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SUSTAINABLE OPERATIONS

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1 Introduction

1.1 Why Focus on Sustainability?

The emerging focus on sustainability can be traced back to several observations regarding the consumption and availability of natural resources. First, from an absolute perspective, the total consumption of these resources has grown substantially. This can be attributed to significant increases in world population (due to reduced mortality rates that stem from medical advances). Second, the increase in per capita incomes of individual consumers (driven in part by the fact that two of the largest populated economies, China and India, have started to develop industrial bases) has also led to an increase in the consumption rate of these resources. Third, there is a finite supply of several natural resources, and this has led to dire predictions on when the current consumption will exhaust the availability of these resources. Finally, even for natural resources that can be replenished, there are two issues of concern: either the replenishment lead times are very long, or the increase in availability can only be achieved through the adoption of approaches (e.g., fracking) that are not environmentally sustainable.

Given these observations, becoming more sustainable seems justified since a commonly accepted definition of the term integrates three critical aspects: (a) the ability to be used without being completely used up or destroyed (e.g., a fusion reaction); (b) the use of methods that do not completely use up or destroy natural resources (e.g., recycling of water); and (c) the ability to last or continue for a long time (e.g., use of solar energy).

A broad perspective of sustainability covers the four interconnected domains of ecology, economics, politics, and culture. Since the early 2000s, firms have started to pay attention to the triple bottom line: profit, people, and the planet (Elkington 1997). These three forces are articulated by Tang and Zhou (2012). As the demand for natural resources continues to rise, the economic activities have generated and will continue generating vast wastes and pollutants to the environment (e.g., electronic waste or e-waste and greenhouse gas emissions). Consumer-advocacy groups have raised concerns about various unethical practices as companies begin outsourcing or offshoring their manufacturing operations to developing countries. With growth slowing in developed countries, fast-moving consumer goods providers are seeking to expand in emerging economies. The reader is referred to Tang and Zhou (2012) for a comprehensive review on broad sustainability using triple bottom line.
1.2 Operations/Supply Chain Management and Sustainability

From an operations/supply chain (O/SC) perspective, the seminal works of Corbett and Kleindorfer (2001) and Kleindorfer et al. (2005) note that there are significant opportunities for O/SC researchers and practitioners in the domain of sustainability. The specific issues that have been addressed can be categorized as those relating to product/process development and design, (forward and reverse) supply chain management, and environmental legislation.

1.2.1 Product/Process Design and Sustainability

“Green” is often used under the umbrella of sustainability. Although green was historically associated with regeneration, fertility, and rebirth for its connections to nature, it is also used as a symbol of environmental protection and social justice by political groups. From an O/SC perspective, it is associated with “green” product development and introduction. The general evidence associated with product/process development is confounded by market reactions; this is well illustrated in a 2010 article in the *New York Times* (September 18, 2010) titled “Can Green Products Deliver?” In this case, consumers were not satisfied with the visual “performance” (i.e., after product use, dishes did not appear to be sparkling!) of a new dish washing product that was better for the environment. There is also anecdotal evidence of successes associated with “green” products such as (a) GE experiencing a 21% growth in its *ecomagination* product line to $17 billion in 2008 sales and (b) P&G realizing $13 billion in cumulative sales from its sustainable innovations product group.

1.2.2 Sustainability in Supply Chains

The notion of sustainability in supply chains is motivated by industry observations that see a growing public concern regarding environmental issues. This has led to the introduction of environmental mandates (e.g., carbon generation caps), increases in the availability of greener products and services, contractual agreements which comprise some elements of green, and more rigorous specifications for green components in conventional products (through, for example, eco-labeling). Corporate social responsibility (CSR) programs reflect firm-level responses to these revised sustainability standards. The essential premise of these programs is that long-term success is a function of the joint consideration of profitability, social, and environmental issues. Firm-level success in sustainability-based contractual arrangements between supply chain partners is documented in the case of Wal-Mart, a company that estimates annual savings of approximately $200 million in combined freight and diesel fuel consumption costs simply by reducing packaging content in one toy product line.

Reverse supply chains provide two sustainability benefits: (a) they can extend the life of existing products, which leads to a smaller consumption of current resources; and (b) they can simultaneously minimize the generation of waste for disposal through recycling efforts. O/SC research and practice in this critical domain primarily focus on product and process design to facilitate recycling efforts as well as examining the impact of extending product life through remanufacturing efforts.

1.2.3 Environmental Legislations

Environmental legislations with a focus on sustainability is an emerging area which is receiving greater attention by O/SC practitioners and researchers. The United States has a long history of
monitoring and regulating clean air/water, pesticide use, and emissions. European countries (and especially Germany), on the other hand, also have stringent standards imposed on waste management. The political difficulties associated with mandating similar electronic waste-focused federal legislation in the United States has led individual states to take the lead in developing and implementing alternative legislation. Examining the efficacy of alternative legislative practices (typically directed at e-waste) is obviously of interest for O/SC researchers and practitioners.

1.3 Organization of This Chapter

The remainder of this chapter is organized as follows. Using the above categorization, Sections 2, 3, and 4 discuss current research and practice in the areas of product/process development and design, (forward and reverse) supply chains, and environmental legislation, respectively. Finally, Section 5 concludes this chapter with directions for future research.

2 Product Design and Process Development

In this section, we describe prior research studies that have addressed key sustainability issues relating to product design and process development.

2.1 Green Product Design and Environmental Performance

Green products that are capable of performing the same function as traditional ones only with significantly less environmental impact could be more expensive than their traditional counterparts. This extra expense is due to lack of scale economies and/or due to the use of more expensive materials or new technologies. If this is the case, success in green product development and introduction would be a function of market conditions (e.g., customer learning and behavior change), technology and operational capabilities (e.g., biotechnology for generic products and better technology for EVs), and the regulatory environments. Given the high degree of Market-Technology-Regulatory (MTR) uncertainties for green product development, Noori and Chen (2003) propose a scenario-driven methodology for designing and developing new green products that jointly analyzes the market, technology, and regulatory conditions in dynamic environments. The proposed methodology employs scenario analysis and back casting to analyze the complex and uncertain future states of new product development and uses continuous monitoring to deal with the changing environment. On the basis of the development process of biotechnology products in a major Canadian spice and seasoning company, a case study is presented to demonstrate how to apply the methodology for developing genetically engineered products.

In order to find the most efficient way to combine product specifications and attributes to achieve better environmental performances through product design, Chen et al. (2012) propose a two-stage network Data Envelopment Analysis (DEA) approach for evaluating the green product design that includes two internal modules: an industrial design module where engineering specifications (inputs) can be combined into product attributes (outputs); and a biodesign module where the links between key product attributes and environmental performances/consequences are examined. The data of product specifications, attributes, and indices of vehicle emissions performances in the vehicle emissions testing database published by the United States’ Environmental Protection Agency (EPA) are used to demonstrate how the approach can be applied to evaluate the sustainable design performances in both public and private sectors. The test results show that designing a green product does not imply a compromise between traditional and environmental attributes. Due to the interrelated nature of subsystems (i.e., material selection,
product reengineering, and expanding the technology frontier), the authors posit that product specifications and attributes can be combined most efficiently so that they lead to lower environmental impacts and/or better environmental performances.

Raz et al. (2013) focus on a profit-maximizing firm that pursues design changes in the manufacturing and use life-cycle stages of its product. Products are differentiated based on product life-cycle length (i.e., functional versus innovative products) and also by the environmental impact during their life-cycle stages (i.e., higher manufacturing stage environmental impact versus higher use stage environmental impact). Using a newsvendor framework, optimal quantity and effort decisions and their environmental impacts are characterized. Through an application of their framework to other products categorized based on life-cycle analysis (LCA), the authors show that functional products will require higher effort investment in manufacturing stage than in use stage, whereas the opposite is true for innovative products. This research also shows that while unit environmental impact is an increasing function of eco-efficient innovations, total environmental impact can either increase or decrease since this is driven by production quantities.

Chen and Liu (2014) study the pricing and design decisions of firms for green product design with virgin and recycled material contents in a duopoly. Products are composed of two materials: a recycled material and a virgin material. The external market is divided into two mutually exclusive segments each of a fixed size: a brown market segment and a green market segment. The firm that targets the brown market segment is referred to as the brown firm, while the firm targeting the green market segment as the green firm. Competition between firms takes place in a two-stage, non-cooperative game. In the first stage, each firm designs the mix of recycled and virgin material contents of its own product. In the second stage, after observing the other firm’s product design choice, the two firms set their prices under a specific type of price leadership. Two cases are used to summarize the two possible price leaderships (i.e., the leader and follower firm) arrangements: the brown firm is the leader while the green firm is the follower; and vice versa. The analysis in the paper characterizes financial incentives for sustainable product design and the authors show that: (a) the brown segment’s base level of efficient quality (i.e., the quality level that maximizes the differences between product valuations and production costs for brown segment customers) provides an “anchor product position” for the price leader no matter whether it is the brown or green firm; and (b) when the brown firm is the price leader and the green firm is the follower, a higher volume of recycled materials are used in product design.

### 2.2 Why Don’t Consumers Buy Green Products?

Public opinion polls consistently indicate that some customers are willing to pay a premium for green products and would prefer to choose a green product over a non-green product. However, observations show that customers keep purchasing those products that are less friendly to the environment. One underlying reason behind this value-action gap could be related to the way green products force customers to make trade-offs between traditional attributes (e.g., price, quality, and performance) and environmental attributes (e.g., ease of disposal and environmentally friendly content). Olson (2013) analyzes the attitudinal and behavioral impact of such trade-offs on customers’ preferences and choice of green products. Preferences for hybrid automobiles are contrasted with preferences for LED TVs through a full-profile conjoint analysis, which reveals attribute importance in the decision making process for these green products. Using data collected from customers in Norway and/or members of Norwegian organizations, the author finds that customers would choose a green product over one that is less friendly to the environment when all other things are equal. The value-action gap observed in the customer market stems from the trade-offs between environmental and traditional attributes. The reduction in
preference is observed to be less for LED TVs in comparison to hybrid automobiles which leads the author to conclude that a green product offering a compensatory advantage on a traditional attribute (i.e., the LED TV) attracts a broader spectrum of customers, while a product which does not (i.e., the Hybrid automobile) only attracts customers who are willing to pay a premium price. For both product categories, however, potential buyers of the greenest technologies tend to choose energy-thirsty specifications on negatively correlated conventional attributes, which in turn offsets some of their choices’ environmental benefits.

2.3 Innovation in Green Product Design

Customer demand for green products is increasingly pronounced to create far-reaching opportunities for businesses to promote their greener offerings and introduce profitable new ones. Lin et al. (2013) examine how market demand affects green product innovation and firm performance in the context of the Vietnamese motorcycle industry. Their study is focused around two issues: the impact of market demand on a firm’s green product innovation and the impact of green product innovation on firm performance. Four major motorcycle manufacturers have been surveyed, and the authors find that there is a positive correlation between market demand and both green product innovation and firm performance. In addition, green product innovation performance has a positive correlation with firm performance. The study also finds that in a highly competitive market, green product innovation is required to achieve a competitive advantage.

2.4 Green Product Offering Strategies

Prior work in this stream develops customer-centric models with a view to providing strategic and policy guidelines. More specifically, consumer preferences toward green products are modeled using traditional quality-based utility models that assume that the consumers’ willingness to pay for a product is increasing in quality and declining in price.

Chen (2001) proposes a quality-based model for green product design and consumer choice, and analyzes the strategic decisions of a monopolist on product development and market segmentation. Products are characterized in terms of two attributes: a traditional attribute and an environmental attribute. Analogously, the market consists of two segments: an ordinary segment comprised of consumers who only value the traditional attributes in products and a green segment consisting of consumers who value both the traditional and environmental attributes. Therefore, two product strategies are considered: (a) a status quo strategy (or mass-marketing strategy) where a single product is introduced to serve both market segments; and (b) a green product development strategy (or market-segmentation strategy) in which a single product is developed specifically for each segment. The author shows that both product strategies would lead to equivalent total environmental quality. When an external environmental standard is imposed, on the other hand, the paper shows that there exists a “danger zone” within which a stricter environmental standard may actually result in lower levels of total environmental quality.

Using a product differentiation model, Yenipazarli and Vakharia (2015a) evaluate alternate green product strategies that a monopolist firm can choose and implement in order to integrate environmental benefits into its product design. Product attributes are classified into two distinct aggregate dimensions (i.e., brown and green). Based on empirical evidence, customers are segmented into three distinct mutually exclusive groups: Traditionals, Fence-Sitters, and Greens. Using this framework, the authors evaluate three single-product strategies: Greening-Off, under which a product defined by a single brown attribute is offered; Greening-Out, where a new product defined in terms of a single environmental attribute is offered; and Greening-Up, under
which the firm redesigns its current brown product to incorporate green attributes so that
the product offering is defined in terms of two attributes. The key results stemming from this
research are that greening up an existing brown product is not necessarily better at reducing the
environmental impact, and that both environmental performance and profits can be simultane-
ously optimized through a focus on serving some but not all market segments.

In a follow-up study, Yenipazarli and Vakharia (2015b) analyze tactical and strategic implica-
tions of expanding a brown product line with a new green product. The focus of this research
is on examining preferred product introduction strategies under aggregate capacity constraints
and by considering two green product pricing choices: low- and high-priced green product. The
authors find that the two-level pricing structure can decrease the adverse effects of cannibali-
zation of green product introduction when adequate capacity is available. On the other hand,
when capacity is limited, a firm can never protect its products from the threat of cannibalization
by merely revising the pricing structure and this can lead to the firm not having an incentive to
introduce a green product.

3 Supply Chains

A multitude of papers examine issues related to the management of sustainable supply chains.
These contributions are described in this section and are categorized in terms of whether they
focus on forward or reverse supply chains.

3.1 Forward Supply Chains

3.1.1 Product and Retail Competition

Liu et al. (2012) examine the impact of customers’ willingness to pay higher prices for envi-
ronmentally friendly products and competition intensity levels—between partially substi-
tutable products made by different manufacturers and the competition between retail stores—on the
profits of different supply chain players. Three supply chain network structures are considered:
(a) a simple structure with no product or retail competition (i.e., there is a single manufacturer
and a single retailer); (b) a structure with only product competition (i.e., two competing manu-
facturers and a single retailer); and (c) a structure with both product and retail competition (i.e.,
two competing manufacturers and two competing retailers). Using a Stackelberg leader-follower
setting (Stackelberg 2011), each supply chain network structure is analyzed. The analysis indicates
that when customers’ environmental awareness increases, the profits of retailers and the green man-
ufacturer increase. The profits for a manufacturer offering only brown products can be increased
through a reduction of costs for environmentally friendly production or if it is possible to increase
product differentiation with a view to reduce product competition. In contrast, the manufacturer
offering green products will find a loss of profit if it does not have a significant cost advantage or
customers are not willing to pay a higher premium for its products. Under stronger retail compe-
tition, retailers are usually worse off while the green manufacturer is usually better off.

3.1.2 Component Commonality and Remanufacturing

Subramanian et al. (2013) study how an original equipment manufacturer’s (OEM’s) choice of
whether to implement component commonality is affected by secondary market considerations.
Three scenarios are analyzed: (a) the benchmark scenario with manufacturing only; (b) a scenario
with the OEM remanufacturing; and (c) a scenario with third-party remanufacturing. Product
offerings are of two types; i.e., high-end and low-end with given exogenous original product qualities. To evaluate commonality-related trade-offs under OEM remanufacturing and under third-party remanufacturing, it is assumed that the high-end product is remanufactured. The authors use this setting to investigate how remanufacturing could lead to a reversal of the OEM’s commonality decision. Relative to when the OEM produces and sells only new products, the authors show that cost reduction and cannibalization effects of commonality may lead to a different strategy choice under remanufacturing. Other specific findings stemming from this work are that under third-party remanufacturing: (a) commonality may result in a cost reduction for both the OEM and the third party and hence, component commonality may not be preferred by the OEM if the remanufacturing cost reduction is substantial; and (b) the cannibalization effect of commonality may instead be beneficial to the OEM, because its low-end product becomes more competitive relative to the third-party’s remanufactured product.

3.1.3 Order Quantities and Customer Environmental Concerns

Zhang et al. (2015) study the effects of customer environmental awareness (CEA) on order quantities for traditional and green products and on coordination of a supply chain with one manufacturer and one retailer. The manufacturer produces two substitute products: a green product and a traditional product. Using a multi-product newsvendor model, three supply chain scenarios are considered: centralized, decentralized, and decentralized with a returns contract. The key results of their study are that the order quantity of the green product increases with CEA, while the impact of CEA on the order quantity of a traditional product depends on the difference between environmental qualities of traditional and green products; the retailer serves as the conduit to develop a market for green products since the retailer’s profit increases monotonically with CEA; and the partial return credit contract for unsold products would provide a win-win solution in terms of green product development for both the manufacturer and the retailer.

3.2 Reverse Supply Chains

Blackburn et al. (2004) note that reverse supply chains are typically organized to manage activities related to used product acquisition; the transportation of used products to sorting facilities; the inspection, sorting, and disposition of collected products; remanufacturing (or refurbishing) of returns; and the creation of secondary markets for remanufactured products. In addition, the issue of reverse supply chain networks is also of relevance. In this section, we highlight the major contributions related to network design, managing the collections process, and remanufacturing.

3.2.1 Reverse Supply Chain Networks

Fleischmann et al. (2001) propose a reverse supply chain network with four levels: (i) plants where new products are manufactured and/or recovery takes place; (ii) warehouses for distribution of new and/or recovered products; (iii) consolidation centers; and (iv) customers. New and/or recovered products are shipped to customers via warehouses while returns are shipped to recovery facilities (or disposal) via consolidation centers. All the returns are sent first to testing centers and then shipped to different facilities. The goal of the firm is to minimize total costs, which include the fixed cost of opening sites and variable costs of transportation, handling, and production. The objective is subject to the constraints of flow balancing at each plant and required disposal rate, and the problem is solved by mixed-integer linear programming (MILP).
Wang et al. (2016a) focus on whether remanufacturing activities in a reverse supply chain should be carried out by the firm (i.e., in-house) or subcontracted to a third party (i.e., outsourcing). Their research is motivated by industry observations of GameStop, which, at the time, outsourced remanufacturing of game consoles to a third party and was contemplating whether this activity should be carried out in-house. Their analysis considers the relative cost-effectiveness of the two approaches, uncertainty in the input quality of the collected/returned used products, consumer willingness-to-pay for remanufactured products, and the extent to which the remanufactured product cannibalizes demand for new product. The authors identify “conflict” scenarios in which the in-house strategy maximizes profits, but outsourcing is better for the environment. To resolve this conflict, a profit-sharing mechanism is proposed where, under certain conditions, outsourcing becomes the retailer’s more profitable strategy while retaining an environmental advantage over the in-house approach. As a final extension, the authors also investigate how the outsourcing dominance region for profit maximization would be influenced by differences in bargaining power between the channel partners. Using an egalitarian bargaining framework, the authors show that the congruence and conflict regions for each strategy choice are similar to those obtained under the Stackelberg leader/follower setting.

3.2.2 Managing the Collection Process

Savaskan et al. (2004) explore the problem of who should collect used products and consider a two-echelon supply chain structure with a manufacturer and a retailer and compare the profitability of different collection modes: (a) manufacturer, (b) retailer, and (c) an independent third party. They find that the preferred collecting agent is the retailer, followed by the manufacturer, and the third party.

Souza et al. (2002) discuss various reasons and time scales of the enormous returns. Trade-in programs as a source of returns for remanufacturing is also of high relevance to reverse supply chains. Ray et al. (2005) assume that traded-in products can be remanufactured (so they have a value) and that consumers also have a feel for the value of their used product. They derive optimal trade-in discounts under three different policies: a discount dependent on the used product’s age, a discount independent of the product age, and no trade-in discount. Li et al. (2011) propose a methodology for forecasting trade-ins based on customer segmentation and signals (return merchandise authorizations, or RMAs).

Guide et al. (2006) use queuing networks to demonstrate the value of speed in recovery on profitability for time-sensitive consumer returns such as consumer electronics. Their analysis indicates that drivers for network design are product value, price decay, return rate, and proportion of unused returns.

3.2.3 Remanufacturing

Should an OEM offer a remanufactured version of its product? This question has been analyzed by several papers, and most of them use a vertical differentiation framework that incorporates the price trade-off between competing products of equivalent or unequal quality. Two implications of offering a remanufactured product are also considered: a market expansion effect, because the remanufactured product which usually has a lower price reaches a segment of consumers who are not willing to pay for the new product; and a cannibalization effect, as some consumers who would have previously purchased the new product switch to the remanufactured product.

Debo et al. (2005) analyze conditions under which it is profitable for a manufacturer to produce a remanufacturable product in a discrete-time, infinite-horizon framework for an industry
in which the manufacturer holds a monopoly in the markets for new and remanufactured products. A discounted profit-optimization problem is developed where the manufacturer’s goal is to maximize the net present value of introducing a remanufacturable product, calculated over the life-cycle of this product. The key results of this work are: high production costs of the single-use product, low remanufacturing costs, and low incremental costs to make a single-use product remanufacturable are the key drivers for investment in remanufacturing; the larger the number of low-end customers (i.e., customers with a low willingness-to-pay for new products) in the market, the lower the remanufacturing potential; and the customer profile and fixed costs interact to determine the optimal level of remanufacturability such that if the fixed costs are higher, the optimal remanufacturability level is lower and the market has more high-end customers. The authors extend their monopoly setting to one where the manufacturer produces only the new product (i.e., it has a monopoly position) but used products are remanufactured by multiple independent competing remanufacturers. In this scenario, the authors show that the optimal level of remanufacturability offered by the manufacturer is lower than that in the monopoly model and it decreases as the number of competing remanufacturers increases.

Ferguson and Toktay (2006) study the trade-offs between cannibalization of new product demand stemming from introducing a remanufactured product and the collection and manufacturing activities which can extend product life. They adopt a two-period setting where remanufacturing in the second period is constrained by the number of cores stemming from new product sales in the first period. The authors first identify conditions under which the firm would choose not to remanufacture its products. Then, they characterize the potential loss of profits stemming from external remanufacturing competition and analyze two third-party entry-deterrent strategies: remanufacturing and preemptive collection. In some cases, the authors find that some remanufactured-branded consumer products do not cannibalize new sales and thus can be used as a strategic deterrent to low-cost competitors. Examples of studies which have extended this analysis are as follows: Vorasayan and Ryan (2006) who focus on the impact of demand uncertainty; Ferrer and Swaminathan (2006) who examine the case where the OEM’s new and remanufactured products are perfect substitutes and the OEM compete with a third-party offering remanufactured product with an inferior quality; and Majumder and Groenevelt (2001) who provide an extension for the case of linearly decreasing demand as a function of price.

Atasu et al. (2008) examine a setting where there is a market segment which has identical valuations for both the remanufactured and new products. They focus on a case where an OEM creates both new and remanufactured products and competes with a low-cost producer of new product. Their key result is that if the consumers have a lower valuation for the competitive product, the competitor will not have any competitive advantage. Pince et al. (2012) show that an OEM will always offer a remanufactured product if such a product can be used to meet demand for warranty replacements.

### 4 Environmental Legislation

#### 4.1 Life-Cycle Assessment and New Product Introduction

Mayers et al. (2005) focus on the Waste Electrical and Electronic Equipment (WEEE) directive within the European Union (EU). Using life-cycle assessment and costing, they are unable to identify a dominant waste management scenario as compared to landfiling. They also find that contrary to belief, the use of targets in the directive would not necessarily lead to increased eco-design efforts on the part of manufacturers. Their key conclusion is to call for a revision of
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the scope of the directive by instead focusing on developing environmental objectives and standards for treatment and recycling processes.

Plambeck and Wang (2009) examine the impact of e-waste (electronic waste) regulation on new product introduction and design for remanufacturability, depending on the level of competition and on the form of regulation. Two specific legislations; i.e., fee upon sale and fee upon disposal, are considered. The authors identify the conditions under which a unique equilibrium for a new product introduction process can be characterized both in a monopoly and in a duopoly setting. The effects of the two e-waste regulations on the new product introduction process, quantity of e-waste, design for remanufacturability, and manufacturer profits are examined. Specifically, it is shown that fee-upon-sale types of e-waste regulation cause manufacturers to increase their development time and expenditure, resulting in increases in the incremental quality for each new product. Such a regulation also increases manufacturers’ profits since customers pay a higher price for each new product as they anticipate using these products for longer. However, the authors find that fee-upon-sale types of e-waste regulation discourage manufacturers to design new products that are remanufacturable. While the social welfare increases in a duopoly, it decreases in a monopoly if and only if e-waste costs are small. In contrast, fee-upon-disposal types of e-waste regulation encourages design for remanufacturability but simultaneously forces manufacturers to introduce new products too rapidly, which in turn generates more e-waste.

4.2 Extended Producer Responsibility (EPR)

Although there are a multitude of legislative practices with an environmental focus that have been proposed, Lifset (1993) contends that all such practices internalize externalities by changing the behavior of producers as well as consumers, and in the long run should promote environmentally oriented technological change. From an economic policy perspective, Palmer and Walls (1997) study Extended Producer Responsibility (EPR)-type legislation that mandate the use of specific secondary materials content in manufacturing. They find that such policies need to be coupled with additional taxes on the final product and other production inputs so as to generate the optimal disposal amount.

Gui et al. (2016) provide an in-depth analysis of implementing an Extended Producer Responsibility (EPR) program in the state of Washington in the United States. They are able to provide guidelines on how to achieve effective and efficient EPR implementations with a focus on design incentives, reuse and refurbishing, product scope, downstream material flows, and operational efficiency. Atasu et al. (2009) derive efficiency conditions for EPR-type legislation. In addition to these legislations being perceived as alleviating fairness concerns, they also incentivize eco-design producers to create larger environmental benefits.

Subramanian et al. (2009) examine the impact of EPR policy parameters on product design. They model a manufacturer supplying a remanufacturable product to a single customer who obtains a fixed utility (or revenue) per period from the product. Three questions are addressed in this paper. First, they address the issue of whether EPR programs provide adequate incentives to manufacturers to design green products. An integrated supply chain is considered in which the average supply chain profit has to be maximized per period. They find that higher charges for environmental impact during product use can lead to better remanufacturability that reduces the end-of-life environmental impact of the product. Additionally, as the customer bears a larger share of charges during product use, the manufacturer is shown to have a greater incentive to design the product to be more remanufacturable. Second, they investigate how contracts can be structured to improve supply chain profitability and environmental product design. A decentralized supply chain under symmetric and asymmetric information is modeled where
the manufacturer and the customer are independent entities who privately maximize their profits. For the case of symmetric information, it is shown that coordination leads not only to higher supply chain profits as expected but also to environmentally more favorable product design. Third, they examine how customer attributes affect incentives for product design and supply chain coordination. They show that a supply chain with an efficient customer lowers the manufacturer’s incentive to design the product with greater remanufacturability, since remanufacturing and disposal costs are incurred less often.

Atasu and Subramanian (2012) turn their attention to comparing collective and individual producer responsibility (CPR and IPR, respectively) models of EPR. Their primary focus is on design for product recovery (DfR) and find that IPR leads to superior DfR incentives since CPR could lead to free-riding. In a follow-up study, Gui et al. (2013) examine collective implementations of EPR. Since current cost allocation mechanisms in these implementations might lead to higher costs for certain producers, this could lead to a market fragmentation. To address this problem, they propose and validate a cost allocation mechanism, which induces participation and simultaneously maximizes efficiency. Atasu et al. (2013) comparatively evaluate two legislative practices: a tax model, where the social planner specifies a take-back fraction and charges the OEM a recovery fee; and a rate model, where it is the responsibility of the OEM to ensure compliance with the take-back fraction. They are able to show that the impacts of this type of legislation can be significantly different, and hence, stakeholder preferences vary across practices.

### 4.3 Policy Implications

There is another stream analyzing how the policy instruments impact the incentive of supply chain members as well as the environmentally favorable design. The typical objective in this stream of research is for the social planner to maximize net social surplus subject to resource constraints, material balance constraints, and production functions. Toffel (2003) provides an excellent overview of developments in take-back legislation and their likely impacts on organizational decision making. Runkel (2003) examines how EPR influences the choice of product durability and social welfare. Several researchers have examined the economic and social efficiencies of various policy instruments such as taxes, subsidies, standards, and take-back requirements (e.g., Calcott and Walls (2000), Eichner and Pethig (2001), Fullerton and Wu (1998), Palmer and Walls (1997), and Dinan (2005)). An environmentally favorable design implies lower material consumption, higher fraction of product recycled, or lower cost of recycling. A consistent finding is that a combined tax/subsidy, where there is a consumption good tax and a recycling subsidy (such as in a deposit-refund system) can yield the socially optimal product design and quantity of waste.

Yenipazarli (2015) studies the impact of emissions taxations on the optimal production and pricing decisions of a manufacturer who could remanufacture its own product. The conditions under what the manufacturer’s decision to remanufacture under an emission regulation reduces its environmental impact while at the same time increasing its profits are characterized. On the policy side, the conditions under what emissions taxes can be instituted to realize the economic, environmental, and social benefits of remanufacturing are also characterized. The analyses are subsequently extended to an emissions trading setting where emissions are regulated using tradable permits, and the economic implications of remanufacturing under emissions trading vis-à-vis emissions taxation are studied.

Wang et al. (2016b) examine the strategic and policy implications of two diametrically opposed legislative practices for regulating and financing e-waste disposal. The first practice (characterized as “Producer Pays”) imposes a fixed market share based fee and a per-unit disposal
fee on an OEM, while the second practice (characterized as “Anticipatory Protection”) charges a per-unit fee to each consumer of an electronic product. To analyze the impact of each legislation, they typify current practices by considering an OEM who offers two competing products: a new product and a remanufactured product. The two legislative practices are evaluated in the context of multiple stakeholder objectives: product prices, OEM profits, and consumer and environmental surplus. Their results reveal that, in most cases, there is a parametric trade-off in the choice of legislative practices. By structurally characterizing this trade-off, the authors identify dominance regions for each strategy choice. Regions where a single strategy choice would be the preferred choice of both a social planner and the OEM are also identified by the authors. From a policy perspective, the authors provide guidelines on how the per-unit fee for the OEM should be structured by the social planner so that both the former and latter players prefer a specific legislative practice.

5 Directions for Future Research

Irrespective of the vast literature on product/process design, we identify the following areas as promising avenues for future thought. The majority of product/process development literature focuses on the demand-side impact on the manufacturer’s decisions. Although the existing work incorporates certain aspects of the supply side, there is still ample room for new and insightful research that focuses on:

- **Integrating product/process development with component recovery.** Product design changes impact the recovery of core (remanufacturable) components. Hence, the testing of the returned products, disassembly costs, and manufacturing process re-engineering all play a role in the product/process design decisions.

- **Interplay between modularity and sustainable product design.** Disassembly operations for products should be integrated along with process changes. The higher the complexity of the product, the higher the benefit due to integrating the design decisions with the disassembly decisions. Although product modularity and its impact on the supply side decisions has been well studied, sustainable product design could influence these decisions extensively.

The existing work on supply chain design can further be strengthened by bridging the gap between the logistics network design and reverse channel design. Most of the existing work includes the decisions of the consumers and various supply chain partners in the presence of green products. In this context, opportunities for future research include:

- **Impact of supply chain decisions on the overall logistics network.** The decisions on who should perform the remanufacturing operations, which channel is used to collect the used products, which channel is used in marketing the products, etc., alter the demand characteristics as well as the logistics requirements. Consequently, supply chain partners may need to rethink their logistics decisions including facility location, demand forecasting, and transportation.

- **Examining the impact of a firm’s sustainability initiatives on supply chain partners.** There is the possibility that a focus on sustainability within a firm might result in a transfer of knowledge/benefits to supply chain partners. As a consequence, a firm’s investment on such an initiative may ultimately benefit its competitors. Such a linkage needs to be integrated in a firm’s investment on environmentally friendly practices as well as operational and strategic decisions.
Finally, in the area of environmental legislations, two specific future research opportunities are:

- **Fit of environmental legislations with industry type.** Legislations may force the supply chain partners to modify the logistics network to avoid possible penalties and to reduce the carbon footprint. In this context, studies that develop frameworks for environmental legislative practice based on their applicability under distinct industry settings would serve as valuable tools.

- **Policy guidelines for social planners.** Since social planners are often struggling with assessing the policy implication when designing environmental legislations, it would be helpful to conduct research that provides insights into how multiple-stakeholders in supply chains are impacted by specific legislations. This would of course vary by industry types and thus, frameworks developed would be particularly useful in formulating these policy guidelines.

**References and Bibliography**


