremendous financial burden to and require enormous remedying efforts from a firm. To attack the roots of today's environmental problems in a cost-effective fashion, we must clean the supply chain by innovating green (environmentally-friendly) products and processes upstream of a product's life cycle so that fewer resources or wastes will be depleted or generated. For example, the demand pull of green consumers makes possible many environmentally-friendly products in the marketplace. Strong relationships between suppliers and producers create opportunities for joint ventures to improve productivity and prevent pollution at the stage of material extraction or manufacturing. As a consequence, Operations Management and Environmental Management can be tightly integrated by innovating green products and processes.

Product development and process management indeed play key roles in the implementation of both operations and environmental management (Florida 1996). According to Tirole (1988), research and development and the adoption of new technologies can be classified into product innovations and process innovations. Product innovations create new goods and services; process innovations reduce the cost of producing existing products. Product development and process management also encompass several key issues in supply chain management, such as inventory control, distribution strategies, supply chain integration, product design, information technology and decision-support systems, and customer value (Simchi-Levi et al. 2000). Successful supply chain management requires the planning and control of material flows among a network of companies or departments involved in the manufacturing and distribution of a product. In order to clean the pathways of material flows, we need to innovate green products and processes that can physically reduce the environmental wastes generated from all the activities in a supply chain system. We can thus identify two major tasks as innovation-driven, environmentally conscious practices for integrating Operations Management and Environmental Management: green product innovation and green process innovation.

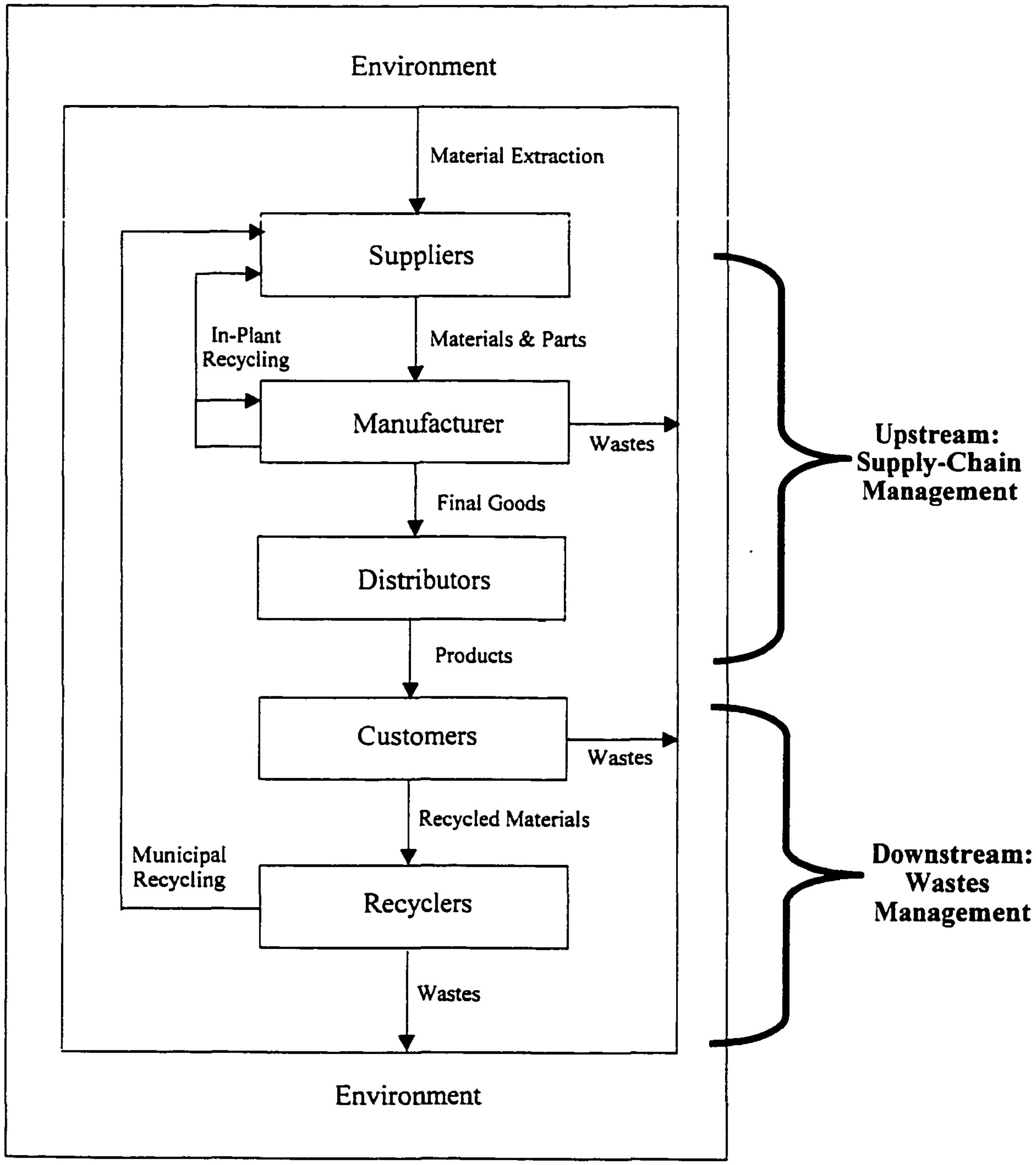

Figure 1-1: Life-Cycle Framework and Supply Chain Management

1.2.3 What Are the Major Tasks for Integrating Operations and Environmental Management?

Green product innovation refers to the development of environmentally friendly products to satisfy customers with additional preferences on such environmental virtues as recyclability and energy efficiency (Henn and Fava 1993). As a practice of supply chain management, green product innovation can greatly improve the environmental performance of a company through cleaning the pathways of material flows (Handfield and Nichols, Jr. 1999), as in the case of recycled papers introduced by most major paper companies in the United States. The process of green product development, however, is generally complex and requires significant interdisciplinary efforts in developing new marketing strategies, selecting "cleaner" suppliers, and resolving technical difficulties such as the conflict between traditional and environmental attributes.

Green process management refers to the improvement of a production system's environmental performance through production planning, inventory control, and technology innovation so that industry wastes and pollutants can be either prevented in the first place or reduced before they enter the natural environment (refer to Clift and Longley 1996). In practice, green process management can be conducted by (1) reducing, reusing, and recycling production inputs (2) controlling and cleaning up production outputs, (3) acquiring and adopting environmentally friendly production processes and technologies, and (4) avoiding the presence and storage of toxic materials and products in the production facility. Green process management, however, is usually costly, requires long-range planning, and is subject to a high degree of risks and uncertainties due to the changing competitive and regulatory environments. As a result, managers must constantly deal with the trade-off between a production system's economic and environmental performances under both the demand and environmental uncertainties.

1.3 Analytical Framework

In order to integrate operations and environmental decisions, we need to analyze the interactions among the three major players in today's marketplace: the consumer, producer, and government. As shown in Figure 1-2, the traditional operations analysis focuses on the links between the producer and its customers who prefer a certain quality level from a particular product and demand a certain quantity of the product. The job of the producer is to design the "right" product and produce the "right" amount of the product to satisfy customers. The product and its production processes, however, may cause negative impacts on the natural environment. In order to control these environmental impacts, the government has imposed various environmental regulations, such as standards and pollution taxes, on either the product itself or the environmental wastes generated from its production processes. As a consequence, the decisions of product development and process management are constrained by the government's environmental regulations. Two important but less notable links in Figure 1-2 are the reverse impacts on public policies from the regulated consumer market or production system. It is crucial for the government to understand the decision-making processes of both consumers and producers in order to determine the right policies that balance the economic and environmental objectives of a society.

To analyze the interactions among the demand, supply, and policy sides of green product development and process management, we follow a three-stage procedure throughout the dissertation. As shown in Figure 1-3, we start with the unconstrained version of a problem under the assumption that the objective of a firm is to maximize its profit or minimize its cost given information about market demand or consumer preference in a regulation-free environment. Then we add in environmental constraints and analyze the decisions of product development and process management with additional environmental considerations. The third step is to conduct sensitivity analyses for evaluating the economic and environmental consequences associated with different levels of environmental constraints. With this analytical procedure, we would be able to identify the "right"

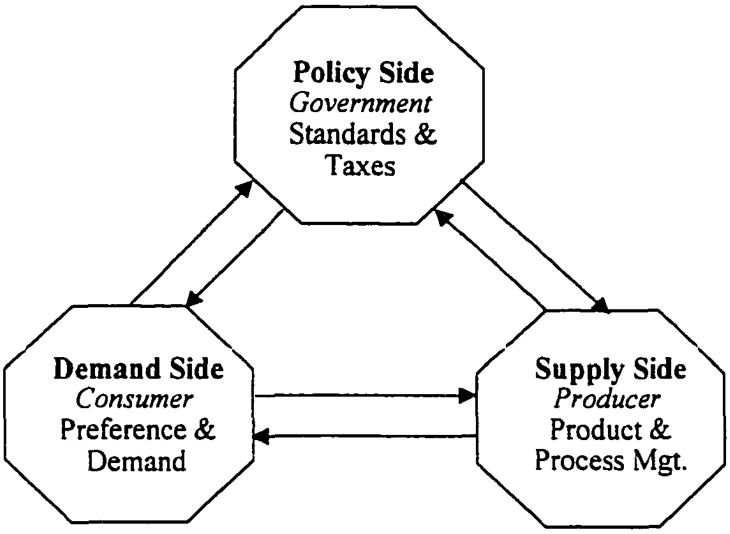

Figure 1-2: An Interactive Analytical Framework

levels of environmental constraints that best attain the economic and environmental goals of a company or of the society as a whole.

The above analytical procedure incorporates an underlying philosophy of this dissertation, which recognizes that profitability is still the ultimate goal of most businesses. Green product development and process management are not only approaches to environmental protection, but also economic practices. Unilaterally pursuing environmental goals without the consideration of a firm's profitability is not only impractical, but may also cause unwanted or even unexpected environmental impacts within a supply chain system, as will be shown by several analytical results in the dissertation. Our analyses differ from many studies in Environmental Economics which simply use the "private cost"–as part of the "social cost"–to summarize a producer's complex decision-making processes concerning production and environmental management. Our analyses also differ from many studies in the area of Environmental Management that focus on how to implement new environmental practices and technologies, such as reverse logistics and recycling, without quantifying their impacts on a firm's profitability. It should be noted that the analytical framework does not preclude the possibility for a firm (or a society) to

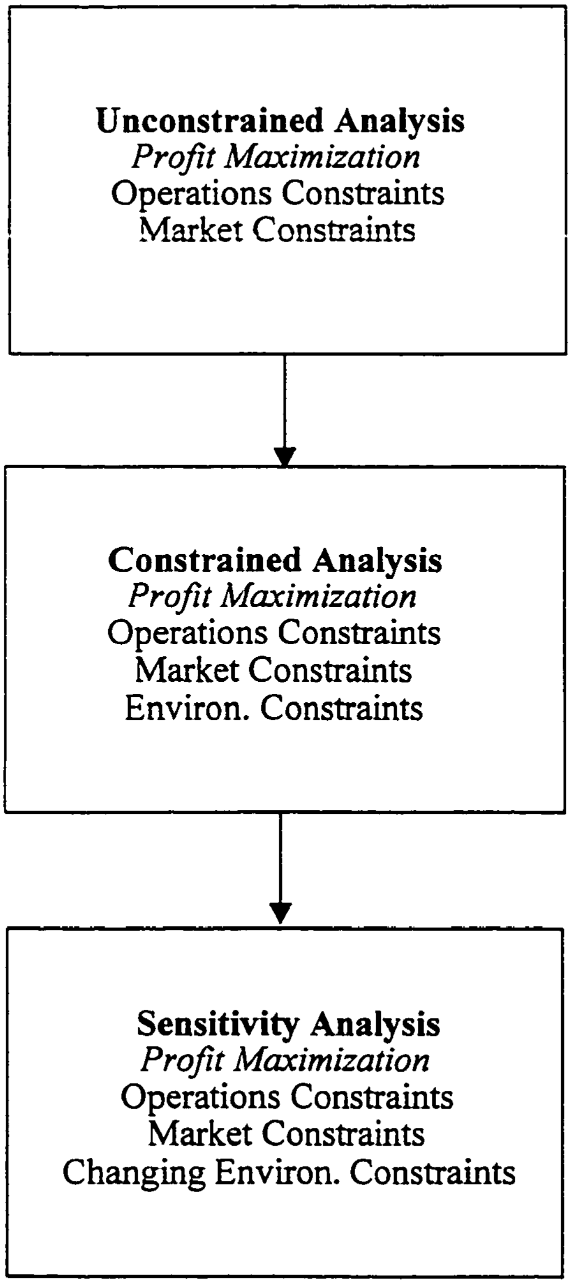

Figure 1-3: Analytical Procedure

pursue non-economic objectives. In fact, the results derived from sensitivity analyses can be used to support decision making with multiple objectives such as profitability and environmental quality. Additionally, for those "green companies" who commit themselves to pursuing premium environmental goals, most analyses in the dissertation can be modified to investigate the situations where the environmental quality, instead of profit or cost, is optimized.

1.4 Research Plan and Methodology

In the dissertation, we analyze two critical issues for integrating operations and environmental management: green product development and green process management. Specifically, the research consists of two major models:

1. **A Model of Green Product Development.** We develop a theoretical model to analyze the processes and impacts of green product development. On the demand side of the problem, we use the conjoint framework to structure the preferences of both green and ordinary customers. On the supply side of the problem, we develop a mathematical program based on the theory of market segmentation with consumer self-selection in order to solve for the optimal product design. On the policy side of the problem, we use the model to analyze the interactions between a company's product strategy and the environmental regulation imposed by the government.

2. **A Model of Green Process Management.** We develop a decision model of production planning and inventory control with both demand and environmental uncertainties under different environmental policies, including standards and pollution charges. We first derive the single-period optimal solution in order to understand the basic relationships among key variables of the model. We then use dynamic programming to solve for the optimal solution in a multi-period planning horizon. Based on the analytical results, we use simulation analysis to develop a

decision-support system that can be applied to a number of real-world situations, such as technology acquisition and policy evaluation.

1.5 Research Questions

The research that focuses on both operations and environmental decision making has significant implications for both private strategies and public policies concerning green product and process innovations. Specifically, the analytical results derived from the models of green product development and process management can help answer questions in the following areas:

1. **Green Product Development.**

    - How can a company combine the marketing and operations considerations of green customers and environmental attributes to design optimal products?
    - What are the economic and environmental consequences of green product development?
    - What are the interactions between a company's green product strategy and the environmental public policy imposed by the government?
    - What is the impact of competition on green product development?

2. **Green Process Management.**

    - What is the optimal policy of production planning and inventory control under both demand and environmental uncertainties?
    - How does the optimal policy evolve over time given different market and regulatory conditions?
    - What are the economic and environmental impacts of the optimal policy?
    - What are the interactions between a company's optimal policy in production planning and inventory control and the government's environmental policy?

1.6 Contributions

This research is one of the few studies on the environment-related issues of Operations Management. It bridges Operations Management and Environmental Management, the two functional fields that are critical to the sustainable development of society. Unlike many studies in Operations Management that merely focus on cost minimization, however, the research encompasses a variety of corporate objectives such as profitability, productivity, and environmental performance. Unlike the traditional research in Pollution Economics that largely ignores the functions of the operations system except for cost reduction, the research places operations decisions at the center stage and analyzes the interactions between private strategies and public policies for achieving industrial and environmental innovations. Only through such an interdisciplinary perspective can we develop cost-effective strategies to enhance the corporate environmental performance and, at the same time, retain the required productivity and competitiveness for future growth.

This research also integrates Operations Management with various functional fields in business administration, such as Marketing, Cost Accounting, Finance, Business Law, and Information Systems. Cross-functional approaches are widely used in developing the models of green product development and process management. According to the author's knowledge, the research is one of the first few studies on the interface between Operations Management and Environmental Management that take such an integrated perspective from various functional fields of business administration.

The ultimate goal of the research is to develop effective private strategies and public policies that can influence the current practices of green product and process innovations. The two theoretical models will shed new light on the qualitative properties of green product development and process management. The simulation model will provide quantitative insights and applications that can be implemented in the real world.

1.7 Overview of the Dissertation

The remainder of the dissertation is organized as follows. In Chapter 2, we develop a model of green product development. In Chapter 3, we develop a model of process management with environmental uncertainty. In Chapter 4, we present a simulation-based decision-support system that can be applied to several real-world problems of process management. Chapter 5 summarizes analytical results, and provides guidelines for managing and regulating green product development and process management. The conclusion of the dissertation is given in Chapter 6.

Chapter 2

Green Product Innovation: Product Development with Green and Ordinary Market Segments

2.1 Introduction

Green and Ordinary Products: *Starting from 1997, Chevrolet began to market its S-10 Electric Pickup truck, which was considered much more environmentally friendly than its other models using conventional combustion engines and fuels.*[1] *In the same year, Ford announced that its 1998 Ranger Pickup would include two versions: the traditional and the EV (electric vehicle) versions.*[2]

Green and Ordinary Customers: *The 1997 Automobile Exhibits held in both Los Angeles and Detroit had very different focuses. The Los Angeles show focused on the impact of automobiles on the environment and how to minimize it, with serious attempts being made to arouse public interest in electric vehicles in advance of impending legislation. In Detroit, there was more glitz and hype, with a focus on the vehicle's*

[1] "SWEPCO Makes First Factory EV Pickup," *Power Engineering*, 101 (August 1997), 10.
[2] "1998 Ford Ranger Pickup Has an EV Version," *Automotive Engineering*, 105 (August 1997), 24-25.

traditional performances and economics as opposed to environmental issues.[3]

Environmental Regulations on Green and Ordinary Products: *The U.S. EPA is currently considering new emissions limits for vehicles, which are tougher than the provisions in the 1990 Clean Air Act. In addition, the proposed regulation is likely to use a California-style "fleet average" emissions system under which auto makers can build vehicles with a range of emission levels, but the total fleet has to average out to a certain overall emission level.*[4]

Green product development, which addresses environmental issues through product design and innovation, has received significant attention from consumers, industries, and governments around the world.

Green products are emerging from the demand-pull of customers with new attitudes toward environmental values (Simon 1992). Both the Roper Organization (1990) and Simmons Market Research Bureau (1992) have proposed to segment customers according to their environmental awareness and attitudes. A survey conducted by Gallup (1992) reports that 65% of Americans, 59% of Germans, and 31% of Japanese express their willingness to pay a green premium on an eco-safe product.[5] Bei and Simpson (1995) suggest that, in addition to the utility obtained directly from a purchased good, green consumers also receive psychological benefits from buying an environmentally friendly product.

Green product development is also stimulated by various forms of environmental standards imposed by governments around the world, which have become increasingly more stringent in the past thirty years. Traditionally, environmental legislation in the United States and several other countries has been limited to the end-of-pipe-control approach that merely focuses on controlling the environmental damages caused by the outputs from industrial activities. Such an approach, however, has often resulted in

[3] "Los Angeles and Detroit Shows," *Automotive Engineer*, 22 (February 1997), 16-18.

[4] "Popular Vehicles May Face EPA Hitch," *The Wall Street Journal*, February 5, 1999.

[5] It should be noted that some people only pay lip service to green consumerism. That is, the consumers' green attitudes are not necessarily transferred into actual purchase behaviors. For details, refer to Simon (1992).

transferring pollutants from one medium to the other and in many cases is not cost-effective (Jain 1993). Green product development, which aims to prevent pollution in the first place through product design and innovation, has thus emerged as an innovative and sustainable tool for solving today's environmental problems. Currently, the U.S. Environmental Protection Agency (EPA), collaborating with the industry, is actively promoting the Design for the Environment Program as part of the effort to establish a national policy of preventing or reducing pollution at the source, which is the basic objective of the Pollution Prevention Act of 1990. As a result of these new regulations and initiatives, green product development is likely to become one of the main focuses of public policy in the coming century.

In response to the increasing public interest in environmental protection, many companies have been actively engaging in designing and marketing environmentally friendly products. For a long time, major paper companies have supplied their customers with both recycled and non-recycled papers. In addition to the automobile manufacturers' efforts to produce and market electric vehicles, mentioned previously, many other companies have introduced green products along with their traditional products, such as IBM's "Green" PS/2 Computer,[6] Toro's grass-recycler mower, and Melitta's unbleached coffee filters (Gillespie 1992). A few companies and industry associations have even adopted some voluntary environmental standards on their products that go beyond the control levels required by the government (Roome 1992). Spurred by the global trend of adopting the environmental management standards specified in *ISO 14000* and attracted by the estimated $56 billion opportunity for environmental products and services (Ottman 1992), green product innovation has received significant attention in today's marketplace.

The current trend of green product development, however, is not without its obstacles and pitfalls. First, many environmental attributes, such as fuel economy and recyclability, have effects that conflict with traditional product attributes or performances, such as

[6] "Green Products for Green Profits," *IEEE Spectrum*, 30 (September 1993), 63-66.

safety, material consistency, and convenience. Incorporating satisfactory levels of both green and traditional attributes in one product may pose technical challenges for manufacturers. Second, despite the introduction of green products as alternatives to already existing ordinary products, many customers still stay with ordinary products with low environmental quality due to either cost and performance considerations or simply ignorance and disbelief (Ottman 1998). Third, like most innovation activities, green product development is a task characterized by high levels of risk and uncertainty. Often the R&D investment is costly and its return is highly uncertain. As a result, some companies still adopt a wait-and-see policy instead of actively committing themselves to the development of green products (Roome 1992).

Finally, and perhaps the most importantly, greening itself is not a well-defined concept. Producers, consumers, and the government may have different views on the "greenness" of a product as well as on its actual benefit to the environment (Kleiner 1991). While many producers have been complaining that some environmental regulations imposed by the government are too stringent and can sometimes deter innovative solutions (Porter 1996), environmentalists have been accusing some manufacturers of "green collar crime"–misleadingly touting their products as environmentally friendly (Gillespie 1992). As a consequence, an analytical model that considers the interactions among consumer preferences, producer product decisions, and government environmental policies is needed in order to better understand the impact of green product development upon consumers, industries, and the society as a whole.

The rest of the chapter is organized as follows. Section 2 reviews relevant literature regarding green consumer market, green product design, and environmental regulations. Section 3 establishes a mathematical framework for green product design and consumer choice. The producer's strategic decisions regarding product development and market segmentation are analyzed in Section 4, and the resulting economic and environmental consequences are compared and evaluated in Section 5. Section 6 presents a modification of the model that takes into account the effects of environmental standards on green product development. Section 7 discusses issues concerning the applications of the model. Section 8 extends the analysis to the competition between two firms. Section 9 discusses the robustness and limitations of the model. Section 10 gives a summary and suggests possible extensions of the model.

2.2 Literature Review

Both the fields of psychology (Fishbein 1967) and economics (Lancaster 1966) suggest that products are defined as bundles of attributes (qualities), and consumers may have heterogeneous preferences over these attributes. According to the U.S. EPA (1991), the environmental attribute of a product has become one of the most important factors that affect green customers' purchase decisions in today's consumer market. Typical environmental attributes that are listed on various green consumer guides include recyclability, recycled content, fuel efficiency, toxic content reduction, and emission-related performance [refer to *Shopping for a Better World* by The Council on Economic Priorities (1994) and *Green Guide to Cars and Trucks* by DeCicco and Thomas (1999)]. Products with environmental attributes to which consumers express quantifiable and reportable response are also recognized by the U.S. EPA (1991). In order to reduce consumer confusion due to technical details or false claims of environmental attributes, the U.S. Federal Trade Commission (FTC) has issued guidelines that apply to any marketing claim about the environmental attributes of a product (FTC, 1992). Surveys and studies on consumer preferences toward environmental attributes can be found in Kassarjian (1970), Fawcett (1996), Murtaugh and Gladwin (1980), Henion (1972), Ashton, Erickson, and Larson (1991), and Bei and Simpson (1995). Berger and Kanetkar (1995) use conjoint analysis to measure consumer preferences over environmental attributes (reduced phosphate content and level of concentration) by decomposing consumers' choices among multi-attribute profiles of laundry detergent.

For producers of green products, the inclusion of environmental attributes as an integral part of the design process has become one of the most important and challenging tasks of product development (Mackenzie 1997). Environmental attributes can be incorporated through various design decisions, such as material selection, package design, and energy and solvent usage. According to the U.S. EPA (1991), however, one of the biggest challenges to industry is to develop environmentally friendly products that do not significantly conflict with traditional product attributes or performances, such as safety, speed, and convenience [also refer to EPA (1992), Office of Technology Assessment (1992), and Thurston (1994)]. Due to the multi-objective nature of green product development, very often the improvement of one attribute can only be accomplished at the expense of another (refer to Keeney and Raiffa 1993). For example, Crandall and Granham (1992) study the conflict between vehicle fuel efficiency and safety rating; Boyd and Mellman (1980) consider the reduction in traditional attributes such as style, acceleration, and luxury of a car due to the improvement in fuel economy; De Neufville et al. (1996) discuss the compromise between low emissions and maximum speed and range of an electric vehicle; Malloy (1996) studies the negative impact that the recyclability of a durable product has on quality consistency; *Appliance Manufacturer* (1994) reports the conflict between recycled plastic content and appearance-related attributes in designing computer covers; and Henstock (1988) studies the trade-off between recyclability and advanced material substitution in automobiles.

Environmental attributes of a product have also been the target of many public policies and regulations. In the United States, for example, the federal government has regulated the emissions and fuel efficiency of automobiles for decades (*Clean Air Act: Mobile Sources* and *Corporate Fuel Economy Standards*). While the European government is currently taking the lead in setting recycling targets for various consumer products (Vink 1995), the U.S. government has also considered the recyclability of a product as a potential target of environmental regulations, as in the case of the *National Recycling Markets Act* proposed in 1991. In order to evaluate the effectiveness of these current and potential environmental regulations, we need a quality-based model for analyzing the environmental impact of a product from a product-attribute perspective. Such a quality-based analysis, as a complement to the traditional end-of-pipe control approach, can thus assist in providing one of the missing parts in life-cycle analysis, whose major task involves putting together environmental impact analyses from different stages of a product's life cycle (Henn and Fava 1994).

A considerable literature exists on theoretical models of pollution economics and environmental quality control. Some excellent categorizations of the literature are included in Baumol and Oates (1988) and Greenberg (1995). Most of the literature, however, aims to obtain the optimal control or emission levels of pollution activities from an end-of-pipe perspective without considering the impacts of green product design and innovation. Moorthy (1984) and Moorthy and Png (1992) develop theories for analyzing two or more customer segments with different valuations on the quality of durable products based on consumer self-selection. Their approach, however, does not take into account the interactions of conflicting product qualities and attributes. Based on Thaler's (1985) acquisition-transaction utility theory, Bei and Simpson (1995) assess the determinants of consumers' purchase decision for recycled products, which include the price, believed quality and psychological benefit. Unlike our model, however, their research is more focused on the descriptive side of the problem. Cook (1997) analyzes the impact of environmental quality on the total quality of a product. His approach, however, does not consider market segmentation by customers' environmental value. In the sections that follow, we will present a theoretical model that jointly considers the demand, supply, and policy aspects of green product development.

2.3 Framework

We assume that a monopolist offers a specific class of durable products with two competing attributes, the traditional and environmental attributes, over which individuals may express quantifiable preferences.[7] Given the assumption that both attributes behave like "qualities" (i.e., consumers who value each attribute prefer higher levels to lower levels on the attribute), we will from now on call them traditional and environmental qualities (denoted by q_t and q_e). Due to the competing nature of the two qualities, the sum of q_t and q_e is a constant and scaled to 1. For example, q_t and q_e can represent the levels of safety rating and fuel economy of a vehicle, which usually conflict with each other. Additionally, q_t and q_e can represent the specified levels of any competing traditional and environmental qualities, such as the material consistency and recycled content of a durable product. Note that in both cases, the sum of q_t and q_e should be scaled to 1.

On the demand side, there are two market segments, the ordinary and green segments (denoted by segments o and g), and the sizes of the two segments are denoted by n_o and n_g. Customers in the ordinary segment value a unit of a product with qualities q_t and q_e at $v_t q_t$, where v_t is the positive marginal valuation on the traditional quality; i.e., the environmental quality q_e is not valued by the ordinary customers at all. Customers in the green segment value a unit of a product with qualities q_t and q_e at $v_t q_t + v_e q_e$, where v_t and v_e are the positive marginal valuations on the two qualities; i.e., green customers derive additional utility $v_e q_e$ from q_e (refer to Bei and Simpson 1995). In the context of conjoint analysis, v_t and v_e represent the part-worths of traditional and environmental attributes. The overall utility derived from any product by a customer is the sum of the part-worths of the individual attribute levels present in that product (refer to Zufryden 1977, Kohli and Sukumar 1990, Raman and Chhajed 1995). We also assume that there is no repeat purchase; i.e., customers will leave the market forever after they have bought a unit of the product, regardless of the product type.

On the supply side, the monopolist intends to supply all the customers $(n_o + n_g)$ in the market with either a single or multiple product type(s).[8] The cost of supplying a

[7] We analyze durable products since their environmental attributes (e.g. energy efficiency, emissions, and CFCs content) are most heavily regulated and controlled by the government.

[8] We assume that the monopolist intends to supply all its customers so that the analyses and comparisons that follow will be based on the same sales volume (i.e. the producer maintains its entire customer base) and consumption pattern (i.e. no customer in the society is excluded from the consumption

product increases as a quadratic function with respect to the levels of its two qualities. That is, the unit cost of a product with qualities q_t and q_e is $c_t q_t^2 + c_e q_e^2$, where c_t and c_e are positive cost coefficients. Assume that there is a fixed cost F associated with introducing any product type (for R&D and other relevant expenses). Assume further that there are no economies of scale so that unit cost is independent of the number of units produced. Notice that, unlike Moorthy and Png's (1992) model, we retain the fixed cost of introducing any product type to the market so that the relatively higher costs in R&D and other relevant fixed expenses for developing green products can be taken into consideration.

Based on the analytical framework established above, we can solve for the two segments' efficient qualities, the qualities that maximize the differences between the customers' valuations and the producer's production cost. In our model, the efficient qualities for the ordinary segment (denoted by q_t^{o*} and q_e^{o*}) maximize $v_t q_t - (c_t q_t^2 + c_e q_e^2)$, and the efficient qualities for the green segment (denoted by q_t^{g*} and q_e^{g*}) maximize $v_t q_t + v_e q_e - (c_t q_t^2 + c_e q_e^2)$. By standard calculus, we have

$$q_t^{o*} = \frac{2c_e + v_t}{2(c_t + c_e)}, \quad q_e^{o*} = \frac{2c_t - v_t}{2(c_t + c_e)}, \text{ and} \tag{2.1}$$

$$q_t^{g*} = \frac{2c_e + (v_t - v_e)}{2(c_t + c_e)}, \quad q_e^{g*} = \frac{2c_t - (v_t - v_e)}{2(c_t + c_e)}. \tag{2.2}$$

If the two market segments are perfectly separable, the producer will maximize her profit by offering two different products to the ordinary and green segments with their respective efficient qualities, and setting the prices equal to the valuations on these products. From now on, we will call the product introduced specifically to the green segment the green product, as opposed to the ordinary product targeted to the ordinary segment. Note that in order to simplify our analysis, though corner solutions might exist, we will focus our attention on the interior solutions throughout the chapter (i.e., $2c_t \geq v_t$ and $2c_e \geq v_e$ so that all the qualities are nonnegative and not larger than 1).

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activity).

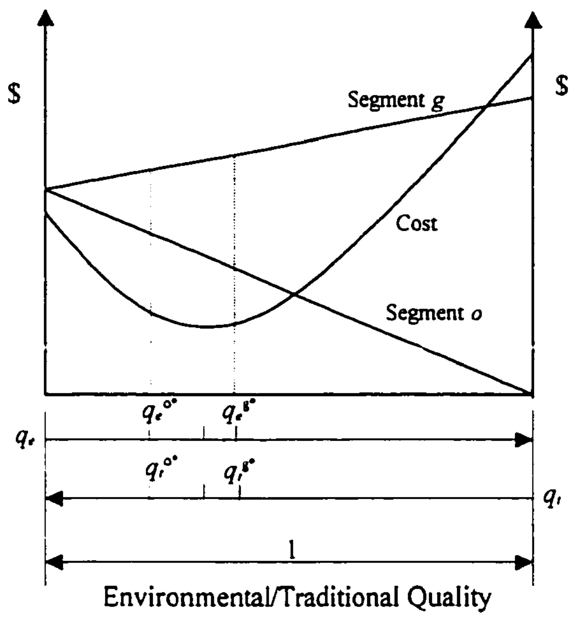

Figure 2-1: Valuation and Cost Structures of the Model

Figure 2-1 shows an example of the cost and preference structures for the problem. Moving toward the left end of the quality axis means increasing the level of the traditional quality while at the same time, due to the technological constraint of conflicting attributes, decreasing the level of the environmental quality. The firm's objective is to find the products with the quality combinations that maximize its profit. It should be noted that the graph is constructed for a particular situation where $v_e > v_t$ and $c_e > c_t$. In all the analyses throughout the chapter, we impose no restrictions on the relationships between v_e and v_t or between c_e and c_t.

2.4 Mass Marketing versus Marketing Segmentation with Self-Selection

In many real-world situations where the ordinary and green customers are not perfectly separable, the producer must jointly address both the ordinary and green segments.

Assume that, given the information about production costs and consumer preferences, the monopolist must adopt a product strategy that specifies the number of products introduced to all its customers as well as the corresponding qualities and prices before any sales take place. Two product strategies are of interest here. The status quo strategy, adopted by most firms that do not engage in green product development, is to introduce a single product to both segments, which is called the mass-marketing strategy in the chapter. In contrast, the strategy of green product development is to introduce a green product, along with its traditional counterpart, to both the green and ordinary segments, which is called the market-segmentation strategy. We will now apply the framework developed in the previous section to analyzing these two product strategies.

2.4.1 The Status Quo Strategy: Mass Marketing

Under the mass-marketing strategy, a single product is developed and introduced to serve both segments, and the firm will face the following problem, where p, q_t, and q_e are the price, traditional quality, and environmental quality of the product.

$$\max\ \pi = (n_o + n_g)(p - c_t q_t^2 - c_e q_e^2) - F, \tag{2.3}$$

subject to:

$$v_t q_t \geq p, \tag{2.4}$$

$$v_t q_t + v_e q_e \geq p, \tag{2.5}$$

$$q_t + q_e = 1, \tag{2.6}$$

$$p, q_t, q_e \geq 0. \tag{2.7}$$

The objective function (2.3) is to maximize the firm's profit from selling the single product to the two segments, which is equal to the revenue minus the production and fixed costs. Constraints (2.4) and (2.5) are the participation constraints imposed to make sure that the utilities derived from the product for both segments are nonnegative. Constraint (2.6) is the technological constraint that reflects the conflicting nature of the traditional and environmental qualities.

To solve the problem, we will follow the solution procedure proposed by Moorthy and Png (1992). Notice that constraint (2.4) is binding because the firm must set the price equal to $v_t q_t$, the ordinary customers' valuation, in order to serve both segments. Any higher price will prevent the ordinary customers, who have a lower willingness-to-pay, from buying the product. Since constraints (2.4) and (2.6) are binding, we can solve the problem and obtain the following proposition concerning the optimal qualities of the single product.

Proposition 1 ***(Optimal Single Product).*** *The optimal traditional and environmental qualities for the mass-marketing strategy are given by*

$$q_t^1 = \frac{2c_e + v_t}{2(c_t + c_e)} \text{ and } q_e^1 = \frac{2c_t - v_t}{2(c_t + c_e)}. \tag{2.8}$$

The proposition indicates that the firm's optimal policy is to design a product with the ordinary segment's efficient qualities (compare (2.1) and (2.8)) and set the price equal to the ordinary customers' valuation on these qualities. Note that since the green segment's participation constraint (2.5) is not binding, the problem is actually optimized as if there were no green customers. This is why mass marketing is referred to as the status quo strategy, corresponding to the situation where a firm adopts a wait-and-see policy and largely ignores the call from green customers for environmentally friendly products.

2.4.2 Green Product Development: Market Segmentation with Self-Selection

If the firm decides to develop a product specifically for the green segment in addition to the ordinary product, it will face the following problem, where p_o, q_t^o, q_e^o, p_g, q_t^g, q_e^g are the prices, traditional qualities, and environmental qualities for the ordinary and green segments.

$$\max\ \pi = n_o(p_o - c_t q_t^{o^2} - c_e q_e^{o^2}) + n_g(p_g - c_t q_t^{g^2} - c_e q_e^{g^2}) - 2F, \tag{2.9}$$

subject to:

$$v_t q_t^o - p_o \geq v_t q_t^g - p_g, \tag{2.10}$$

$$v_t q_t^g + v_e q_e^g - p_g \geq v_t q_t^o + v_e q_e^o - p_o, \tag{2.11}$$

$$v_t q_t^o \geq p_o, \tag{2.12}$$

$$v_t q_t^g + v_e q_e^g \geq p_g, \tag{2.13}$$

$$q_t^o + q_e^o = 1, \tag{2.14}$$

$$q_t^g + q_e^g = 1, \tag{2.15}$$

$$p_o, p_g, q_t^o, q_e^o, q_t^g, q_e^g \geq 0. \tag{2.16}$$

The objective function (2.9) is to maximize the revenues from selling products in both segments minus the production costs and the fixed charge for introducing two different product types. In addition to the participation constraints (2.12) and (2.13), constraints (2.10) and (2.11) are the self-selection constraints imposed to make sure that customers in each segment will voluntarily choose the product-price combination designated to them, which provides them with higher utility than the product designated to the other segment.

To solve the problem, we must deal with possible cannibalization between the two products. Notice that constraint (2.13) cannot be binding or else the customers in the green segment will switch to the ordinary product and enjoy a positive surplus, since $p_o \leq v_t q_t^o \leq v_t q_t^o + v_e q_e^o$. Nothing, however, can prevent the firm from extracting the entire consumer surplus from the ordinary segment, and thus constraint (2.12) is binding ($p_o = v_t q_t^o$). Observe that $v_t q_t^g - v_t q_t^o \leq p_g - p_o$ by constraint (2.10) and $p_g - p_o \leq (v_t q_t^g + v_e q_e^g) - (v_t q_t^o + v_e q_e^o)$ by constraint (2.11). Therefore, constraints (2.10) and (2.11) cannot both be binding or else $q_e^g = q_e^o$ (i.e., only one product is offered). Since customers in the green segment have a higher willingness-to-pay given any positive level of environmental quality, p_g should be determined at the level where green customers are indifferent between the two products (i.e., constraint (2.11) is binding). Note that p_g is not a monopoly pricing because, in order to avoid cannibalization, the producer cannot extract the entire consumer surplus from the green segment. Since constraints (2.11) and (2.12) are both binding, we can solve the problem and obtain the following proposition concerning the optimal qualities under the market-segmentation strategy, where n_o^g denotes the ratio between the two market sizes (n_g/n_o).

Proposition 2 ***(Optimal Multiple Products).*** *The optimal traditional and environmental qualities for the market-segmentation strategy are given by*

$$q_t^{o,2} = \frac{2c_e + v_t + n_o^g v_e}{2(c_t + c_e)},\ q_e^{o,2} = \frac{2c_t - v_t - n_o^g v_e}{2(c_t + c_e)} \text{ and} \tag{2.17}$$

$$q_t^{g,2} = \frac{2c_e + v_t - v_e}{2(c_t + c_e)},\ q_e^{g,2} = \frac{2c_t - v_t + v_e}{2(c_t + c_e)}. \tag{2.18}$$

The proposition indicates that the firm's optimal policy requires supplying the green segment with a "green product" with the segment's efficient qualities, while adjusting q_t^o and q_e^o (or more specifically, increasing q_t^o and decreasing q_e^o) according to $n_o^g v_e/2(c_t+c_e)$ so that green customers will not switch to the ordinary product. Figure 2-2 is an illustration of the optimal prices and qualities for both the mass-marketing and market-segmentation strategies. Notice that the optimal qualities for the market-segmentation strategies are located on the opposite sides of the optimal quality for the mass-marketing strategy, and $q_t^{o,2}$ and $q_e^{o,2}$ are so determined that green customers are indifferent between the ordinary and green products under the market-segmentation strategy (i.e., $v_t q_t^{g,2} + v_e q_e^{g,2} - p_g = v_t q_t^{o,2} + v_e q_e^{o,2} - p_o$).

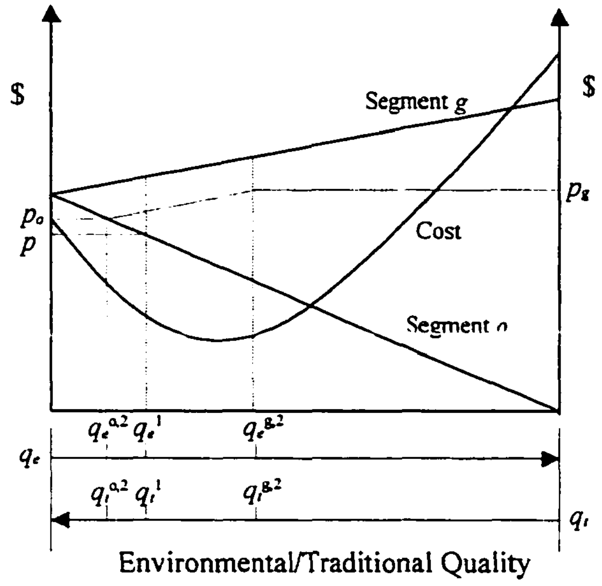

Figure 2-2: The Mass-Marketing and Market-Segmentation Strategies

2.5 Environmental and Economic Consequences

Based on the optimal prices and qualities obtained in the previous section, we will examine the environmental and economic consequences under both the mass-marketing and market-segmentation strategies. Specifically, we are interested in the overall environmental quality supplied by the firm and the economic incentive for green product development.

2.5.1 Can Green Products Benefit the Environment?

The total environmental quality is defined as the aggregate sum of environmental quality specified in all the products in the market. That is, the overall environmental quality is assumed to be linearly additive across all the products.[9] Let TG_1 and TG_2 denote

[9]The index of total environmental quality represents the improvement in environmental quality or the reduction in environmental damage as a result of the use of all products sold by the monopolist with the environmental attribute of interest. If the gas mileage of a car is the environmental attribute of interest, for example, then the total environmental quality can be used to compute the total gasoline consumption

the total environmental qualities under the mass-marketing and market-segmentation strategies. The comparison of $TG_1 = (n_o + n_g)q_e^1$ and $TG_2 = n_o q_e^{o,2} + n_g q_e^{g,2}$ yields the following surprising result.

Proposition 3 *(Environmental Quality). A monopolist will supply the same amount of total environmental quality under both the mass-marketing and market-segmentation strategies, and this quality is equal to*

$$TG_1 = TG_2 = (n_o + n_g)\left[\frac{2c_t - v_t}{2(c_t + c_e)}\right]. \tag{2.19}$$

The proposition indicates that the overall environmental quality is not improved as a result of green product development. The reason behind such a surprising result can be found by inspecting (2.8), (2.17), and (2.18). Due to the introduction of a green product to the green segment, the overall environmental quality is improved by $n_g v_e/2(c_t + c_e)$ compared to that of the mass-marketing strategy. To prevent the green customers from switching to the ordinary product, however, the environmental quality of the ordinary product is decreased according to $n_o^g v_e/2(c_t + c_e)$ in order to "spoil" the green customers' taste for the ordinary product. As a consequence, the improvement in environmental quality from the green product is negated by the degradation in environmental quality from the ordinary product with the same amount, and the total environmental quality does not actually increase. To determine the actual "greenness" of a company, it is important to examine the environmental quality of all its products introduced to different market segments. This is possibly why some environmental regulations, such as the *Corporate Average Fuel Economy Standards* and the newly proposed California-style emission standards by EPA, are focused on the average or aggregate instead of the highest level of environmental quality achieved by a company's products.

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of the company's entire new fleet given information about the total gas mileage and average mileage traveled by car per year. Similarly, if the environmental attributes are recyclability, recycled content, emission reduction, and toxic content reduction, the total environmental quality would represent the total solid waste reduction, source reduction, emission reduction from tailpipes, and toxic waste reduction, respectively.

2.5.2 Economic Incentive for Green Product Development

We will now turn our attention to the economic consequences under the two strategies. Particularly, we are interested in the economic incentive for the firm to switch from mass marketing, the status quo strategy, to the market-segmentation strategy via green product development. Let's start with calculating π_1 and π_2, the profits under the mass-marketing and market-segmentation strategies, respectively. Substituting the optimal prices and qualities under the two strategies into (2.3) and (2.9), we have

$$\pi_1 = (n_o + n_g)\left[\frac{4c_e(v_t - c_t) + v_t^2}{4(c_t + c_e)}\right] - F \text{ and} \tag{2.20}$$

$$\pi_2 = n_o\left[\frac{4c_e(v_t - c_t) + v_t^2 - {n_o^g}^2 v_e^2}{4(c_t + c_e)}\right] + n_g\left[\frac{4c_e(v_t - c_t) + v_t^2 + v_e^2 + 2n_o^g v_e^2}{4(c_t + c_e)}\right] - 2F. \tag{2.21}$$

The economic incentive for green product development is defined as the additional profit obtained by switching from the mass-marketing strategy to the market-segmentation strategy. A profit-maximizing firm will introduce two products, one for each segment, if and only if the economic incentive is nonnegative. Let I denote the economic incentive for green product development. We can solve for I by calculating $\pi_2 - \pi_1$ from (2.20) and (2.21), which leads to the next proposition.

Proposition 4 ***(Economic Incentive).*** *The producer's economic incentive for green product development is*

$$I = \frac{n_g v_e^2(n_o^g + 1)}{4(c_t + c_e)} - F. \tag{2.22}$$

The importance of Proposition 4 is in identifying the major driving forces and obstacles for green product development. The driving forces include the number of green customers and their marginal valuation on environmental quality, while the obstacles include the number of ordinary customers, the fixed cost, and the cost coefficients for installing both the green and traditional qualities. Additionally, Proposition 4 also implies that green innovations can be encouraged through proper manipulation of the economic incentive. For example, a number of "green consumer guides" published by environmental groups have been aimed to increase the number of green customers as well as to enhance their environment values through better consumer education. A variety of environmental policies, such as the regulatory and voluntary environmental standards, have been implemented by both the government and industry-wide or international standardization associations for the purpose of providing the industry with greater incentive for green product development. Based on the model developed above, we are going to evaluate the effects of the standards approach, one of the most widely adopted environmental policies, in the following section.

2.6 Effects of Environmental Standards

The rather discouraging result in the previous section that the introduction of a green product to green customers does not necessarily benefit the environment as a whole can be avoided by the enforcement of environmental standards. Such standards include those specifically required by the government and those self-regulated environmental standards guided by industry-wide associations (such as the *Responsible Care* program for the chemical industry) or by international standardization organization (such as the *ISO 14000*). As we will see in our analysis, given a required minimum level of environmental quality so that the firm cannot reduce the environmental quality of the ordinary product to too low a level, green product development can actually benefit the environment.

We will start with the three critical levels of environmental qualities: q_e^1, $q_e^{o,2}$, and $q_e^{g,2}$, which are the optimal environmental quality under the mass-marketing strategy and the optimal environmental qualities for the ordinary and green segments under the market-segmentation strategy, respectively (see (2.8), (2.17) and (2.18)). We have the following relationship:

$$q_e^{o,2} = \frac{2c_t - v_t - n_o^g v_e}{2(c_t + c_e)} \leq q_e^1 = \frac{2c_t - v_t}{2(c_t + c_e)} \leq q_e^{g,2} = \frac{2c_t - v_t + v_e}{2(c_t + c_e)}. \tag{2.23}$$

Assume that there is a standard that requires r as the minimum level of environmental quality. For this standard to be effective, we need $q_e^{o,2} < r < q_e^{g,2}$. Otherwise, any $r \leq q_e^{o,2}$ would have no effect on any of the optimal environmental qualities, and any $r \geq q_e^{g,2}$ would eliminate the market-segmentation strategy (i.e., only one product can be offered). Let's now examine the effects of the environmental standards on both the mass-marketing and market-segmentation strategies.

2.6.1 The Regulated Mass-Marketing Strategy

To evaluate the effect of the environmental standard on the mass-marketing strategy, we discuss two different cases depending on whether or not the standard is effective within a certain range. In the first case, $r \leq q_e^1$, the environmental standard has no effect on the mass-marketing strategy, and the regulated total environmental quality (denoted by TG_1^r) and profit (denoted by π_1^r) are the same as TG_1 and π_1 given in (2.19) and (2.20); i.e., $TG_1^r = TG_1$ and $\pi_1^r = \pi_1$ for $r \leq q_e^1$. In the second case, $r > q_e^1$, the environmental standard will be higher than the optimal environmental quality under the unregulated mass-marketing strategy, and the new optimal qualities are given by $q_e^r = r$ and $q_t^r = 1-r$. We thus have the total environmental quality and profit for $r > q_e^1$ as follows:

$$TG_1^r = (n_o + n_g)r \text{ and} \tag{2.24}$$

$$\pi_1^r = (n_o + n_g)\left[v_t - c_t + (2c_t - v_t)r - (c_t + c_e)r^2\right] - F. \tag{2.25}$$

By comparing (2.19) to (2.24) and (2.20) to (2.25), we have $TG_1^r \geq TG_1$ and $\pi_1^r \leq \pi_1$, which indicates that any $r > q_e^1$ will reduce the firm's profit but enhance the total environmental quality under the mass-marketing strategy.

2.6.2 The Regulated Market-Segmentation Strategy

By adding to the market-segmentation problem (refer to Section 2.4.2) the additional constraints $q_e^o \geq r$ and $q_e^g \geq r$ and solving the problem accordingly, the optimal environmental qualities for the ordinary and green segments are given by $q_e^{o,r} = r$ and $q_e^{g,r} = q_e^{g,2}$, respectively. These regulated optimal environmental qualities indicate that the producer should still supply a product with the segment's efficient qualities to the green segment, while supplying a product with the required minimum level of environmental quality to the ordinary segment. Based on the optimal qualities, we can calculate the regulated total environmental quality (TG_2^r) and profit (π_2^r) for any $r > q_e^{o,2}$ as follows:

$$TG_2^r = n_o r + n_g \left[\frac{2c_t - v_t + v_e}{2(c_t + c_e)}\right] \text{ and} \tag{2.26}$$

$$\pi_2^r = n_o \left[v_t - c_t + (2c_t - v_t)r - (c_t + c_e)r^2\right] + n_g \left[\frac{4c_e(v_t - c_t) + v_t^2 + v_e^2 + 2v_e(2c_t - v_t) - 4v_e(c_t + c_e)r}{4(c_t + c_e)}\right] - 2F. \tag{2.27}$$

By comparing (2.19) to (2.26) and (2.21) to (2.27), we have $TG_2^r \geq TG_2$ and $\pi_2^r \geq \pi_2$, which indicates that any effective environmental standard will reduce the firm's profit but enhance the total environmental quality under the market-segmentation strategy.

2.6.3 Can the Standards Approach Benefit the Environment?

By comparing the total environmental qualities in (2.19), (2.24), and (2.26), we obtain the relationship $TG_1 = TG_2 \leq TG_1^r < TG_2^r$ for any $q_e^{o,2} < r < q_e^{g,2}$, which leads to our next proposition.

Proposition 5 ***(Environmental Standards).*** *The total environmental quality of the regulated market-segmentation strategy is higher than that of the regulated mass-marketing strategy and those of the unregulated mass-marketing and market-segmentation strategies.*

The important message revealed from Proposition 5 is that, given an appropriate environmental standard, green product development can actually benefit the environment.

Finding such a standard, however, is not a straightforward task, as we demonstrate in the analysis that follows. Although both (2.24) and (2.26) suggest that the stricter the environmental standard (the larger r), the higher the resulting total environmental quality, the firm's actual response to the standard cannot be fully understood without examining its impact on profitability.

We now turn our attention to the firm's profit under the regulated mass-marketing and market-segmentation strategies. Specifically, we are interested in the incentive for green product development given any effective environmental standard. Observe that both π_1^r and π_2^r in (25) and (27) are concave in r. It can be shown (see Appendix) that as r increases from $q_e^{o,2}$ to $q_e^{g,2}$, π_2^r decreases faster than does π_1^r. In fact, given any positive unregulated economic incentive for green product development, it can be shown that there exists a unique critical standard level r^c within the range $(q_e^{o,2}, q_e^{g,2}]$ that leaves the firm with no incentive at all. As a consequence, the firm will switch back to the mass-marketing strategy after the environmental standard is tightened beyond its critical level.

2.6.4 The Danger Zone

Based on the above analysis, Figure 2-3 illustrates the path which the firm will follow as it reacts to an environmental standard that is tightened from $q_e^{o,2}$ to $q_e^{g,2}$ given any positive unregulated economic incentive for green product development.[10] According to the graph of profit functions, the firm will choose the market-segmentation strategy before the critical level of environmental standard r^c is reached and will choose the mass-marketing strategy afterwards. As a result of the switch in product strategy, the total environmental quality will experience a slump right after the environmental standard is tightened beyond its critical level. As shown in the graph of total environmental (green) qualities, there exists a "danger zone" within which the total environmental quality is

[10]There is a slightly different version of this graph where the two profit functions intersect within the range $[q_e^1, q_e^{g,2}]$. The analytical results derived from the two versions, however, are quite similar.

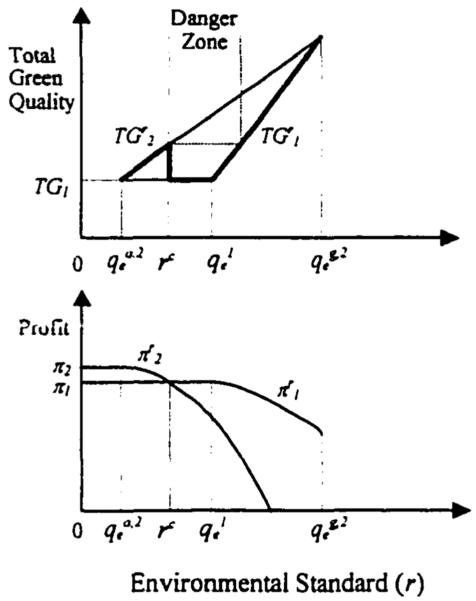

Figure 2-3: Relationship between Regulated Profit & Total Environmental Quality

lower than its adjacent regions, which leads to our next proposition.

Proposition 6 ***(Danger Zone).*** *Given an environmental standard being tightened from $q_e^{o,2}$ to $q_e^{g,2}$, there exists a range within which a stricter standard may result in a lower level of total environmental quality.*

While a stricter environmental standard can directly lead to a higher level of total environmental quality (as shown in Proposition 5), it can also deprive the firm of flexibility in introducing different products to different market segments. As the environmental standard becomes stricter and stricter, the firm may eventually lose its incentive for green product development and be content with its role as a compliance-only producer who merely introduces a single product with the required minimum level of environmental quality. The existence of the danger zone thus demonstrates the importance of balancing the strictness and innovation-friendliness of a good environmental standard.

As mentioned in Section 1, the newly proposed vehicle emission standards by EPA may use a California-style "fleet average" emissions system that requires an average environmental quality from the entire fleet of an automaker instead of from each individual product. It can easily be shown that such a system has the advantage of avoiding the danger zone since it is equivalent to requiring an aggregate level of environmental quality given a fixed number of total customers. However, the regulator should be aware of the possibility of driving the firm out of business, since, as shown in Figure 2-3, a tightened aggregate standard would have a larger impact on the firm's profitability than a tightened standard on each individual product.

2.7 Applications

The success of green product development and its actual benefit to the environment depend heavily on the joint effort by both the private and public sectors. The model presented in this chapter can be applied to different levels of managerial or governmental decision-making processes, including the production and pricing decisions at the technical and operational levels as well as the formulation of environmental policy at the strategic level.

2.7.1 Designing and Pricing Green Products

The recent trend of globalization has called for the implementation of international environmental standards, such as *ISO 14000*, by cross-functional teams, including production, marketing, accounting, and legal personnel, at almost every level of the managerial decision-making processes (Schiffman, Delaney, and Fleming 1997). The model presented in this chapter, which addresses the issue from an interdisciplinary perspective, provides a decision-supporting tool for dialog as well as for arriving at joint decisions concerning green product development among different departments within an organization. Four types of information are of importance here: the technical trade-off between traditional and environmental qualities, the part-worths from conjoint analysis, the numbers of ordinary and green customers, and the levels of environmental standards. With the correct assessment of all these critical data by cross-functional teams, a firm would be able to design green products with the optimal quality levels given in Section 3 and Section 5.

The model also provides a simple rule of thumb for pricing green products. The conventional perception that the price of a green product should be higher than that of its ordinary counterpart is not necessarily true. It can be easily shown from the analytical results in Section 3 that $p_g - p_o > 0$ if and only if $v_e > v_t$. That is, if the green customers' marginal valuation on the environmental quality is higher than that on the traditional quality, the green product should be priced higher than the ordinary product, and vice versa.[11]

2.7.2 Environmental Policy Making

For the private sector, the model can serve as a basis for planning and implementing a company's environmental policy through the environmental management system required by *ISO 14000*. Specifically, the analytical results in Section 5 can be used to set up environmental objectives and targets as well as to monitor continuous improvement. Recall that the minimum level of environmental quality r can represent either the external standard imposed by the government or the internal green target voluntarily adopted by a company. The reaction paths exhibited in Figure 2-3 can thus be applied to identifying the product strategy that leads to better environmental quality as a voluntary target becomes higher and higher in order to ensure continuous improvement over time. Additionally, for those firms who commit themselves to pursuing premium greening objectives, the analytical framework can be modified to maximize the total environmental quality given a pre-specified profit level.

For the public sector, the model can be used to analyze the important trade-off between the environmental and economic impacts of an environmental regulation. Green product development is not only an environmental performance, but also an economic

[11]A survey done by Cude (1993) also reports that the prices of green products are not necessarily higher than ordinary products.

practice. While a meaningful internal or external environmental standard is needed in order to ensure the environmental benefit from green product development, unilaterally pursuing environmental goals without considering the industry's economic incentive may end up in the "danger zone," where a stricter standard leads to a lower overall environmental quality. To encourage innovative environmental solutions such as green product development, it is of crucial importance for the government to balance the strictness and innovation-friendliness of its environmental regulations.

2.8 Competition between Two Firms

In this section, we extend our analysis to the competition between two firms in a market with both ordinary and green segments. Suppose that a new entrant is about to enter the market, and it has the same cost structure as does the incumbent who is currently using the market-segmentation strategy. What type(s) of products should the new entrant introduce and how should the incumbent respond to the competition triggered by the new entrant?

We start with a simple situation where the new entrant introduces only a single product. Given the cost and valuation structures illustrated in Figure 2-2, suppose that the new entrant introduces a product with the optimal qualities under the mass-marketing strategy (i.e., q_t^1 and q_e^1), and prices it just a little lower than the ordinary customers' valuation on the product (i.e., p in Figure 2-2). It can be shown that the new entrant would then capture the entire market (with both segments). Since the current strategy adopted by the incumbent is to extract as much consumer surplus as possible from all its customers, any new entrant who is willing to undercut the prices is likely to attract those customers who are barely satisfied by the current products and prices offered by the incumbent.

How will the incumbent defend its market given the competition from the new entrant? To protect the green segment, the incumbent will lower the price of the green

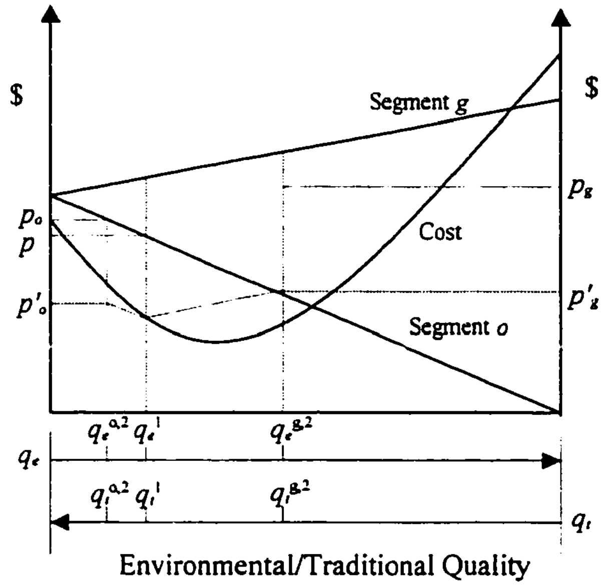

Figure 2-4: The Impact of Competition

product to a level where green customers receive more utility from the incumbent's product than that from the new entrant's. Suppose that the new entrant lowers its price all the way down to its marginal cost at the quality levels q_t^1 and q_e^1, as in the case of Bertrand paradox (refer to Tirole 1988), the incumbent will protect the green segment by lowering its price down to p'_g, as shown in Figure 2-4. As a consequence, the overall consumer surplus of green customers will increase due to the competition between the incumbent and the new entrant.

To protect the ordinary segment, however, the incumbent must do something more than lowering its price of the ordinary product. As shown in Figure 2-4, if the new entrant prices its product at the marginal cost, the incumbent must lower the price of the ordinary product all the way down to p'_o in order to protect the ordinary segment, which will result in a negative profit since the price is now lower than the marginal cost of the ordinary product with quality levels $q_t^{o,2}$ and $q_e^{o,2}$. In order to remain competitive as well as to earn a positive profit, the incumbent must therefore increase the environmental quality of the ordinary product (to a level higher than q_e^1) as well. As a result of competition, the incumbent voluntarily increases its supply of total environmental quality even in the absence of regulatory pressure. We thus show that competition can also benefit the environment.

It is noted that the above analysis is based merely on a single move by the new entrant. In order to analyze more realistic situations, we need to consider the actions and reactions by both the incumbent and new entrant in a dynamic, competitive environment. The problem would be further complicated when both competition and cannibalization among all the products in the market are taken into consideration.

2.9 Robustness of the Model

In this chapter, we derive a number of qualitative results concerning how green product development is conducted and regulated by industry and government based on a mathematical model that jointly considers the demand, supply, and policy sides of the problem. Several key assumptions of the model, however, are untested, and, as a result, need to be further investigated. Three key issues concerning the robustness of the model are discussed as follows:

The Quadratic Cost Function

For simplicity, we assume quadratic cost functions in the model. This assumption is needed in order for the optimal solution to exist, given the linear structure of consumer preference. It can be shown that the qualitative results derived from the model will still be valid given different types of convex cost functions. For example, the cost function in the form of aq^b, where $a > 0$ and $1 \leq b \leq 2$, can also lead to optimal solutions for both the mass-marketing and market-segmentation strategies. Although the exponential cost function will complicate the optimal solutions, its two-parameter functional form can better represent the cost structure of product development in many real-world situations than the quadratic form cq^2 which has only a single parameter.

Competing Product Attributes

The model primarily concerns the design of green products with competing environmental and traditional attributes under the existing product boundary or efficient frontier within which product attributes are physically packaged (refer to Cook 1997). It should be noted that, however, some environmental innovations involve developing breakthrough products or technologies that will expand the existing product boundary or efficient frontier so that both the traditional and environmental attributes can be simultaneously improved. Such a situation is beyond the scope of the model. For example, with the technological advance in manufacturing lighter but stronger all-aluminum chassis that matches steel's strength and resistance, the design goals of safety and fuel economy of an automobile would no longer be mutually exclusive (Henry 1999). As a result, the assumption of competing relationship between environmental and traditional attributes corresponding to the current product concept of an automobile (made primarily from steel) may no longer hold.

It should also be noted that the scope of the model is restricted by the assumption that the competing relationship between traditional and environmental attributes is linear (i.e., $q_t + q_e = 1$). In many real-world situations where product decisions involve more than two attributes, all the traditional and environmental attributes must be grouped according to their interactions with one another (refer to Cook 1997). The model can then be used to deal with those attribute pairs with linear competing relationship. The model cannot be used, however, in situations where the competing relationship is not linear or where there exist three-way interactions among multiple attributes. Under such situations, a producer needs to use other methods for multi-attribute product design such as Quality Function Deployment (refer to Green and Srinivasan 1990, Cook 1997).

Measurability of Attributes

The scope of the model is restricted by the assumption that a green customer is able to express quantifiable valuation on a product's environmental attributes whose different levels can be directly related to the product's contribution to the improvement of the natural environment, such as fuel efficiency, recyclability, and recycled content. These attributes generally fall into the category of "intrinsic attributes" in marketing literature (refer to Olson and Jacoby 1973), as they are part of the physical product. The assumption may not be applied to a product's extrinsic type of environmental attributes that are not part of the physical properties of the product, such as "no animal testing" and "manufactured through green processes," since it would be quite difficult for a consumer to quantitatively relate their different levels to the very product's direct impact on the natural environment. Additionally, for those products whose environmental attributes cannot be accurately assessed without in-depth technical and scientific knowledge, a consumer may not be able to undertake a quantifiable evaluation without proper informational aides, even when the attributes are intrinsic in nature, as in the case of ozone-depleting products. Green labels and green consumer guides may provide valuable information that is originally beyond the reach of most consumers. Nevertheless, the accuracy and effectiveness of the methodologies used to evaluate products' environmental attributes and to award green labels remain quite controversial (Wynne 1994, Wagner 1997). It should be noted that, without an effective product labeling or information system, a consumer may not be able to evaluate those technically complex environmental attributes due to their poor observability (refer to Chen 2000).

2.10 Concluding Remarks

The current trend of green product development is pulled by the consumers, spurred by the government's regulations, and implemented by the industries. The model presented in this paper jointly considers the interactions of all the three major forces in today's marketplace. On the demand side, we use the framework of conjoint analysis to model the purchase behavior of green customers. On the supply side, we apply the theories in optimal product design and market segmentation to the analysis of the firm's strategic decisions regarding the number of products introduced and their corresponding prices and qualities. On the policy side, we employ our model to examine the interactive relationships among environmental standards, the firm's strategic choices, and the overall environmental quality. In addition, we use the model to present two major findings: green product development and stricter environmental standards might not necessarily benefit the environment. In the future, it is expected that the model developed here can be applied to analyzing other strategic and policy issues that are not considered in this paper. Some possible examples include the firm's option of serving the green segment only as the number of green customers becomes larger and larger, and the government's regulatory options such as taxes and marketable pollution permits.

As mentioned previously, an environmental problem usually involves multiple pollution sources. The results derived from the model, which only focuses on one product-related environmental attribute, should therefore be combined with impact analyses at other stages of a product's life cycle in assessing the overall environmental quality. In the chapters that follow, we will develop theoretical and simulation models for green process management which can be integrated with the model of green product development in assessing the overall environmental impact of a supply chain system.

Chapter 3

Green Process Innovation: Process Management with Stochastic Environmental Limits

Environmental Limits Impact Production Processes: *Canada appears to be following the worldwide trend to replace sulfate-based titanium dioxide production with the chloride-based method, which is projected to use to 40% sulfate process and 60% chloride process by 2000. A stepped-up effort by the Canadian Minister of Environment to limit effluents stemming from factory threatens a Tioxide plant with closure and requires Kronos Canada to implement waste treatment at its sulfate-based plant. A motivating factor in the move from sulfate-based processing is decreased wastes, as each ton of pigment produced in sulfate-based processing yields 6 tons of waste, whereas chloride-based plants have a 1-to-1 ratio.*[1]

Environmental Limits Impact Production Planning: *Louisiana-Pacific has invested $70 million in a recovery island for its market pulp mill at Samoa, California. The island has made a major difference in environmental, production, and maintenance areas. The project will include a new low-odor recovery boiler, distributed control system,*

[1] "Titanium Dioxide: Canada Going Sulfate," *Chemical Marketing Reporter*, 241 (June 22, 1992), 3.

and other environmental control equipment. By firing 3 million lbs. of dry solids per day, the new mill will replace 2 existing units that fired 2.1 million lbs. per day. This has allowed the mill to increase production to about 700 ton per day from a previous level of about 630 ton per day. Meanwhile, the mill has been able to significantly improve air quality in the city.[2]

Environmental Limits Impact Inventory Policy: *The gas prices have been sky-rocketing in the Midwest since the early June when the oil industry was required by new environmental regulations to make cleaner-burning gasoline. The oil industry claimed that the cleaner-burning gasoline is more difficult to make than conventional gas and cannot be produced in the same higher volumes. In addition, there is a patent dispute over the process to make the cleaner-burning gasoline. In response to the blame from the industry, the EPA contested that the tight gasoline supplies were not the reason behind the high gasoline prices because total gasoline stocks in the Midwest are 650,000 barrels higher than last year.*[3]

3.1 Introduction

As an essential part of industrial activities, the production process is usually held responsible for most environmental damage that has occurred and continues to take place. From an environmental point of view, the function of a production system is to convert resources into products as primary outputs and wastes as by-products. For each unit of products produced, a certain amount, or ratio, of resources will be generated as wastes. This ratio is referred to as the "pollution index" associated with the production of a particular product type throughout this dissertation. If the pollution index is fixed, the more products the system produces, the higher amount of wastes it will generate. In turn,

[2] "L-P Samoa Mill Improves Air Quality with Recovery Island Modernization," *Pulp & Paper*, 65 (September 1991), 180-185.

[3] "U.S. Gasoline Producers Blame Washington for High Prices," *U.S. News in CNN.com* (June 16, 2000).

given an environmental standard that prohibits the system from generating more than a certain amount of wastes, the stricter the standard, the fewer items the firm can possibly produce. The environmental standard will thus be handled by a firm as a capacity-like limit to the maximum amount of products that a production system can produce.

In many real-world situations, however, the pollution index is not a constant. There are a number of possible causes for an uncertain pollution index. For example, pollution prevention or control technologies that are responsible for waste reduction or treatment may be unavailable for varying periods of time due to unplanned maintenance, human errors, or patent disputes.[4] The concentration of wastes emitted into the natural environment may vary given different spatial and climatic conditions.[5] Even though the environmental standard imposed by the government is fixed, with an uncertain pollution index, the environmental limit perceived by the firm is actually stochastic. As a result, a typical production system faces two kinds of uncertainties: the demand uncertainty and the uncertainty associated with stochastic pollution index given a fixed environmental standard.

Throughout history, industrial wastes have been considered as the primary sources of environmental damages, and, as a result, most environmental standards fall into the category of the so-called "end-of-pipe" approaches, which only focus on controlling production wastes as they enter the natural environment. The recent trend of environmental management, however, emphasizes the prevention and control of environmental impacts along a product's entire life cycle, including energy and material extraction, manufacturing, storage, transportation, consumption, and disposal of the product. The fact is that focusing merely on controlling environmental wastes at the end of the production process may result in transferring pollutants from one medium to another. A life-cycle framework is thus needed in order to identify and then control the overall environmental

[4]For uncertainties associated with environmental technologies, see Lindsey (1998).

[5]For examples of concentration variations of environmental wastes due to spatial or seasonal effects, see Lendvay, et al. (1998) for water pollutants, Salcedo, et al. (1999) for airborne pollutants, and Chandran and Derr (1999) for solid (soil) wastes.

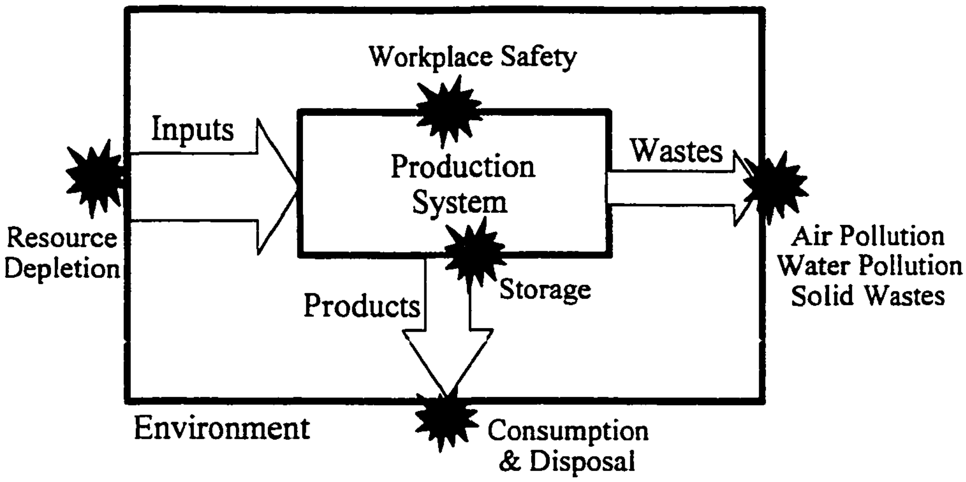

Figure 3-1: A Life-Cycle View of Production System

impact of a production system.

Figure 3-1 illustrates the interaction between a production system and its surrounding natural environment from a life-cycle perspective. A production system can impact the environment in many different ways: its inputs that deplete natural resources; the consumption and disposal of its outputs as final products; the air, water, and solid-waste pollution caused by its outputs as wastes; the environmental risks associated with the storage of semi or final products; and the concern of workplace safety. All these environmental impacts can be identified by tracking the throughput and stock levels of the production system from time to time. Specifically, the following information is necessary in conducting a life-cycle analysis of environmental impacts.

1. **Production**: The amount of production is proportional to the amount of each type of material and energy inputs used as well as the amount of each type of wastes generated during the manufacturing process. The amount of production is also an indication of potential safety concerns and environmental risks in the workplace.

2. **Sales**: The amount of sales reflects the potential environmental risks associated with the consumption and disposal of products.

3. **Inventory**: The amount of inventory indicates the potential environmental risks associated with the storage of semi and final products.

In this chapter, we develop a model to analyze the process that integrates the operations and environmental decisions in a production system. Based on a stochastic inventory model, we explore the qualitative impacts of an uncertain, end-of-pipe environmental limit on the optimal policy of production planning and inventory control. In addition, numerical experiments will be conducted in the next chapter to show how the model can be applied to assisting life-cycle environmental impact analysis by tracking the throughput and stock levels in the production system. Based on the results from qualitative analyses and numerical experiments, we then provide some important managerial insights to process management with both demand and environmental uncertainties.

3.2 Literature Review

Life-cycle analysis is an evolving management approach for assessing the impact of a product upon human health and the environment by examining each stage of the life span of a manufactured item from extraction of raw materials through production or construction, distribution, use, and disposal (Society of Environmental Toxicology and Chemistry 1991). The purpose of such an analysis is to systematically analyze the environmental impacts of products and processes "from cradle to grave" and identify the opportunities to minimize these impacts (Henn and Fava 1994). While green product development and design for the environment have received significant attention from researchers and practitioners, as discussed in the previous chapter, a considerable literature also exists in the areas of green supply chain management and reverse logistics. An excellent categorization of the literature is included in Narasimhan and Carter (1998). Most of the literature, however, is focused on the descriptive side of environmental supply chain management. Extensive surveys of quantitative models that are applied to environmental problems are given in Greenberg (1995) and Bloemhof-Ruwaard et al. (1995).

Few papers in the literature, however, analyze the decisions of production planning and inventory control with additional environmental considerations. Stuart, Ammons, and Turbini (1999) develop a mixed integer programming model for product and process selection with multidisciplinary environmental considerations. Unlike our research that analyzes production decisions constrained by environmental limits or pollution charges, the environmental factors considered in their model are process alternatives such as waste recycling.

A considerable literature exists in Pollution Economics that analyzes the impact of environmental policies on firms' production decisions from macroeconomic perspectives (refer to Baumol and Oates 1988). Beavis and Walker (1983) first model a firm's production and waste-treatment decisions under a probabilistic environmental standard. Their approach is extended to different types of regulatory constraints by Beavis and Dobbs (1987). Most of the economic models, however, do not consider inventory management as an essential way for a production system to deal with demand and environmental uncertainties. Stochastic models for process management and inventory control with various external and internal uncertainties, such as random demand, yield, and capacity, have been widely studied by operations researchers (see Arrow, Karlin, and Scarf 1958, Hadley and Whitin 1963, Hax and Candea 1984, Monahan and Smunt 1989, Henig and Gerchak 1990, Anupindi and Akella 1993, Ciarallo, Akella, and Morton 1994, Wang and Gerchak 1996). Most of the operations models, however, do not take into account the environmental implications of a firm's decisions concerning production planning and inventory control. By adding environmental components, such as pollution indexes, environmental standards, and pollution charges, into a classic stochastic inventory model, we will develop a model for production planning and inventory control with both demand and environmental uncertainties that integrates the economic and operations models mentioned above in the next section.

3.3 Framework

Suppose that in order to produce one unit of a product, e units of a particular type of environmental waste will be generated from the production system. The total amount of the environmental waste is restricted by an environmental standard so that no more than L units of waste can be generated from the production system in any time period. In order not to violate the standard, the total amount of production in each period cannot exceed a capacity-like environmental limit $Y = L/e$; i.e., the total items produced must be less than or equal to Y. For example, suppose that in order to produce one unit of a paint product, 0.1 tons of waste water will be generated from a paint shop. Given an environmental standard that prohibits the shop from generating more than 1000 tons of waste water, the maximum number of items that can be produced in each period is $Y = 1000/0.1 = 10000$ units. Now suppose that e is in fact a random variable between 0.1 and 0.5 (tons per item). Given the same environmental standard that prohibits the firm from generating more than $L = 1000$ tons of waste water, the maximum number of items that can be produced would then be a random variable between 2000 and 10000.

Let Z be a random variable, with distribution $Q(z)$ and density function $q(z)$, which represents the amount of demand in a period. Assume that the amount of production is constrained by an random environmental limit y, with distribution $F(y)$ and density function $f(y)$. Let p, c, and h denote the penalty, production, and holding costs for each unit of item, respectively. Also denote by a the stock level after replenishment but before sales take place. It should be noted that both the production cost c and holding cost h are the so-called "private costs" which do not include the external costs corresponding to the environmental damages and risks associated with the production and storage of each item. We assume that the firm does not take environmental costs into account when making production decisions, and, as a result, the only environment-related concern to the firm is the uncertain environmental limit. As a consequence, the objective of the firm is to minimize the total expected cost of meeting the random demand by choosing the amount of production that does not exceed the random environmental limit.

In the sections that follow, we will first analyze the situation where there is no environmental limit. Then we will discuss the situation where there exists a environmental limit that cannot be violated as well as the situation where the environmental limit can be violated by paying a pollution charge.

3.4 Production Planning and Inventory Control without Environmental Limits

Without any environmental limit, the actual amount of production is exactly the same as the planned production. Let u and x denote the unconstrained amount of production and starting inventory, respectively. The single-period cost, $g(x, u)$, can be written as

$$g(x,u) = cu + \int_{x+u}^{\infty} p(z-x-u)q(z)dz + \int_{0}^{x+u} h(x+u-z)q(z)dz. \qquad (3.1)$$

The first and second partial derivatives of $g(x, u)$ with respect to u, the planned production, are

$$\frac{\partial}{\partial u}g(x,u) = c - p + (p+h)Q(x+u) \text{ and} \qquad (3.2)$$

$$\frac{\partial^2}{\partial u^2}g(x,u) = (p+h)q(x+u), \qquad (3.3)$$

which lead to the following proposition.

Proposition 7 *The optimal level of planned production, u^*, satisfies*

$$c - p + (p+h)Q(x+u^*) = 0.$$

Proof. u^* satisfies the first-order condition by (3.2), and the second-order condition is satisfied by (3.3) since $q(\cdot)$ and $f(\cdot)$ are both probability density functions. □

First notice that the second-order condition indicates that the cost function is convex. Also notice that the optimal stock level (before replenishment), $a^* = x + u^*$, is a constant, which suggests that the items available to satisfy demand after replenishment is independent of the starting inventory.

Let's now extend the planning horizon to N periods, indexed by $0, 1, ..., k, ..., N-1$. Let x_k and u_k denote the starting inventory and planned production in period k, and let $g(x_k, u_k)$ denote the single-period cost incurred in period k. Denote by $G(x_k, u_k)$ the expected cost for periods k through $N-1$, when an optimal policy is used in periods $k+1$ through $N-1$. Define $G_k^*(x_k) \equiv \min_{u_k} G_k(x_k, u_k)$ as the optimal cost for periods k through $N-1$, when starting inventory is x_k. Also define $G_N^*(x_N) \equiv 0$; i.e., any item left at the end of the planning horizon has no resale value. For simplicity, we assume that the unsatisfied demand in any period is lost. Then $G_k(x_k, u_k)$, the expected cost in period k, can be written as follow:

$$G_k(x_k, u_k) = g(x_k, u_k) + \int_0^\infty G_{k+1}^*(x_k + u_k - z)q(z)dz. \tag{3.4}$$

Using (3.2), the first partial derivative of $G_k(x_k, u_k)$ with respect to u_k, the planned production, is

$$\frac{\partial}{\partial u_k} G(x_k, u_k) = c - p + (p+h)Q(x_k + u_k) + \int_0^\infty G_{k+1}^{*'}(x_k + u_k - z)q(z)dz. \tag{3.5}$$

The first-order condition for the problem can thus be written as follows, where u_k^* denotes the optimal planned production in period k,

$$c - p + (p+h)Q(x_k + u_k^*) + \int_0^\infty G_{k+1}^{*'}(x_k + u_k^* - z)q(z)dz = 0. \tag{3.6}$$

To find out the optimal level of planned production in each period, we first notice that the problem in period $N-1$ is exactly the same as the single-period problem. By differentiating $G_k(x_k, u_k)$ in (3.4) and applying (3.6), it can be easily shown by induction that $G_k^{*'}(x_k) = -c$ for any k, $k = 0, ..., N-1$. We thus have the following proposition.

Proposition 8 *The optimal level of planned production, u_k^*, in period k satisfies*

$$-p + (p+h)Q(x_k + u_k^*) = 0, \; k = 0, ..., N-2 \text{ and} \quad (3.7)$$

$$c - p + (p+h)Q(x_k + u_k^*) = 0, \; k = N-1. \quad (3.8)$$

Proof. u_k^* satisfies the first-order condition in (3.6) since $G_k^{*'}(x_k) = -c$ for $k = 0, ..., N-1$ and $G_N^{*'}(x_N) = 0$. The expected cost function is convex since its second derivative with respect to u_k is $(p+h)q(x_k+u_k)$, which is nonnegative. We can thus obtain the supremum for each period by the first-order condition. The amount of production given in the proposition is an optimal policy by Theorem 4-1 in Heyman and Sobel (1984). □

First notice that the above proposition suggests a stationary optimal stock level (items available after replenishment) from periods 0 to $N-2$ (i.e., $a_0^* = a_1^* = ... = a_{N-2}^*$) since the value of $Q(x_k + u_k^*)$ is a constant. Also notice that this optimal stock level is independent of x_k, the starting inventory; i.e., $a_k^* = x_k + u_k^*$ is a constant. During these periods, the planned production is to bring the stock up to its optimal level. As a consequence, the marginal benefit of each extra unit of on-hand inventory, $G_k^{*'}(x_k)$, is exactly the same as the cost to produce this unit; i.e., an additional unit of starting inventory will reduce the optimal cost by c, the unit production cost, in bringing the stock up to its optimal level. In period $N-1$, the optimal stock level a_{N-1} is lower than those in previous periods due to the assumption that an unsold item at the end of the planning horizon is lost.

3.5 Production Planning and Environmental Control with Environmental Standards

Let's now consider the situation where there exists a standard on the amount of environmental wastes generated from the production system. The objective of the firm is to minimize its total expected cost of meeting random demand, given an uncertain environmental limit that is translated from the fixed environmental standard and random pollution index. Violating the environmental limit is strictly prohibited. This corresponds to the so-called command-and-control standard approach under which generating wastes beyond the level specified by an environmental standard may result in criminal charge or shutdown of the production facility by the government. For simplicity, the command-and-control standard approach will be referred to as the "standard approach" throughout the dissertation.

Let v denote the planned amount of production under a command-and-control environmental standard. Given a random environmental limit y that restricts the maximum amount of production, the actual amount of production is given by $\min(v, y)$. It is noted that the structure of the problem is similar to that of stochastic inventory models with capacity uncertainty. In the subsection that follows, we will modify the model in Ciarallo et al. (1994) to derive optimal policies for problems with both single and multi-period planning horizons.

3.5.1 Single-Period Problem

The single-period cost, $s(x, v)$, can be written as

$$\begin{aligned} s(x,v) &= \int_v^\infty \int_0^{x+v} [cv + h(x+v-z)]q(z)dzf(y)dy \\ &+ \int_v^\infty \int_{x+v}^\infty [cv + p(z-x-v)]q(z)dzf(y)dy \\ &+ \int_0^v \int_0^{x+y} [cy + h(x+y-z)]q(z)dzf(y)dy \\ &+ \int_0^v \int_{x+y}^\infty [cy + p(z-x-y)]q(z)dzf(y)dy, \end{aligned} \tag{3.9}$$

which simplifies to

$$\begin{aligned} s(x,v) &= (1-F(v))\left[cv + \int_0^{x+v} h(x+v-z)q(z)dz + \int_{x+v}^\infty p(z-x-v)q(z)dz\right] \\ &+ \int_0^v \int_0^{x+y} h(x+y-z)q(z)dzf(y)dy + \int_0^v \int_{x+y}^\infty p(z-x-y)q(z)dzf(y)dy \end{aligned}$$

$$+c\int_0^v yf(y)dy. \tag{3.10}$$

The first and second partial derivatives of $s(x,v)$ with respect to v, the planned production, are

$$\begin{aligned}\frac{\partial}{\partial v}s(x,v) &= (1-F(v))\left[c-p+(p+h)Q(x+v)\right] \quad \text{and} &(3.11)\\ \frac{\partial^2}{\partial v^2}s(x,v) &= (p+h)(1-F(v))q(x+v) - f(v)[c-p+(p+h)Q(x+v)], &(3.12)\end{aligned}$$

which lead to the following proposition.

Proposition 9 *The optimal level of planned production, v^*, satisfies*

$$(1-F(v^*))[c-p+(p+h)Q(x+v^*)] = 0. \tag{3.13}$$

Proof. v^* satisfies the first-order condition by (3.11). To satisfy the second-order condition, we will prove that $s(x,v)$ is quasi-convex. First notice that $c-p+(p+h)Q(x+v) \leq 0$ for $v \leq v^*$ since $c-p+(p+h)Q(x+v^*) = 0$ and the distribution function $Q(\cdot)$ is increasing. The second-order condition is satisfied by (3.12) given the fact that $F(\cdot)$ and $q(\cdot)$ are distribution and density functions, respectively. The cost function $s(x,v)$ is thus convex for $0 \leq v \leq v^*$. For $v > v^*$, by (3.11) we have

$$\frac{\partial}{\partial v}s(x,v) > 0.$$

This is because $(1-F(v)) \geq 0$ and $c-p+(p+h)Q(x+v) > 0$ for $v > v^*$. Since $s(x,v)$ is convex for $v \leq v^*$ and increasing for $v > v^*$, the minimum at v^* is the global minimum. □

3.5.2 N-Period Problem

We again extend the problem to N periods. Let x_k and v_k denote the starting inventory and planned production in period k, and $S(x_k, v_k)$ denote the expected cost for periods k through $N-1$, when an optimal policy is used in periods $k+1$ through $N-1$. Define $S_k^*(x_k) \equiv \min_{v_k} S_k(x_k, v_k)$ as the optimal cost for periods k through $N-1$, when starting inventory is x_k. Also define $S_N^*(x_N) \equiv 0$; i.e., any unsold item at the end of the planning horizon is lost. Let's also adopt all the other notations and assumptions about the cost and decision structures of the firm specified in the previous sections. Then $S_k(x_k, v_k)$, the expected cost in period k, can be written as follows:

$$\begin{aligned} S_k(x_k, v_k) &= s(x_k, v_k) + (1 - F(v)) \int_0^\infty S_{k+1}^*(x_k + v_k - z) q(z) dz \\ &\quad + \int_0^{v_k} \int_0^\infty S_{k+1}^*(x_k + y - z) q(z) dz f(y) dy. \end{aligned} \tag{3.14}$$

Using (3.11), the first partial derivative of $S_k(x_k, v_k)$ with respect to v_k, the planned production, is

$$\frac{\partial}{\partial v_k} S(x_k, v_k) = (1 - F(v_k)) \left[c - p + (p+h) Q(x_k + v_k) + \int_0^\infty S_{k+1}^{*'}(x_k + v_k - z) q(z) dz \right]. \tag{3.15}$$

The first-order condition for optimality for the problem can thus be written as follows, where v_k^* denotes the optimal planned production in period k,

$$(1 - F(v_k^*)) \left[c - p + (p+h) Q(x_k + v_k^*) + \int_0^\infty S_{k+1}^{*'}(x_k + v_k^* - z) q(z) dz \right] = 0. \tag{3.16}$$

To obtain the optimal solution, we first establish the convexity of $S_k^*(x_k)$ in the following proposition.

Proposition 10 *The optimal cost from period k to $N-1$, $S_k^*(x_k)$, is convex in x_k; i.e., $S_k^{*''}(x_k) \geq 0$.*

Proof. Let v_k^* denote the optimal planned production in period k. For period $N -$

1, the last period, the problem is exactly the same as the single-period problem. By differentiating $s(x, v)$ and apply Proposition 9, we have

$$S_{N-1}^{*''}(x_{N-1}) = \frac{\partial^2}{\partial x_{N-1}^2} s(x_{N-1}, v_{N-1}^*) = (p+h)\int_0^{v_{N-1}^*} q(x_{N-1}+y)f(y)dy \geq 0. \quad (3.17)$$

The above expression is nonnegative since $q(\cdot)$ is a density function. Now suppose that $S_k^{*''}(x_k) \geq 0$ for $k+1, \ldots, N-1$. Then by differentiating $S_k(x_k, v_k)$ twice and applying (3.16), we have

$$S_k^{*''}(x_k) = \int_0^{v_k} [(p+h)q(x_k+y)]f(y)dy + \int_0^{v_k}\int_0^{\infty} S_{k+1}^{*''}(x_k+y-z)q(z)dzf(y)dy \geq 0.$$

The above expression is nonnegative since $q(\cdot)$ is a density function and $S_{k+1}^{*''}(\cdot) \geq 0$ by the induction hypothesis. □

We will now prove that the expected cost from period k to $N-1$, $S_k(x_k, v_k)$, is quasi-convex in v_k, as in the single-period problem.

Proposition 11 *For $v_k \leq v_k^*$, $\partial^2 S_k(x_k, v_k)/\partial v_k^2 \geq 0$; for $v_k > v_k^*$, $\partial S_k(x_k, v_k)/\partial v_k \geq 0$.*

Proof. The second derivative of $S_k(x_k, v_k)$ with respect to v_k is

$$\begin{aligned}\frac{\partial^2}{\partial v_k^2} S(x_k, v_k) &= (1-F(v_k))\left[(p+h)q(x_k+v_k) + \int_0^{\infty} S_{k+1}^{*''}(x_k+v_k-z)q(z)dz\right] \\ &\quad - f(v_k)\left[c - p + (p+h)Q(x_k+v_k) + \int_0^{\infty} S_{k+1}^{*'}(x_k+v_k-z)q(z)dz\right].\end{aligned} \quad (3.18)$$

First notice that the bracketed portion on the second line of (3.18) is increasing since $Q(\cdot)$ is a distribution function and $S_{k+1}^{*''}(\cdot) \geq 0$ by Proposition 10. For $v_k \leq v_k^*$, the value of the bracketed portion, which will be equal to 0 at $v_k = v_k^*$ according to the first-order condition, is non-positive. Since $(1-F(v_k)) \geq 0$, $q(\cdot) \geq 0$, and $S_{k+1}^{*''}(\cdot) \geq 0$, the expression in (3.18) is nonnegative for $v_k \leq v_k^*$.

Similarly, since the bracketed portion of (3.15) is increasing, we have $\partial S_k(x_k, v_k)/\partial v_k \geq 0$ for $v_k > v_k^*$. □

By the above proposition, the minimum achieved by v_k^*, the optimal level of planned production, which satisfies the first-order condition in (3.16), is a global minimum.

We now explore some interesting properties of the optimal planned production.

Proposition 12 *The optimal order quantity plus on-hand inventory is a constant in any period k; i.e.,*

$$\frac{dv_k^*}{dx_k} = -1,$$

or else the planned production is equal to the maximum possible level of production under the environmental limit.

Proof. By differentiating the left-hand side of (3.16) with respect to x_k, given $v_k^*(x_k)$, we have

$$\begin{aligned} & (1 + \frac{dv_k^*}{dx_k})(1 - F(v_k^*)) \left[(p+h)q(x_k + v_k^*) + \int_0^\infty S_{k+1}^{*''}(x_k + v_k^* - z)q(z)dz\right] \\ - \quad & \frac{dv_k^*}{dx_k} f(v_k^*) \left[c - p + (p+h)Q(x_k + v_k^*) + \int_0^\infty S_{k+1}^{*'}(x_k + v_k^* - z)q(z)dz\right] = 0. \end{aligned} \tag{3.19}$$

Notice that the term on the second line of (3.19) is zero according to the first-order condition. The bracketed portion on the first line is nonnegative since $q(\cdot)$ and $S_k^{*''}(x_k)$ are both nonnegative. By solving the term on the first line, we have $dv_k^*/dx_k = -1$ or $F(v_k^*) = 1$. The former expression implies that the optimal order quantity plus on-hand inventory is a constant. The latter implies that, if the planned production for achieving the constant optimal stock level is greater than the maximum possible level of production, the firm should set up its production at the maximum level where $F(v_k^*)$ is equal to 1. □

The above proposition indicates that, given an uncertain environmental limit, there is some optimal quantity of stock to meet demand if the production plan is feasible. Regardless of the level of starting inventory, the firm will try to set up the inventory target at the optimal level in each period, and hope that the production within the environmental limit is sufficient to achieve the optimal level for meeting the uncertain demand.

Proposition 13 *Given the same starting inventory x_k in any period k, the optimal level of planned production, v_k^*, is higher than that of the problem without any environmental limit; i.e., $v_k^* \geq u_k^*$.*

Proof. We will first show that $S_k^{*'}(x_k) \leq -c$ for $k = 0, ..., N-1$. Notice that the problem in period $N-1$ is exactly the same as the single-period problem. By differentiating $s(x, v)$ in (3.10) with respect to x_{N-1} and applying (3.13), we have

$$\begin{aligned}
S_{N-1}^{*'}(x_{N-1}) &= -c(1 - F(v_{N-1}^*)) + \int_0^{v_{N-1}^*} [-p + (p+h)Q(x_{N-1} + y)] f(y)dy \\
&\leq -c(1 - F(v_{N-1}^*)) + \int_0^{v_{N-1}^*} [-p + (p+h)Q(x + v_{N-1}^*)] f(y)dy \\
&= -c(1 - F(v_{N-1}^*)) + \int_0^{v_{N-1}^*} (-c) f(y)dy = -c. \qquad (3.20)
\end{aligned}$$

The above inequality is due to the fact that the distribution function $Q(\cdot)$ is increasing and that y is integrated from 0 to v_{N-1}^*. The equality on the last line is due to the first-order condition in (3.13).

Similarly, for $k = 0, ..., N-2$, by differentiating $S_k(x_k, v_k)$ with respect to x_k and applying (3.16), we have

$$\begin{aligned}
S_k^{*'}(x_k) &= -c(1 - F(v_k^*)) + \int_0^{v_k^*} [-p + (p+h)Q(x_k + y) \\
&\quad + \int_0^{\infty} S_{k+1}^{*'}(x_k + y - z) q(z) dz] f(y)dy \\
&\leq -c(1 - F(v_k^*)) + \int_0^{v_k^*} [-p + (p+h)Q(x_k + v_k^*) \\
&\quad + \int_0^{\infty} S_{k+1}^{*'}(x_k + v_k^* - z) q(z) dz] f(y)dy
\end{aligned}$$

$$= \quad -c(1 - F(v_k^*)) + \int_0^{v_k^*} (-c) f(y) dy = -c. \tag{3.21}$$

Similar to the previous analysis for period $N-1$, the above inequality is due to the fact that y is integrated from 0 to v_k^* and that the function within the bracketed portion of the first and second lines of (3.21) is increasing in v_k, as discussed in the proof of Proposition 11. The equality on the last line is due to the first-order condition in (3.16).

Given the same starting inventory x_k, it can be easily shown by (3.8) and (3.16) that $u_{N-1}^* = v_{N-1}^*$ since $G_N^{*\prime}(x_N) = 0$ and $S_N^{*\prime}(x_N) = 0$. For $k = 0, ..., N-2$, (3.7) and (3.16) can be written as

$$-p + (p+h)Q(x + u_k^*) \quad = \quad 0 \qquad \text{and} \tag{3.22}$$

$$-p + (p+h)Q(x + v_k^*) \quad = \quad -c - \int_0^{\infty} S_{k+1}^{*\prime}(x + v_k^* - z) q(z) dz \geq 0. \tag{3.23}$$

By inspecting (3.22) and (3.23), we have $v_k^* \geq u_k^*$. □

The above proposition indicates that, in order to deal with the uncertainty associated with the environmental limit over time, the firm sets up a higher production target than that in the problem without the environmental limit. Recall that $G_k^{*\prime}(x_k)$, the marginal benefit of each extra unit of on-hand inventory without the environmental limit, is equal to $-c$, the unit production cost. Now we have $S_k^{*\prime}(x_k) \leq -c$, which suggests that the marginal benefit of the additional unit of on-hand inventory includes two components: the saving in production cost and possible shortage reduction in the future when the production is constrained by the environmental limit. The optimal stock level in each period includes an allocation for meeting the uncertain demand as well as an amount that plans for possible production shortfalls in future periods due to the uncertain environmental limit. As a consequence, the firm tends to produce more during the "good time" when environmental limit is still beyond reach so that a sufficient level of inventory is available to satisfy the demand during the "bad time." This is possibly why, despite the tight gasoline supply due to a new environmental standard and patent dispute, the total gasoline stocks in the Midwest in June 2000 were 650,000 barrels higher than those in the previous year, as mentioned in the beginning of this chapter.

From a life-cycle perspective, a production system can impact the natural environment in many different ways, including its end-of-pipe wastes, the storage of semi or final products (which can be toxic), input depletion (materials and energy), and workplace hazards. Environmental standards, which in many cases are intended to constrain a firm's production through the so-called end-of-pipe control approach, may actually "encourage" the firm to set up a higher production target and to keep a higher inventory level compared to the problem without any environmental limit. As a result, the enforcement of such environmental standards does not necessarily benefit the environment, especially when high environmental impacts may occur at such stages of a product's life cycle as input extraction, manufacturing, and storage.

3.6 Production Planning and Inventory Control with Pollution Taxes

In the previous section, the firm's production is restricted by an uncertain environmental limit due to the environmental standard imposed by the government. Violating the environmental limit is strictly prohibited. In this section, we will analyze the situation where the government permits the firm to exceed the environmental limit, but imposes a pollution charge t for each unit of production that is beyond the environmental limit. This policy used by the government will be referred to as the "tax approach" throughout the dissertation. As we will show in the analysis that follows, the tax approach has the potential of avoiding the environmental problems caused by the standard approach, as discussed in the previous section.

With the flexibility to violate the environmental limit y, the planned amount of production w is exactly the same as the actual production under the tax approach. We will again derive the optimal policies for problems with both single- and multi-period planning horizons.

3.6.1 Single-Period Problem

The single-period cost, $r(x,w)$, can be written as

$$\begin{aligned} r(x,w) &= cw + \int_w^\infty \int_0^{x+w} h(x+w-z)q(z)dzf(y)dy \\ &+ \int_0^\infty \int_{x+w}^\infty p(z-x-w)q(z)dzf(y)dy \\ &+ \int_0^w \int_0^{x+w} [h(x+w-z)+t(w-y)]q(z)dzf(y)dy \\ &+ \int_0^w \int_{x+w}^\infty [p(z-x-w)+t(w-y)]q(z)dzf(y)dy, \end{aligned}$$

which simplifies to

$$r(x,w) = cw + \int_{x+w}^\infty p(z-x-w)q(z)dz + \int_0^{x+w} h(x+w-z)q(z)dz + \int_0^w t(w-y)f(y)dy. \tag{3.24}$$

The first and second partial derivatives of $r(x,w)$ with respect to w, the planned production, are

$$\frac{\partial}{\partial w}r(x,w) = c-p+(p+h)Q(x+w)+tF(w) \quad \text{and} \tag{3.25}$$

$$\frac{\partial^2}{\partial w^2}r(x,w) = (p+h)q(x+w)+tf(w), \tag{3.26}$$

which lead to the following proposition.

Proposition 14 *The optimal level of planned production, w^*, satisfies*

$$c-p+(p+h)Q(x+w^*)+tF(w^*)=0. \tag{3.27}$$

Proof. w^* satisfies the first-order condition by (3.25) and the second-order condition by (3.26) since $q(\cdot)$ and $f(\cdot)$ are probability density functions. □

3.6.2 N-Period Problem

Now we extend the problem to N periods. Let x_k and w_k denote the starting inventory and planned production in period k, and $R(x_k, w_k)$ denote the expected cost for periods k through $N-1$, when an optimal policy is used in periods $k+1$ through $N-1$. Define $R_k^*(x_k) \equiv \min_{w_k} R_k(x_k, w_k)$ as the optimal cost for periods k through $N-1$, when starting inventory is x_k. Also define $R_N^*(x_N) \equiv 0$; i.e., any unsold item at the end of the planning horizon is lost. Let's again adopt all the other notations and assumptions about the cost and decision structures of the firm specified in the previous sections. Then $R_k(x_k, w_k)$, the expected cost in period k, can be written as follows:

$$R_k(x_k, w_k) = r(x_k, w_k) + \int_0^\infty R_{k+1}^*(x_k + w_k - z)q(z)dz. \tag{3.28}$$

We first prove a proposition that will be used to establish the optimal condition of the problem.

Proposition 15 *The optimal cost $R_k^*(x_k)$ is convex in x_k; i.e., $R_k^{*''}(x_k) \geq 0$.*

Proof. Let w_k^* denote the optimal planned production in period k. For period $N-1$, the last period, the problem is exactly the same as the single-period problem. We thus have

$$R_{N-1}^{*''}(x_{N-1}) = \frac{\partial^2}{\partial x_{N-1}^2} r(x_{N-1}, w_{N-1}^*) = (p+h)q(x_{N-1} + w_{N-1}^*) \geq 0.$$

Now suppose that $R_k^{*''}(x_k) \geq 0$ for $k+1, \ldots, N-1$. Then by differentiating $R_k(x_k, w_k)$ in (3.28) twice, we have

$$R_k^{*''}(x_k) = (p+h)q(x_k + w_k^*) + \int_0^\infty R_{k+1}^{*''}(x_k + w_k^* - z)q(z)dz \geq 0.$$

The first term on the right-hand side is nonnegative since $q(\cdot)$ is a density function. The second term is nonnegative due to the induction hypothesis. □

The next proposition concerns the optimal level of planned production that minimizes the expected total cost in each period.

Proposition 16 *The optimal level of planned production, w_k^*, in period k satisfies*

$$c - p + (p+h)Q(x_k + w_k^*) + tF(w_k^*) + \int_0^\infty R_{k+1}^{*'}(x_k + w_k^* - z)q(z)dz = 0. \quad (3.29)$$

Proof. The first and second partial derivatives of $R_k(x_k, w_k)$ in (3.28) with respect to w_k, the planned production, are

$$\frac{\partial}{\partial w_k}R(x_k, w_k) = c - p + (p+h)Q(x_k + w_k) + tF(w_k) + \int_0^\infty R_{k+1}^{*'}(x_k + w_k - z)q(z)dz$$

and (3.30)

$$\frac{\partial^2}{\partial w_k^2}R(x_k, w_k) = (p+h)q(x_k + w_k) + tf(w_k) + \int_0^\infty R_{k+1}^{*''}(x_k + w_k - z)q(z)dz. \quad (3.31)$$

Notice that w_k^* satisfies the first-order condition in (3.30). The second-order condition is also satisfied since $q(\cdot) \geq 0$, $f(\cdot) \geq 0$, and $R_{k+1}^{*''}(\cdot) \geq 0$ by Proposition 15. □

We now explore some interesting properties of the optimal planned production.

Proposition 17 *The optimal order quantity plus on-hand inventory is not a constant. Specifically, we have*

$$-1 < \frac{dw_k^*}{dx_k} < 0.$$

Proof. By differentiating the left-hand side of (3.29) with respect to x_k, given $w_k^*(x_k)$, we have

$$(p+h)q(x_k+w_k^*)\left(1 + \frac{dw_k^*}{dx_k}\right) + tf(w_k^*)\frac{dw_k^*}{dx_k} + \left(1 + \frac{dw_k^*}{dx_k}\right)\int_0^\infty R_{k+1}^{*''}(x_k+w_k^*-z)q(z)dz = 0,$$

which can be reduced to

$$\frac{dw_k^*}{dx_k} = -\frac{(p+h)q(x_k + w_k^*) + \int_0^\infty R_{k+1}^{*''}(x_k + w_k^* - z)q(z)dz}{(p+h)q(x_k + w_k^*) + \int_0^\infty R_{k+1}^{*''}(x_k + w_k^* - z)q(z)dz + tf(w_k^*)}. \quad (3.32)$$

Since $f(\cdot)$ is a density function, the value of the above expression is within $(-1, 0)$, which indicates that the sum of w_k^* and x_k is not a constant for any $t > 0$. □

The above result is different from that in Proposition 12 for the problem under the standard approach where the optimal order quantity plus on-hand inventory is a constant; i.e., $dv_k^*/dx_k = -1$. The reason can be identified by inspecting (3.32). The value of $tf(w_k^*)$, which is related to the potential penalty of producing over the environmental limit, is the driving force for dw_k^*/dx_k to deviate from -1. In fact, the tax approach induces the firm to internalize environmental considerations into its (private) cost of producing over the environmental limit. As a consequence, the firm becomes conservative in terms of replenishing the on-hand inventory, as will be shown in the next proposition, because it will be held financially responsible for any violation of the environmental limit.

Proposition 18 *Suppose that there is no starting inventory in period k; i.e., $x_k = 0$. Then the optimal level of planned production under the tax approach is lower than that under the standard approach; i.e., $w_k^* \leq v_k^*$.*

Proof. We will first show that the optimal planned level of production is decreasing in t. By differentiating (3.29) with respect to t, given $w_k^*(t)$, we have

$$(p+h)q(x_k + w_k^*)\frac{dw_k^*}{dt} + tq(w_k^*)\frac{dw_k^*}{dt} + F(w_k^*) + \frac{dw_k^*}{dt}\int_0^\infty R_{k+1}^{*''}(x_k + w_k^* - z)q(z)dz = 0.$$

Since $q(\cdot) \geq 0$, $F(\cdot) \geq 0$, and $R_k^{*''}(x_k) \geq 0$ by Proposition 15, we have

$$\frac{dw_k^*}{dt} = \frac{-F(w_k^*)}{(p+h)q(x_k + w_k^*) + tq(w_k^*) + \int_0^\infty R_{k+1}^{*''}(x_k + w_k^* - z)q(z)dz} \leq 0. \tag{3.33}$$

It can be easily shown that $w_k^* = u_k^*$ at $t = 0$ since the cost function in (3.28) will be exactly the same as that in (3.4), as the firm is free to produce over the environmental limit without any penalty. In this sense, the environmental limit has no impact on the firm's decisions. Since w_k^* is decreasing in t by (3.33), we have $w_k^* < u_k^*$ for any $t > 0$. Combining the above result with Proposition 13 leads to $w_k^* \leq u_k^* \leq v_k^*$. □

Proposition 18 presents a surprising result that is in contrast to convention wisdom regarding the effectiveness of the standard approach in pollution control. Despite its inefficiency in achieving the social optimum, the standard approach has been considered by many a more direct and effective way to constrain a firm's production and, as a result, to control the pollution from a production system than the tax approach which renders the firm with the "right to pollute." Given the uncertainty associated with the environmental limit, however, the standard approach actually induces the firm to set up a higher production target than that in the problem without the environmental limit so that the extra items produced during the good time can be used to satisfy demand during the bad time. In contrast, with the flexibility of violating the environmental limit, the tax approach actually induces the firm to set up a lower production target than that under the standard approach since the pollution charge is "internalized" as part of the cost for producing any unit beyond the limit. It should be noted that the higher planned production target under the standard approach may not be achieved by the firm's actual production due to the uncertain environmental limit. Likewise, the overall production quantity under the standard approach over the entire planning horizon is not necessarily higher than that under the tax approach.

From a life-cycle perspective, the additional items produced during the good time under the standard approach may raise some environmental concerns at other stages of the product's life cycle, such as workplace safety and environmental risks associated with the storage of toxic semi or final products. These are the issues that will be further investigated in the next chapter.

3.7 Concluding Remarks

In this chapter, we establish the framework for analyzing the management of production processes with demand and environmental uncertainties. We also derive optimal policies for situations where an environmental standard is enforced by the government in different fashions: the standard approach and the tax approach. As we find out, under the standard approach, the firm will use a strategy that leads to a higher production level than that under the situation without any environmental limit in order to accumulate enough items for satisfying demand during periods when the actual amount of production is restricted by the environmental limit. In contrast, the tax approach induces the firm to internalize the pollution charge as part of the cost for producing any unit beyond the limit.

In order to understand the overall environmental impact from a life-cycle perspective, we need to systematically track the quantities of stocks and throughputs of the production system over time. Such a task cannot be fully accomplished by the qualitative analysis presented in this chapter since the distributions of both the demand and environmental limit are not specified. For example, under the standard approach, the planned production is not necessarily equal to the actual production due to the uncertain environmental limit. As mentioned previously, the planned production under the standard approach is higher than that under the tax approach in certain situations. This may not be the case for the actual amount of production, especially when the environmental limit is so stringent that the firm cannot produce enough items even during the good time. As a consequence, the analytical results derived in this chapter must be tested with different distributions of environmental limits in order to identify all the actual and potential environmental impacts from the production system. In the next chapter, we will conduct numerical experiments to show how to apply the model to environmental impact analyses under a life-cycle framework.

Chapter 4

A Life-Cycle Based Decision-Support System for Process Management with Environmental Limits

International Standards Require Life-Cycle Analysis: *ISO 14001 Procedure for Tracking Chemical Inventory requires that chemical data be entered into a software information system. It should be indicated whether the chemical is planned or on-site. The quantity of the chemical in use, storage, and being discharged needs to be recorded on an ongoing basis. The discharged amount would be in accordance with the permits and regulations and include going to sewers, water bodies, air, and land fill.*[1]

Federal Law Requires Life-Cycle Analysis: *The Community Right-To-Know Act requires that the operator of a production facility shall provide "Emergency and Hazardous Chemical Inventory Forms" with the following information: (1) The chemical name, (2)*

[1] Kuhre, W. L. (1995), "Procedure for Tracking Chemicals," *ISO 14001 Certification Environmental Management Systems: A Practical Guide for Preparing Effective Environmental Management Systems,* Upper Saddle River, NJ: Prentice Hall PTR, 103-113.

The maximum amount of the chemical present at the facility at any time, (3) The average daily amount of the chemical present at the facility, and (4) the manner of storage of the chemical, etc.[2]

4.1 Introduction

In this chapter, we use simulation analysis to develop a life-cycle based decision-support system that is capable of quantifying the economic and environmental impacts of production decisions under both demand and environmental uncertainties. As shown in the above examples, the implementation of life-cycle based environmental management systems is required not only by environmental regulations, such as *The Community Right-To-Know Act*, but also by industry-wide or international environmental standards, such as *ISO 14000*. The objective of such a system is to assist a company in quantifying all the potential environmental risks associated with the throughputs and stocks in a production system, including the amount of outputs as final products, amount of outputs as environmental wastes, and the inventory of semi or final products. The theoretical model presented in the previous chapter, which analyzes the problem of production planning and inventory control with uncertain environmental limits, thus provides the foundation for developing the decision-support system.

The purpose of analyzing an environmental problem from a life-cycle perspective is to systematically control environmental impacts of a production system so that environmental risks will not be transferred from one stage of a product's life cycle to another. In our previous analysis, for example, the firm uses a strategy that leads to a high production level during the good time so that enough items will be available to satisfy demand when actual production is constrained by the environmental limit. As discussed previously, this strategy may increase the presence of chemicals or other toxic materials in the production facility, which endangers workplace and community safety. In addition,

[2] "Emergency and Hazardous Chemical Inventory Forms," Section 11022 of the *Emergency Planning and Community Right-To-Know Act of 1986.*

the relatively high level of stock being kept from one period to another may increase the environmental risks associated with the storage of toxic semi or final products, such as the environmental problems of air pollution and leakage caused by oil storage (refer to Cottrill 1995). To fully understand the environmental impacts along a product's life cycle, we need to identify all the potential sources of environmental risks by systematically tracking the throughput and stock levels in a production system.

Conducting simulation experiments allows us to quantify all the throughput and stock levels in a production system, as required by the life-cycle analysis. In the previous chapter, we present several qualitative properties of a dynamic-programming policy that can be used to manage production processes under demand and environmental uncertainties without giving their specific distributions. It is noted that, however, the actual amount of production that is constrained by an environment standard is contingent upon the distribution of the corresponding uncertain environmental limit. For instance, if the environmental limit is distributed within the range between 1000 and 3000, and the demand is distributed within the range between 3000 to 5000, then the firm will not be able to implement the strategy that leads to high production and stock levels even during the good time; e.g., there will be nothing left in stock even when the environmental limit is equal to 3000, the maximum level of environmental limit. On the other hand, if the distribution of environmental limit leads to a situation where the actual production is rarely restricted, the firm does not have to implement the strategy that leads to high production and stock levels. In order to quantify the economic and environmental impacts of the optimal policy for process management under demand and environmental uncertainties, we will perform simulation analyses by specifying the distributions of demand and environmental limit as well as all the relevant costs.

The remainder of the chapter is organized as follows. In Section 2, we discuss the design of the simulation model and the specifications of functional forms for various elements of the model. In Section 3, we conduct a simulation analysis to investigate the structure of the optimal policy for production planning and inventory control with uncertain environmental limits, and discuss important simulation results. In Section 4, we use the simulation model as a decision-support system to analyze several real-world problems concerning process management with uncertain environmental limits. Concluding remarks are given in Section 5.

4.2 Simulation Design

The simulation experiments use a dynamic programming model and Monte Carlo simulation written in Visual Basic and run in Microsoft Excel. To make the quantification practical in the simulation, we assume that the demand, environmental limit, and production can only take eleven discrete levels: $0,\ 1000, 2000, ..., 10000$. Both demand and pollution index are generated from normally distributed random variables whose means and standard deviations will be specified later.

For a given set of parameter values, the dynamic programming procedure for identifying the optimal policies is described as follows. Starting from the last period of a 12-period planning horizon, we generate random values of demand and pollution index and calculate the expected total cost associated with each level of planned production given different levels of starting inventory. The policy that leads to the lowest expected cost is then identified, and the values of the corresponding planned production and expected cost are recorded. The process is then repeated for periods $11, 10, ..., 1$, and a series of optimal policies that are contingent upon the levels of starting inventory are identified for the entire planning horizon.

Figure 4-1 describes the simulation inputs and outputs of the production system to be investigated. The inputs are the random demand and environmental limit (given a fixed standard and random pollution index). The outputs of the simulation model and their notations are as follows:

1. **Cost:** The system cost in each period (C) and the expected total cost throughout the planning horizon (TC).

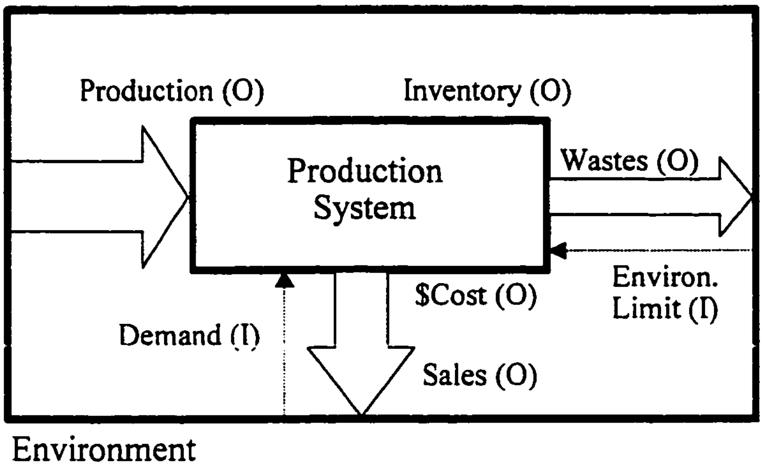

Figure 4-1: Inputs and Outputs of the Simulation Model

2. **Sales**: The number of items sold in each period (S) and the expected total number of items sold throughout the planning horizon (TS).

3. **Production**: The amounts of planned production (PP) and actual production (AP) in each period and the expected total production throughout the planning horizon (TP).

4. **Inventory**: The number of items at the end of each period (I); i.e., after sales take place, and the total number of items being stored in the facility throughout the planning horizon (TI).

5. **Wastes**: The amount of end-of-pipe waste generated in each period (W) and the expected total wastes generated throughout the planning horizon (TW).

The default set of parametric values for the simulation analysis, which will be referred to as the based parameter values throughout the chapter, are given in Table 4.1. These values are so chosen that the states of the production system and its interactions with the random demand and environmental limit can be observed within the specified range.

Parameters	Values
Planning Horizon	$N = 12$ periods
Demand	$D = \text{Normal}(5000, 1000)$
Pollution Index	$e = \text{Normal}(1, 0.3)$
Environ. Standard	$L = 5000$ (units of wastes)
Production Cost	$c = 5$ ($/item)
Penalty Cost	$p = 10$ ($/item)
Holding Cost	$h = 1$ ($/item)
Pollution Tax	$t = 0$ ($/item)

Table 4.1: Base Parameter Values

Figure 4-2 presents a sample output sheet generated from the based parametric values under the standard approach. Here x and v represent the starting inventory and optimal planned production in each period, and TC, TP, TI, TS, and TW represent the expected total cost, expected total production, total items stored, expected total sales, and expected total wastes from the current period to the end of the planning horizon if the optimal policies are used. These optimal policies are presented in a sample summary sheet, as shown in Figure 4-3, which includes a series of optimal levels of planned production throughout the entire planning horizon given different levels of starting inventory. With the output and summary sheets, the firm can plan its production in the beginning of each period and keep tracking all the economic and environmental data throughout the entire planning horizon. In the section that follows, we will perform a simulation analysis to investigate the economic and environmental impacts of the firm's production decisions given different levels of environmental limits.

4.3 Simulation Analysis

We now use the simulation model to conduct experiments given different system elements and specifications. Particularly, we are interested in the economic and environmental consequences of the optimal policy of production planning given different levels of an environmental standard on the end-of-pipe wastes generated from a production system.

Period	1					
x	v	TC	TP	TI	TS	TW
0	7000	334,771	56,296	12,693	55,970	53,368
1,000	6000	327,895	55,813	13,399	56,487	53,042
2,000	5000	322,027	55,141	14,171	56,815	52,558
3,000	4000	316,830	54,277	14,655	56,951	51,852
4,000	3000	311,804	53,304	14,764	56,978	50,938
5,000	2000	306,804	52,304	14,764	56,978	49,942
6,000	1000	301,804	51,304	14,764	56,978	48,946
7,000	0	296,804	50,304	14,764	56,978	47,950
8,000	0	292,331	49,490	16,221	57,164	47,266
9,000	0	288,197	48,564	17,457	57,238	46,413
10,000	0	284,171	47,585	18,536	57,259	45,455

Period	2					
x	v	TC	TP	TI	TS	TW
0	7000	307,057	51,533	11,425	51,208	48,858
1,000	6000	300,178	51,054	12,148	51,728	48,532
2,000	5000	294,313	50,380	12,911	52,054	48,045
3,000	4000	289,091	49,527	13,429	52,201	47,352
4,000	3000	284,064	48,561	13,568	52,235	46,443
5,000	2000	279,059	47,562	13,568	52,236	45,436
6,000	1000	274,058	46,562	13,570	52,236	44,429
7,000	0	269,059	45,562	13,572	52,237	43,421
8,000	0	264,670	44,730	15,022	52,404	42,716
9,000	0	260,569	43,792	16,232	52,467	41,846
10,000	0	256,547	42,809	17,295	52,484	40,884

Figure 4-2: A Sample Output Sheet

Optimal Policy												
x	N = 1	N = 2	N = 3	N = 4	N = 5	N = 6	N = 7	N = 8	N = 9	N = 10	N = 11	N = 12
0	7000	7000	7000	7000	7000	7000	7000	7000	7000	7000	6000	5000
1,000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	5000	4000
2,000	5000	5000	5000	5000	5000	5000	5000	5000	5000	5000	4000	3000
3,000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	3000	2000
4,000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	2000	1000
5,000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	1000	0
6,000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	0	0
7,000	0	0	0	0	0	0	0	0	0	0	0	0
8,000	0	0	0	0	0	0	0	0	0	0	0	0
9,000	0	0	0	0	0	0	0	0	0	0	0	0
10,000	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4-3: A Sample Summary Sheet of Optimal Policy

Standard (L)	Scenario	Description
3000	Low Limit	Strict environmental limits
5000	Base	Medium environmental limits
7000	High Limit	Lenient environmental limits
NE	No Limit	No environmental limits

Table 4.2: Levels of Environmental Standard

The purpose of the simulation experiments is to verify the analytical results derived previously from the theoretical model. In addition, the experiments can assist decision makers in quantifying the economic and environmental impacts of their production policies under uncertain environmental limits.

In the simulation analysis, we examine the effects of three different levels of environmental standard: L = 3000, 5000, 7000, plus the situation where there is no environmental standard (denoted by NE). Table 4.2 presents a general description of the four scenarios, each with a different level of environmental standard. Since the demand has a mean of 5000 (items) and the pollution index has a mean of 1 (units of wastes/item), L = 5000 represents the "Base Scenario," while L = 3000 and L = 7000 represent the "Low-Limit Scenario" and "High-Limit Scenario" under which the environmental limit is either strict or lenient. For the purpose of comparison, we also include the "No-Limit Scenario" to represent the situation where the production system is not constrained by any environmental limit at all.

The outputs from the simulation experiment for the first period are summarized in Figures 4-4 to 4-9, which include the optimal amount of planned production (v), expected total cost (TC), expected total production (TP), expected total sales (TS), expected total end-of-pipe wastes (TW), and total inventory items (TI) throughout the 12-period planning horizon, respectively. First notice that the optimal policies for planned production in Figure 4-4 exhibit an order-up-to property; i.e., the firm sets up a constant stock target for a given environmental standard regardless of the starting inventory. Also notice that the stricter the environmental standard, the higher the stock target. Given a tightened environmental standard, the firm expects more production shortfalls in the future. As a result, the firm sets up a higher stock target so that the excess items produced during the good time can be used to satisfy demand when the production is constrained by the environmental limit.

Let's now turn our attention to the economic impact of the environmental standard. Compared to the No-Limit Scenarios, the increase in total cost and the decrease in sales volume are not significant under both the Base and High-Limit Scenarios, as shown in Figures 4-5 and 4-6, since the firm adjusts to different levels of the environmental limit by producing more items during the good time. As long as the excess items produced during the good time are sufficient to cover the possible shortage during the bad time, the firm will be able to maintain its profitability and sales volume even with a stricter environmental standard. When the standard is tightened beyond a certain range, however, it becomes more difficult for the firm to accumulate enough items since the production is still highly restricted by the environmental limit even during a "relatively" good time. This is why the expected total cost and sales volume both drop significantly when the level of environmental standard is tightened to 3000, as shown in Figures 4-5 and 4-6.

The strategy used by the firm to deal with the uncertain environmental limit and maintain its profitability and sales volume, however, may result in some unexpected environmental consequences. As shown in Figures 4-7 and 4-8, under the Base and High-Limit Scenarios, both the expected total production and end-of-pipe wastes do not decrease significantly–as one would expect from a tightened environmental standard. For example, when the standard is tighten from 7000 to 5000, the average reduction in the end-of-pipe wastes per period is only around 250 units, which is a lot less than the reduction in standard level (2000 units). More importantly, the tightened environmental standard may cause new environmental problems. According to Figure 4-9, the number of total items being stored increases as the environmental standard is tightened form 7000 to 5000. As a consequence, the control of the end-of-pipe wastes by the stricter environmental standard may actually transfer environmental risks from one stage of a product's life cycle to another. For those products whose presence or storage involves high environmental risks, such as toxic chemicals, the overall environmental cost associated with the higher production or stock level may exceed the overall environmental benefit from the reduction of end-of-pipe wastes.

Judging sorely by the results in Figures 4-7, 4-8, and 4-9, one might come to a conclusion that all the environmental problems described above are caused by a standard that is not strict enough. If the environmental standard is set at the level of 3000 units, both the amount of end-of-pipe wastes and the total number of items stored can be reduced significantly compared to the No-Limit Scenario. Such an environmental standard, however, will have great impacts on the firm's profitability and sales, as shown in Figures 4-5 and 4-6. It should be noted that environmental protection is only one of many goals of society. The trade-off between the economic and environmental costs and benefits must be carefully dealt with by policy makers as well as by those firms who intend to pursue environmental goals such as green manufacturing and green supply chain management. The simulation model presented here, which systematically quantifies all the economic and environmental data from a life-cycle perspective, can thus serve as a decision-support tool for both public policy analysis and private strategy formulation. In the section that follows, we will present applications of the simulation model by both the public and private sectors.

4.4 Applications

In this section, we use the simulation model to support decision making for three problems related to process management with uncertain environmental limits. In the first application, we examine the effectiveness of the so-called linear environmental control under either a deterministic or stochastic environmental limit. In the second application, we discuss how the simulation model can be used to evaluate pollution prevention and control technologies. In the last application, we analyze the situation where the cost associated with environmental impact is internalized by the firm.

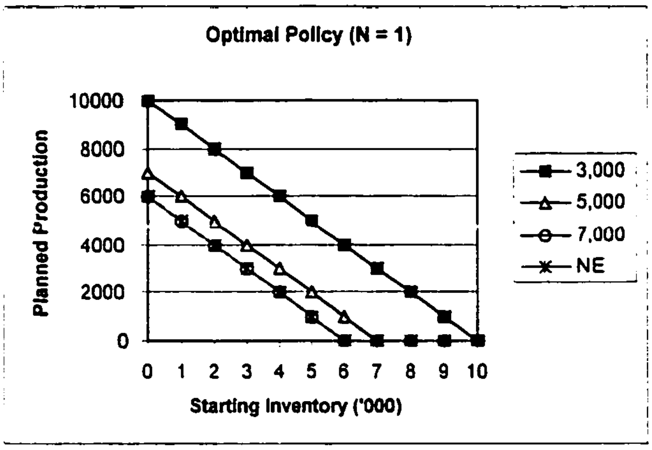

Figure 4-4: Optimal Policy of Planned Production

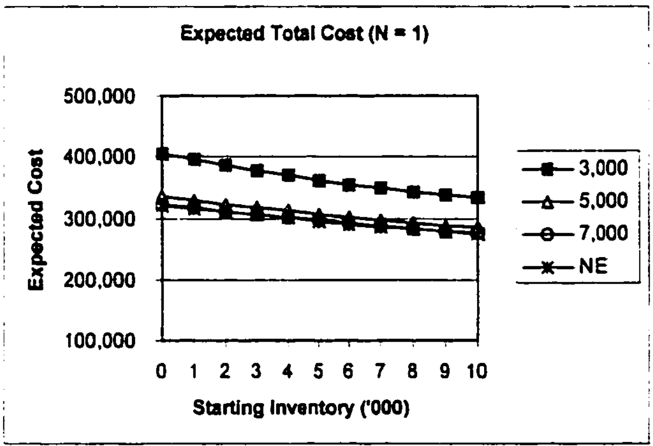

Figure 4-5: Expected Total Cost (12 Periods)

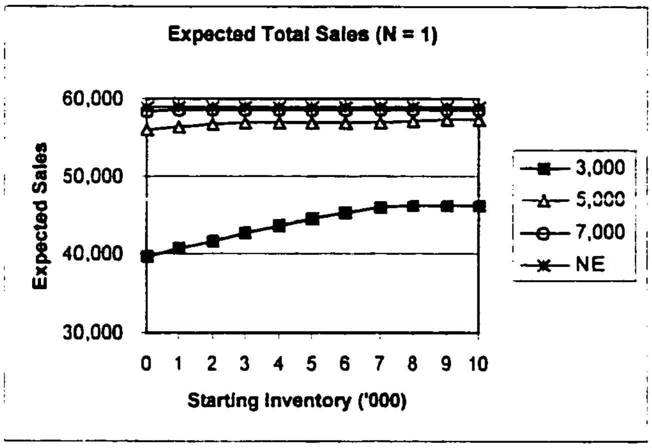

Figure 4-6: Expected Total Sales (12 Periods)

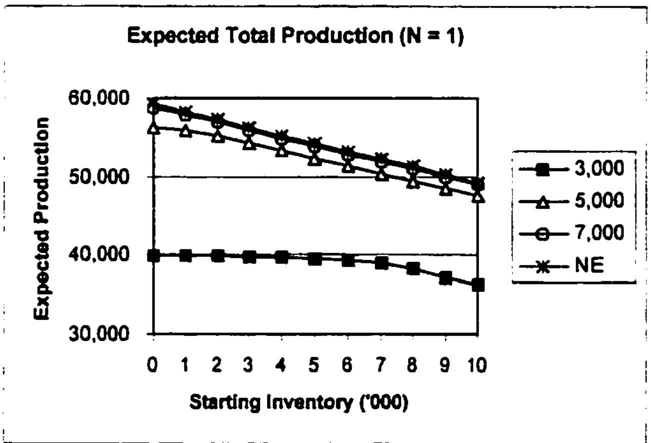

Figure 4-7: Expected Total Production (12 Periods)

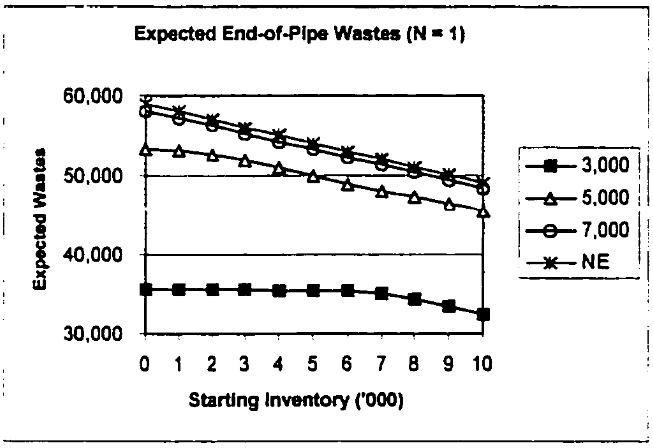

Figure 4-8: Expected End-of-Pipe Wastes (12 Periods)

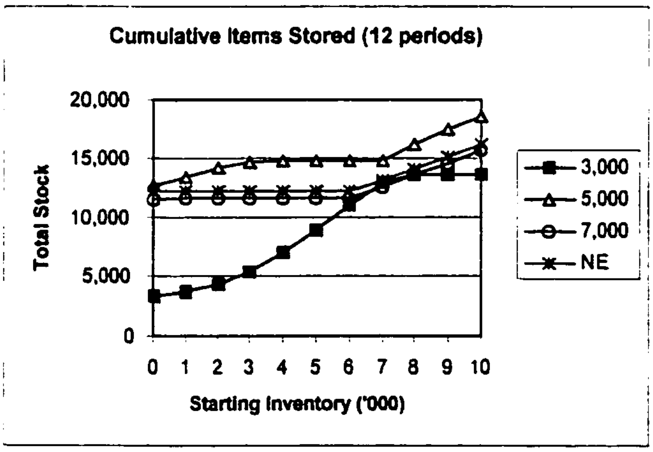

Figure 4-9: Total Inventory Items (12 Periods)

Parameters	Scenario 1	Scenario 2
Planning Horizon	$N = 12$ periods	$N = 12$ periods
Demand	$D = \text{Normal}(5000, 1000)$	$D = \text{Normal}(5000, 1000)$
Pollution Index	$e = 1$	$e = \text{Normal}(1, 0.3)$
Environ. Standard	$L = 3000$ - 7000	$L = 3000$ - 7000
Production Cost	$c = 5$ (\$/item)	$c = 5$ (\$/item)
Penalty Cost	$p = 10$ (\$/item)	$p = 10$ (\$/item)
Holding Cost	$h = 1$ (\$/item)	$h = 1$ (\$/item)

Table 4.3: Parameter Values for Linear Control Simulation

4.4.1 Linear Environmental Control

Description of the Application

Linear environmental control means that controlling the environmental impact at a certain stage of a product's life cycle also controls the environmental impacts occurred at other stages. According to the Material Balance Principle (Mills and Graves 1986), production does not create or destroy matter, but they just change its form (by converting, combining or breaking down materials). When a certain material output of a production system is controlled and reduced, for example, conventional wisdom suggests that less material input and stock will be used or stored in the production system. With a random environmental limit, however, the strategy of linear environmental control would be difficult to implement since the firm has to set up a higher stock target than that with a deterministic environmental limit in order to deal with the environmental uncertainty, as shown in the simulation analysis that follows.

Simulation Analysis

In this analysis, we will compare the total items stored (TI) throughout the entire planning horizon under two different scenarios. In the first scenario, the pollution index for a production process is fixed. In the second scenario, the pollution index is random. Table 4.3 shows the parameter values for the two scenarios.

The simulation results are shown in Figure 4-10. Given a fixed pollution index ($e = 1$)

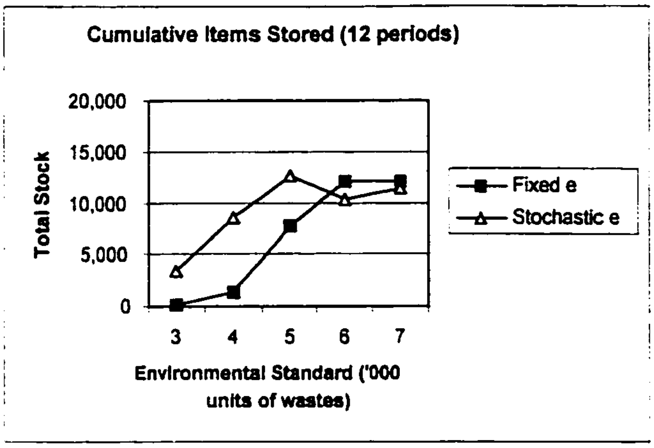

Figure 4-10: Linear and Nonlinear Environmental Control

and the corresponding fixed environmental limit ($L = 5000$), the total number of items stored does experience a linear reduction when an environmental standard is tightened from 6000 to 4000. Given an uncertain pollution index and the corresponding uncertain environmental limit, however, the linear relationship no longer exists. As mentioned previously, in order to deal with the uncertainty associated with the environmental limit, the firm uses a strategy that leads to higher production and stock levels during the good time, which results in the nonlinear relationship between the total items stored and the tightened environmental standard. This example illustrates the importance for policy makers to understand the uncertain nature of environmental limits due to the uncertain pollution index associated with a production system. Such understanding is essential for assessing the overall environmental impact of an environmental standard.

4.4.2 Pollution Prevention and Control Technologies

Description of the Application

From the environmental perspective, the function of a production system is to convert resources into products as primary outputs and wastes. The amount of wastes that are eventually discharged into the environment can be either prevented in the first place or treated after they are generated. In the conventional end-of-pipe control approach, the firm adds a pollution control technology to treat the environmental wastes generated from the production system in order to clean up their hazardous contents or to reduce their potential environmental damage, such as scrubbers used by most power plants to control air emissions. In contrast, the pollution prevention strategy uses such practices as material substitution, process modification, in-plant recycling, and product reformulation in order to reduce the generation of wastes at source during the production and operations processes.

In general, pollution prevention technologies differ from their pollution control counterparts in two major aspects. First, while the acquisition of most pollution control technologies involves the additions of new equipment or facility to treat environmental wastes after the production process is completed, the implementation of pollution prevention technologies is much more knowledge- or idea-oriented, which usually involves improving and modifying the operations and management procedures of the existing production system. Clift and Longley (1996) even use the terms "clean-up technology" and "clean technology" to distinguish between the end-of-pipe-control and pollution prevention technologies. As they point out, a pollution prevention technology is really an approach to providing services and benefits, not a recognizable set of technologies. Second, in terms of the nature of innovation, a pollution prevention technology can be classified as a preventive innovation whose benefits are usually uncertain and may not be easily observed. As Rogers (1995) points out, a preventive innovation is an idea that an individual adopts at one point in time in order to lower the probability that some future unwanted event will occur. The unwanted future event might not have happened anyway, even without adoption of the preventive innovation, so the benefits of adoption may not be clear-cut. As a result, implementing a pollution prevention technology usually involves a higher degree of uncertainty than does acquiring a pollution control technology (refer to Lindsey 1998, Lindsey 1999).

Simulation Analysis

Let's now apply the simulation model to the analysis of technology choice between pollution prevention and control technologies. Suppose that a firm has an end-of-pipe pollution control technology that can treat up to L units of environmental wastes. If the government allows no untreated wastes being discharged to the environment, the capacity of the pollution control technology L would be regarded as an environmental standard (as in our previous analysis) by the firm since it prohibits the firm from generating more than a certain amount of end-of-pipe wastes. Also suppose that, with the current pollution prevention technology, the production process will generate e units of end-of-pipe wastes in order to produce one unit of the product. Since the implementation of a pollution prevention technology usually involves a high degree of uncertainty, we assume that e is a random variable. Then we have a production planning problem with uncertain environmental limits which has the same structure as the model developed previously.

Assume that the current pollution control technology has a capacity of 5000 units ($L = 5000$) and that, with the current pollution prevention technology, the production system has a normally distributed pollution index with a mean of 1 and standard deviation of 0.3. For simplicity, we also assume that there is no starting inventory in the beginning of a 12-period planning horizon. By using the based parameter values specified in Table 4.1, we conduct simulation experiments to investigate the economic and environmental performances of three technology options as follows.

1. An end-of-pipe pollution control technology with capacity of 5500 units. The acquisition cost of the technology is $10000.

2. A pollution prevention technology that reduces the mean of the pollution index from 1 to 0.8. The acquisition cost of the technology is $8000.

3. A pollution prevention technology that reduces the standard deviation of the pollution index from 0.3 to 0.2. The acquisition cost of the technology is $3000.

Table 4.4 summarizes the simulation results with all the relevant economic and environmental data (for 12 periods) for the three technology options. From the economic perspective, Technology 3 is the best option since it leads to the lowest total cost. From the environmental perspective, Technology 2 will be the best option if the end-of-pipe wastes is the biggest environmental concern for the production system. Among the three options, technology 1, a pollution control technology, not only costs the most but also generates the highest amount of end-of-pipe environmental wastes.

The simulation results presented above reflect several important facts regarding the acquisition of environmental technologies. First of all, pollution prevention technologies, such as Technologies 2 and 3, usually perform better than pollution control technologies, such as Technology 1, from both the economic and environmental perspectives. Since the firm can deal with the shortage of waste-treatment capacity by using a strategy that leads to more production during the good time, as discussed previously, the contribution to cost reduction by Technology 1 that merely increases the waste-treatment capacity is not significant. In addition, pollution prevention technologies that only involve reducing the uncertainty of the production system, such as Technology 3, is usually the cheapest to implement since acquiring additional pollution control capacity or improving the average pollution prevention capability is usually costly. Furthermore, there usually exists no "winning technology" with both the best economic and environmental performances. For example, Technology 2 is more effective in reducing environmental wastes but more expensive than Technology 3. In order to choose the technology that best fits into a production system, a firm should evaluate all the economic and environmental data generated from the simulation analysis and deal with the trade-off between financial and environmental objectives (refer to Boden and Brayton 1993).

Options	Cost	Sales	Prod.	Stock	Wastes
Technology 1	338849	56851	9271	56497	54911
Technology 2	334333	57555	10222	57196	44688
Technology 3	333092	56325	8983	55982	54819

Table 4.4: A Comparison of Technology Options

4.4.3 Internalization of Environmental Costs

Description of the Application

Many environmental problems are due to the fact that most producers do not take into account the external costs of environmental damages and risks caused by production activities when making their production decisions. If the external environmental costs are added into the total production cost, the amount of production can be reduced to the level of the so-called "social optimum" (refer to Pearce and Turner 1990). As mentioned previously, all the costs used in the model of production planning and inventory control are the so-called private costs that do not include the external costs of environmental damages and risks caused by production activities. It would be interesting, however, to analyze the situation where the firm internalizes the external environmental costs into its production decisions.

The internalization of environmental costs can be either voluntary or involuntary. In the voluntary case, responsible producers are aware of the potential environmental damages and risks caused by their production systems, and willingness to adopt prevention or control measures that may increase their total production costs. For example, an oil company that recognizes the potential environmental risks of leakage and air emission associated with oil storage may redesign its storage tanks, which will increase the unit holding cost. A higher holding cost will then induce the company to keep fewer items in stock, which eventually reduces the potential environmental risks caused by oil storage. In the involuntary case, producers are forced to internalize the environmental costs by either environmental regulations or pollution charges imposed by the government. For example, the tax approach is in fact a way for the government to induce the firm to internalize environmental considerations into its production decisions, as discussed in the previous chapter. In the simulation experiment that follows, we will analyze both the voluntary and involuntary cases of internalizing environmental costs and compare the resulting economic and environmental consequences.

Simulation Analysis

Suppose that the government concerns about the environmental risks associated with the storage of a particular type of toxic products in a production facility. Assume that the external environmental cost for holding each item in stock is \$1, and, as a result, the total social cost for holding each item is \$2, which is equal to the sum of the private cost and the external cost. Now the government wants to use the tax approach to induce the firm to internalize the external environmental cost for holding each item in stock, and the objective of the government is to find the tax rate that will influence the firm to keep its stock level as low as that under the situation where the environmental cost for storage is internalized.[3] We now conduct simulation experiments with all the base parameter values specified in Table 4.1 except that the tax rate will take five discrete values: $t = 1, 2, ..., 5$.

Table 4.5 shows the simulation results with all the economic and environmental data. If the environmental cost for storage is internalized, as in the Internalization Scenario, the number of total items in stock will be 7882 units. In order to induce the firm to reduce its stock to this level, the tax rate must be increased to \$5, as in the Tax 5 Scenario where the number of total items in stock is 7776. The government then successfully uses the tax approach to reduce the environmental risks associated with the storage of the toxic products. It is interesting to note that, if the firm internalizes the external environmental cost in the first place so that the government does not need to use the tax approach (i.e., $t = 0$), the total cost will be \$343237, which is lower than the total cost under the Tax

[3] We assume that the government is unable to directly impose a pollution charge on the firm for holding each inventory item in the production facility due to the difficulty in monitoring and enforcement.

Scenario	Cost	Sales	Prod.	Stock	Wastes
Tax 1 ($t = 1$, $h = 1$)	326425	58842	59223	12158	58978
Tax 2 ($t = 2$, $h = 1$)	332673	58745	59126	11955	58881
Tax 3 ($t = 3$, $h = 1$)	338558	57710	58091	9916	57893
Tax 4 ($t = 4$, $h = 1$)	342921	56945	57326	8119	57082
Tax 5 ($t = 5$, $h = 1$)	347209	56448	56651	7776	56420
Internalization ($t = 0$, $h = 2$)	343237	54888	55210	7882	52697

Table 4.5: The Tax Approach vs. Voluntary Internalization

5 Scenario ($347209). This saving in total cost may provide the firm with incentive to voluntarily internalize the environmental cost given the threat of high tax rates from the government.

4.5 Concluding Remarks

In this chapter, we use simulation analysis to develop a decision-support system for process management based on the optimal policies derived in the previous chapter. A life-cycle framework is used to organize the complex material and information flows within the production system so that the economic and environmental consequences under different simulation scenarios can be analyzed on a consistent basis. As we find out, if the production system is constrained by an uncertain environmental limit, a firm will adopt a strategy that leads to a higher production level during the good time than that under the situation without any environmental limit. This production strategy will not only affect the effectiveness of a tightened environmental standard but also increase the potential environmental risks associated with the storage of toxic semi or final products. In addition, we apply the simulation model to analyzing three real-world problems, which include linear environmental control, technology acquisition, and the internalization of environmental costs.

Incorporating environmental considerations into production decisions is a process full of risks and uncertainties. To maximize the welfare of society, it is necessary to examine and compare all the possible economic and environmental consequences of our decisions.

Another important task is to convert all the environmental impacts from a production system into a single environmental index for further analyses (refer to Bloemhof-Ruwaard et al. 1995). Although finding such an environmental index is beyond the scope of this dissertation, we believe that understanding a firm's response to uncertain environmental challenges, as we have done in this chapter, is the critical first step toward the development of a green production strategy in accordance with the sustainable development of human society.

Chapter 5

Managerial Insights to Green Product Development and Process Management

In this chapter, we summarize the analytical results derived previously and propose guidelines to green product development and process management for both operations managers and environmental policy makers. Operations managers refer to those who are responsible of making product and process decisions in order to maximize a firm's profit under production, marketing, and environmental constraints. Environmental policy makers refer to those who are responsible of setting up the environmental goals or standards that will be realized by operations managers as environmental constraints. It should be noted that environmental policy makers include not only legislators and regulators in the public sector but also those decision makers who are responsible of setting voluntary environmental targets for private organizations, as required by many industry-wide or international environmental programs such as the *Responsible Care* for the chemical industry and *ISO 14000*.

5.1 Managerial Insights to Green Product Development

In the model of green product development, a producer intends to develop products to satisfy customers with different environmental values. While ordinary customers only care about a product's traditional attributes, green customers care about a product's environmental attributes in addition to the traditional attributes. We analyze the firm's two strategies for product development: the mass-marketing strategy and the strategy of green product development, which specify the number of products introduced and their respective prices and quality levels. We also evaluate and compare the economic and environmental consequences of the two strategies. Then we introduce an standard that requires a minimum level of environmental quality from a product, and analyze the economic and environmental impacts of such a standard. The analytical results and their managerial implications are summarized as follows.

5.1.1 Guidelines for Operations Managers

Guideline 1: Green consumerism provides new market opportunities.

Contrary to conventional belief that environmentalism is an annoying burden to industry, the existence of green customers and their calls for green products actually provide producers with new market opportunities in terms of product development and market segmentation. As shown in the model, the driving forces for a profitable strategy of green production development include the number of green customers and their marginal valuation on environmental quality, while the obstacles include the number of ordinary customers, the fixed cost, and the costs for installing both the green and traditional qualities.

Guideline 2: Cross-functional information is needed for green product development.

The analytical framework of the model suggests that four types of information are of importance for green product development, which include the technical trade-off between traditional and environmental qualities, the part-worths from conjoint analysis, the numbers of ordinary and green customers, and the levels of environmental standards. With the correct assessment of all these data, a company can use the model to identify the best strategy of product development and determine the optimal prices and quality levels of its product(s).

Guideline 3: Cannibalization prevention is necessary for profit maximization.

In order to maximize the profit from green product development, the firm should prevent the possible cannibalization between its own green and ordinary products. According to the analytical results derived from the model, such cannibalization can be prevented if the firm does the following two things: to reduce the price of the green product and to decrease the environmental quality of the ordinary product.

Guideline 4: The firm should switch from the strategy of green product development to the mass-marketing strategy as the environmental standard is tightened.

The incentive for green product development decreases as the environmental standard is tightened since the firm would then not be able to prevent the cannibalization between its own products by decreasing the environmental quality of the ordinary product. To protect its profit, when the environmental standard is tightened beyond a certain critical level, the firm should switch from the strategy of green product development to the mass-marketing strategy by introducing a single product for both market segments with the exact level of environmental quality required by the standard.

5.1.2 Guidelines for Environmental Policy Makers

Guideline 1: Without any environmental standard, green product development does not necessarily benefit the environment.

Compared to the mass-marketing strategy, the strategy of green product development does not necessarily lead to a higher level of overall environmental quality since the environmental quality of the ordinary products is reduced by the firm to prevent cannibalization, which negates the improvement in environmental quality achieved by the green products. In order to ensure that the overall environmental quality under the strategy of green product development is higher than that under the mass-marketing strategy, a standard that requires a minimum level of environmental quality is needed to prohibit the firm from reducing the environmental quality of the ordinary products to too low a level.

Guideline 2: Stricter environmental standards do not necessarily benefit the environment.

When the environmental standard is tightened beyond a critical level, the firm will switch from the strategy of green product development to the mass-marketing strategy. As a consequence, the overall environmental quality will experience a slump right after the environmental standard is tightened beyond its critical level, and there exists a danger zone within which a stricter environmental standard leads to a lower overall environmental quality. Environmental policy makers should either try to avoid the danger zone or use the "fleet-average" type of environmental standards that require an average or aggregate level of environmental quality from all the producer's products.

Guideline 3: Encouraging competition can benefit the environment.

When a competitor enters the market with a new product that provides both ordinary and green customers with higher utilities than the existing products, the incumbent will respond by reducing the prices of all its products and increasing the environmental quality of its ordinary products in order to protect its profits and market shares in both segments. The competition between the new entrant and the incumbent will thus improve both the consumer surplus and the overall environmental quality.

Guideline 4: Environmental and economic factors should both be taken into consideration when setting up an environmental standard.

Environmental policy makers should recognize that profit maximization is still the ultimate goal for most firms. Green product development is not only an environmental performance, but also an economic practice. Unilaterally pursuing environmental goals without considering the resulting economic impact not only hurts a firm's profitability but may also lead to a lower overall environmental quality, as shown in our analysis of the danger zone. It is of crucial importance for environmental policy makers to consider both the economic and environmental factors when setting up an environmental standard.

5.2 Managerial Insights to Green Process Management

In the model of green process management, we analyze a firm's decisions concerning the management of production processes with uncertain environmental limits. We develop optimal policies for production planning and inventory control under both the standard and tax approaches used by the government, and derive several qualitative properties regarding production decisions under both demand and environmental uncertainties. Based on the optimal policies for production planning and inventory control, we develop a life-cycle based decision-support system in order to systematically quantify all the potential environmental damages and risks associated with the throughout and stock levels in a production system. The decision-support system is then applied to several real-world problems of process management with uncertain environmental limits, including technology acquisition and the internalization of environmental costs. Key analytical results and their managerial implications are summarized as follows.

5.2.1 Guidelines for Operations Managers

Guideline 1: A standard on environmental wastes should be treated as an uncertain limit on the amount of production.

To produce one unit of a product, a production system converts a certain ratio of resources into environmental wastes. This ratio, which is referred to as pollution index in our analyses, is usually random due to such factors as technology uncertainty and climatic condition. Given a random pollution index, a fixed standard on the amount of environmental wastes generated from the production system should be realized as an uncertain environmental limit on the amount of production. Operations managers should therefore consider both demand and environmental uncertainties when making decisions concerning production planning and inventory control.

Guideline 2: The planned production under the standard approach should be increased given an uncertain environmental limit.

Under the standard approach, the firm is not allowed to violate the environmental limit. In this situation, the firm can use a strategy that leads to a higher amount of planned production than that in the situation where there is no environmental limit. The additional items produced during the periods when production capacity is sufficient can be used to satisfy demand when the amount of production is constrained by the environmental limit.

Guideline 3: The planned production under the tax approach is lower than that under the standard approach.

Under the tax approach, the firm is allowed to violate the environmental limit by paying a pollution charge. In this situation, the firm can use a strategy that leads to a lower amount of planned production than that under the standard approach. With the flexibility to violate the environmental limit, the firm can be conservative in terms of replenishing its on-hand inventory.

Guideline 4: Pollution prevention technologies are often more cost-effective than pollution control technologies.

In general, pollution prevention technologies are used to influence the distribution of the pollution index of a production system, while pollution control technologies are used to increase the capacity of waste treatments. According to our simulation analyses, the problem caused by the shortage of waste-treatment capacity can usually be solved by producing more during the good time. As a result, pollution control technologies are often less cost-effective than pollution prevention technologies.

5.2.2 Guidelines for Environmental Policy Makers

Guideline 1: The production strategy used to deal with environmental uncertainty may raise environmental concerns about higher stock levels.

The strategy used by the firm to deal with the uncertain environmental limit, which requires a higher production level during the good time than that under the situation without any environmental limit, may result in more items being stored in the production facility. For those toxic semi or final products whose presence or storage involves a high degree of environmental risks, this strategy may raise environmental concerns about workplace and community safety.

Guideline 2: A stricter standard on environmental wastes may increase environmental risks associated with higher stock levels.

When a standard on environmental wastes is tightened, the firm will use a strategy that leads to a higher production level during the good time. While the total amount of environmental wastes decreases as a result of the tightened standard, the total number of items stored in the production facility increases instead, which may again cause potential environmental risks regarding the presence or storage of toxic semi or final products. From a life-cycle perspective, the environmental risks are transferred from one stage of a product's life cycle to another due to the tightened environmental standard.

Guideline 3: The tax approach can induce the firm to internalize the external environmental costs.

In order to deal with the environmental problem associated with the large number of items being stored in a production facility due to uncertain environmental limits, a policy maker can use the tax approach to induce the firm to internalize the external environmental cost for holding inventory. Our analyses show that the firm's total cost under the scenario where the external environmental cost is voluntarily internalized can be lower than that under the scenario where a high tax rate is imposed by the government.

Guideline 4: Environmental and economic factors should both be taken into consideration when setting up environmental standards and choosing among policy approaches.

Similar to the results derived from the model of product development, the model of process management also shows the importance for a policy maker to understand the strategies used by the firm to deal with environmental challenges. Unilaterally pursuing environmental goals, such as imposing stricter standards on environmental wastes, may force the firm to use the strategy that leads to high planned production and stock levels, which results in transferring environmental risks from one stage of a product's life cycle to another. In order to determine the best level of environmental control and choose an effective policy instrument, a policy maker should consider both the economic and environmental impacts of the firm's production decisions under demand and environmental uncertainties.

Chapter 6

Conclusion

Operations Management and Environmental Management are two functional fields that are critical to the prosperity and welfare of human society. The objective of the dissertation is to integrate these important yet challenging areas from an interdisciplinary perspective. Analyzing environmental issues from the operations perspective can fundamentally attack the roots of most environmental problems that are caused by production-related activities. Incorporating environmental considerations into operations decisions can ensure not only the continuous growth of a company but also the sustainable development of human society.

The dissertation investigates two key issues for integrating operations and environmental management: green product development and process management. For each of the two key issues, we develop an analytical model, derive the optimal policies given different strategic or policy settings, and compare the economic and environmental impacts of the optimal policies. Based on the analytical results, we also propose guidelines that can be used by both operations managers and policy makers for managing and regulating green product and process innovations.

In the model of green product development, we analyze a firm's strategic decisions concerning the design of new products to satisfy customers who differ in their environmental values. According to our analysis, the strategy of green product development does not necessarily benefit the environmental since the firm will reduce the environmental quality of its ordinary products to prevent cannibalization. The analysis then focuses on the economic and environmental impacts of environmental standards on green product development, and shows that a stricter environmental standard does not necessarily benefit the environment.

In the model of green process management, we analyze a firm's decisions of production planning and inventory control under an uncertain environmental limit. With the environmental limit, the firm will use an optimal policy that leads to a higher level of planned production than that under the situation without any environmental limit in order to deal with both demand and environmental uncertainties. The level of planned production can be decreased if the firm is given the flexibility to violate the environmental limit with a financial penalty. Based on the theoretical model of process management, we use simulation analysis to develop a decision-support system for the purpose of deriving quantitative properties of the problem. The simulation experiments show that the strategy that requires higher planned production may also lead to a higher total stock level over the entire planning horizon, which results in transferring environmental risks from one stage of a product's life cycle to another.

Integrating operations and environmental decisions is a complex process full of risks and uncertainties. On the demand side, a decision maker must consider customer needs in terms of the quality and quantity of a product. On the supply side, a decision maker must deal with issues at both the strategic level, such as market segmentation and technology acquisition, and the tactical level, such as production planning, inventory control, pricing, and product design. On the policy side, a decision maker must take into consideration both the economic and environmental impacts of various environmental standards imposed on products and production processes. This dissertation, which analyzes the interactions among the demand, supply, and policy aspects of green product development and process management, is the first step toward developing effective private strategies and public policies for managing and regulating green product and process innovations.

In the future, it is expected that the analytical results presented in the dissertation will be empirically tested so that they can influence the practices of green product and process innovations in today's dynamic business world.

Appendix

To prove that π_2^r decreases faster than does π_1^r as r increases from $q_e^{o,2}$ to $q_e^{g,2}$, we will show that the derivative of the function π_2^r with respect to r is smaller than that of π_1^r and that both derivatives are non-positive for any r within the range $(q_e^{o,2}, q_e^{g,2})$.

First notice that π_2^r is a quadratic function in r that assumes its maximum at $q_e^{o,2}$. For $q_e^{o,2} < r \leq q_e^1$, $\pi_1^r = \pi_1$ in (2.20), which is independent to r. Therefore, the derivative of π_1^r with respect to r (which is zero) is larger than that of π_2^r (which is negative). For $q_e^1 < r < q_e^{g,2}$, π_1^r is given by (2.25), which is a quadratic function in r with its maximum at q_e^1. Take the first derivatives of π_1^r and π_2^r with respect to r, we have

$$\frac{\partial \pi_1^r}{\partial r} = (n_o + n_g)\left[2c_t - v_t - 2(c_t + c_e)r\right] \text{ and} \tag{A.1}$$

$$\frac{\partial \pi_2^r}{\partial r} = n_o\left[2c_t - v_t - 2(c_t + c_e)r\right] - n_g v_e. \tag{A.2}$$

It can be easily shown that, given $q_e^1 < r < q_e^{g,2} = (2c_t - v_t + v_e)/2(c_t + c_e)$, we have (A.2) < (A.1) < 0.

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