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Sustainable supply chain management: Review and research opportunities

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Abstract Anthropogenic emissions likely pose serious threat to the stability of our environment; immediate actions are required to change the way the earth's resources are consumed. Among the many approaches to mitigation of environmental deterioration being considered, the processes for designing, sourcing, producing and distributing products in global markets play a central role. Considerable research effort is being devoted to understanding how organisational initiatives and government policies can be structured to facilitate incorporation of sustainability into design and management of entire supply chain. In this paper, we review the current state of academic research in sustainable supply chain management, and provide a discussion of future direction and research opportunities in this field. We develop an integrative framework summarising the existing literature under four broad categories: (i) strategic considerations; (ii) decisions at functional interfaces; (iii) regulation and government policies; and (iv) integrative models and decision support tools. We aim to provide managers and industry practitioners with a nuanced understanding of issues and trade-offs involved in making decisions related to sustainable supply chain management. We conclude the paper by discussing environmental initiatives in India and the relevance of sustainability discussions in the context of the Indian economy.

Introduction

A broad consensus has by now emerged that anthropogenic emissions pose serious threat to the stability of our environment, and that the resulting changes will affect our ecosystem by disrupting food and water supplies, submerging coastal wetlands, and causing severe weather patterns and species extinction. The global average temperature has been rising since the early 1900s, and has risen by more than 0.5 °C in the last 50 years alone, with an accompanying rise in global average sea levels and drop in Northern Hemisphere snow cover (IPCC, 2007a). Decades of careful data collection, analysis and projections by groups

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of scientists and researchers around the world have confirmed that the world faces severe changes with an expected 2—4 °C rise in global average temperature by the year 2100: 30—40% of the species could be extinct, close to a third of global coastal wetlands are in danger of being submerged, millions of people will likely face food and water shortages, and many densely populated areas of the world, including many parts of Asia, will face higher rates of morbidity and mortality from heat waves, floods and droughts (IPCC, 2007b).

A large part of the blame has been attributed to the six greenhouse gases (GHGs) that are known to trap heat into the earth's atmosphere and contribute to a rise in global temperature: primary ones being carbon dioxide, methane, and nitrous oxide. As measurements have shown, concentrations of GHGs in the earth's atmosphere have been relatively stable over the last 10,000 years (at between 250 and 300 parts per million). However, in the last 150 years or so—since the beginning of industrial revolution—concentrations of carbon dioxide in the atmosphere have shot up by more than 30% (from less than 300 ppm to close to 400 ppm), and concentrations of methane have almost doubled (IPCC, 2007a). Several large scale model projections have shown that a business-as-usual scenario, with no changes in our production methods and consumption habits, will lead to an imbalance in the ecosystem and damage the stability of our environment.

There is an obvious need for urgent action to change the way we consume the earth's resources. Among the many approaches to mitigation and adaptation being considered, the processes for designing, sourcing, producing and distributing products in global markets play a central role, as these activities account for a bulk of the resources consumed and the environmental impact. For example, in the United States, industrial activities account for about a third of fossil fuel related carbon dioxide emissions; another 40% are accounted for by transportation (EPA, 2007). Evidently, design and management of supply chain activities is a primary factor in promoting environmental sustainability.

In this paper, we review the current state of academic research in designing and managing sustainable supply chains, and provide a discussion of future directions and research opportunities in this rapidly evolving field. In Section 2, we provide a definition and description of Sustainable Supply Chain Management. In Section 3, we summarise and discuss existing classifications and reviews of research in this field, and describe how our perspective differs from those in the literature. Section 4 presents the bulk of recent research in this area that fits our integrative perspective, summarised under four broad categories: (i) Strategic considerations; (ii) Decisions at functional interfaces; (iii) Regulation and government policies; and (iv) Integrative models and decision support tools. We conclude in Section 5 with a discussion of some environmental initiatives in India and the relevance of sustainability discussions in the context of the Indian economy.

Sustainable Supply Chain Management (SSCM)

We define Sustainable Supply Chain Management (SSCM) as a set of managerial practices that include all of the following:

- Environmental impact as an imperative;
- Consideration of all stages across the entire value chain for each product; and
- A multi-disciplinary perspective, encompassing the entire product life-cycle.

This definition implies a few broad themes in our perspective on environmental sustainability. First, firms must view environmental impact of their activities as an integral part of decision-making, rather than as a constraint imposed by government regulation or social pressure, or as a fad to exploit by appearing to be "green". Second, firms must pay attention to environmental impact across the entire value chain, including those of suppliers, distributors, partners and customers. Third, firms' view of sustainability must transcend a narrow functional perspective and encompass a broader view that integrates issues, problems and solutions across functional boundaries.

In keeping with this definition, our review of the literature on SSCM adopts a firm perspective, rather than societal or policy-makers' perspective, and focuses on organisational decisions related to the entire product life-cycle that involves design, production, distribution, consumer use, post-use recovery and reuse. We do not limit ourselves to literature in any one academic discipline; rather, we focus on interactions across functional areas including corporate strategy, product design, production and inventory management, marketing and distribution, and, regulatory compliance.

The paper is intended to provide managers and industry practitioners with a nuanced understanding of issues and trade-offs involved in making decisions related to SSCM. The paper is also intended to provide management researchers with a summary of the current state of the art in SSCM research, and a roadmap for future research directions.

SSCM research: reviews and classification

Several excellent reviews have been written over the years that examine various aspects of SSCM-related research. While these reviews adopt different perspectives from ours, readers interested in exploring a particular aspect of SSCM would find them useful. For instance, many of the existing reviews explore the SSCM literature for implications of environmental concerns on firm's individual functions involving activities such as product design, production planning, or inventory management. On the contrary, we examine the existing studies from a value-chain perspective, and discuss environmental concerns in managerial decisions across functions. Moreover, most of the existing reviews cover literature that is, in some cases, over a decade old. Our review focuses on more recent research in this fast changing and growing field.

Early research efforts in SSCM were largely devoted to understanding the technical and operational considerations inherent in collecting, testing, sorting, and remanufacturing of returned products. Research in this domain can broadly be classified under the following headings: (i) Production planning, scheduling and control; (ii) Inventory management; and (iii) Reverse logistics. While research in these areas continues, given the availability of excellent reviews covering this domain, we will abstract from these issues in our review, and encourage the readers to consult the papers mentioned below.

In an early review of the literature, Greenberg (1995) surveys the use of mathematical programming models for controlling environmental quality, focussing on air, water, and land. The paper is limited to general equilibrium models with multiple decision making agents, where an equivalent mathematical program can be formulated to compute a fixed point. The review provides an annotated bibliography with more than 300 papers, and identifies many research avenues for studies using mathematical programming in addressing environmental concerns. Fleischmann et al. (1997) focus on quantitative models of reverse logistics, and subdivide the literature in three areas: distribution planning, inventory control, and production planning. For each of these areas, the authors discuss the implications of the product reuse efforts being explored at the time, review the mathematical models proposed in the literature, and point out the areas in need of further research. Carter and Ellram (1998) also focus on reverse logistics, but present a more holistic view that includes the reduction of materials in the forward system in such a way that fewer materials flow back, reuse of materials is made possible, and recycling is facilitated. The paper develops a broadened view of the role of logistics personnel in reverse logistics, and identifies gaps where future research is needed. In particular, the authors identify important players and influencing factors (internal, external and environmental) involved in reverse logistics and provide a framework to study these issues.

Gungor and Gupta (1999) focus on 'environmentally conscious manufacturing and product recovery', described as integrating environmental thinking into new product development including design, material selection, manufacturing processes, product delivery to the consumers, and end-of-life management of the product. The authors review and categorise more than 300 papers based on four stages of product life-cycle analysis: product design, manufacturing, use, and recovery. The paper argues that two key issues involved in 'environmentally conscious manufacturing' are: (i) understanding the life-cycle of the product and its impact on the environment at each of its life stages, and (ii) making better decisions during product design and manufacturing so that the environmental attributes of the product and manufacturing process are kept at a desired level. Consistent with bulk of the research efforts at the time, the review focuses on the product recovery process (divided into 'recycling' and 'remanufacturing'), and provides an analysis of issues relevant in collection, disassembly, inventory control and production planning of used products. Similar issues are tackled in Guide and van Wassenhove (2002) and Guide, Jayaraman, and Srivastava (1999).

In a departure from the narrower focus of articles summarised above, Kleindorfer, Singhal, and van Wassenhove (2005) review various sustainability themes covered in the first 50 issues of *Production and Operations Management* journal. The authors use the term sustainability broadly to include environmental management, closed-loop supply chains, and triple-bottom-line thinking that integrates profit, people and the planet into the culture, strategy and operations of companies. The authors suggest that businesses are under an increasing pressure to pay more attention to the environmental and resource consequences of the products and services they offer and the processes they deploy. In turn, operations management (OM) researchers and practitioners face new challenges in integrating sustainability issues within their traditional areas of interest. The paper concludes with some thoughts on future research challenges in sustainable operations management, highlighting three areas—green product and process development, lean-and-green OM, and, remanufacturing and closed-loop supply chains—that integrate essential aspects of sustainable OM.

"Closed loop supply chain management" (CLSC) can be defined as the design, control, and operation of a system to maximise value creation over the life-cycle of a product, with dynamic recovery of value from different types and volumes of returns over time (Guide & van Wassenhove, 2006). This perspective has gained increasing attention among researchers in the last decade. Guide and van Wassenhove (2009) focus on business aspects of closed-loop supply chain research and provide a personal perspective on value-added recovery activities, but do not review the existing literature. The authors summarise evolution of CLSC research through five phases, which is useful in understanding the evolution of a subset of research activities within SSCM. The paper claims that Phase 1 consisted of early research that focused almost exclusively on technical problems and individual activities of reverse logistics. Phase 2 has expanded research problems to include inventory control, reverse logistics networks, and remanufacturing/shop line design issues. Phase 3 involves coordinating reverse supply chains using an economic perspective and game theoretic models, understanding strategic implications of product recovery, contracting issues, incentive alignment, and channel design. Phase 4 involves 'Global system design for profitability', that primarily includes issues such as time value of product returns and maximising value over entire product life-cycle. Phase 5 involves a focus on marketing issues such as pricing of product returns, cannibalisation, and understanding consumer behaviour.

While these reviews and classifications provide different perspectives on sustainability research in supply chain management, none of them provides an integrative, comprehensive overview of the field from a firm's perspective, adopting a strategic decision-based approach. We seek to integrate these perspectives in our review below.

Integrative SSCM

Following our discussion in Section 2, we consider a broad range of managerial decisions, categorised along the following dimensions:

I. Strategic considerations:
   a. Organisational strategy
   b. Supply chain strategy and structure
   c. Marketing strategy
II. Decisions at functional interfaces:

  d. Product design and product life-cycle
  e. Pricing and valuation of returns
  f. Forecasting, information provision, and value of information
III. Regulation and government policies:
  g. Extended producer responsibility
  h. Cap and trade programs
IV. Integrative models and decision support tools

In the following sections, we briefly summarise the major issues and concerns in each of these categories, review and summarise some of the academic efforts that have addressed these issues, and outline promising avenues for future research in these areas.

Strategic considerations

Organisational strategy

From a strategic perspective, organisational decisions on sustainability revolve around the following questions: (i) How does the organisation view sustainability? (ii) What options does the organisation have to incorporate environmental considerations into strategic decisions? (iii) How do these considerations affect theories of the firm that provide an economic rationale to firm's existence, behaviour, structure and relationship to markets? While there are broad debates in literature on corporate social responsibility (of which sustainability discussions could be seen as a subset), we limit ourselves here to a value chain perspective and summarise the major issues via three papers that discuss, respectively, the strategic value of pollution prevention and resulting productivity gains, compare specific methods and techniques for controlling greenhouse gas emissions on their estimated costs, and outline the strategic importance of reverse value chain activities. These themes recur throughout this article and we will expand on them, and their impact on supply chain related decisions, in the following sections.

In an influential article, Porter and van der Linde (1995) view pollution from the perspective of resource inefficiency, and discuss green initiatives in terms of their implications on firm's competitiveness. In particular, they view the inherent trade-off between environmental regulations and competitiveness as ecology versus economy: the regulations provide social benefits via strict environmental standards, however, higher private costs for prevention and cleanup increase prices and hence reduce competitiveness. The authors argue that policy makers, business leaders, and environmentalists have focussed on the static cost impact of environmental regulations and have ignored the more important offsetting productivity benefits from innovation. Moreover, the authors claim that pollution prevention through product and process design is superior and economical to pollution control through waste management. In this regard, they propose a resource productivity framework based on innovation and improvements in operational efficiency.

While Porter and van der Linde (1995) argue for the benefits of pollution prevention over pollution control, Enkvist, Naucler, and Rosander (2007) focus on GHG emissions and provide detailed cost curves that enable a deeper understanding of the significance and cost of each possible method of reducing emissions. The cost curves show estimates of the prospective annual abatement cost in Euros per ton of avoided emissions of GHGs, as well as the abatement potential of these approaches in gigatons of emissions. The study covers six sectors (power generation, manufacturing with a focus on steel and cement, transportation, residential and commercial buildings, forestry, and agriculture and waste disposal) in six regions (North America, Western Europe, Eastern Europe including Russia, other developed countries, China, and other developing nations) spanning three time horizons (2010, 2020 and 2030). For the most part, at the low end of the curve are measures that improve energy efficiency, whereas at the higher end are approaches for adopting more greenhouse gas-efficient technologies and for shifting to cleaner industrial processes.

In contrast to the papers discussed above, Jayaraman and Luo (2007) focus on reverse value chain activities (reuse, repair, refurbishing, recycling, remanufacturing, or redesign of returned products from the end-user), and present a redefined value chain strategy that entails a closed-loop system for industries in which such activities may create additional competitive advantages for the firm. The analysis presented in this paper is relevant from a strategic management perspective for the following three reasons: (i) through reverse logistics, the value chain is no longer portrayed as unidirectional, but as a closed-loop system in which additional values are generated from the existing resources; (ii) the competitive advantage paradigm can be further enlightened by a new source of competitive edge—tangible values from the physical side and intangible values from the information side of reverse logistics; (iii) the reverse logistics framework has implications for the resource-based view of the firm.

Supply chain strategy and structure

The next level of organisational decisions involves the structure of the supply chain and strategic choices the firms must make in order to incorporate sustainability considerations. Research effort here has largely focused on designing the reverse supply chain to collect and re-use end-of-life products returned by customers, structuring supply chain incentives to properly motivate partners, and managing competition between remanufactured and new products. The following summary provides the major issues and findings in the literature.

Savaskan, Bhattacharya, and van Wassenhove (2004) address the problem of choosing appropriate reverse channel structure for the collection of used products from customers for remanufacturing. In particular, a manufacturer in the supply chain has three options for collecting used products: (i) collect directly from the customers, (ii) incentivise the existing retailer to induce collection, or (iii) subcontract the collection activity to a third party. The proposed noncooperative game theoretic model has decentralised decision-making system with the manufacturer as the Stackelberg leader. The authors show that simple coordination mechanisms can be designed such that the collection effort of the retailer and the supply chain profits are attained at the same level as in a centrally coordinated system.

Savaskan and van Wassenhove (2006) extend the above model to a multiple retailers setting. The authors focus on the interaction between a manufacturer's reverse channel choice to collect post-consumer goods and the strategic product pricing decisions in the forward channel when retailing is competitive. They first examine how the allocation of product collection to retailers impacts their strategic behaviour in the product market, and later discuss the economic trade-offs the manufacturer faces while choosing an optimal reverse channel structure. The authors show that when a direct collection system is used, channel profits are driven by the level of returns, whereas in the indirect reverse channel, supply chain profits are driven by the competitive interaction between the retailers. Moreover, from the supply chain coordination perspective, they show that the buy-back payments transferred to the retailers for post-consumer goods provide a wholesale pricing flexibility that can be used to price discriminate between retailers.

The effect of competition from remanufactured products is a primary concern for a manufacturer. This competition can be from products the manufacturer introduces himself, or from another remanufacturer who enters the market, intercepts used products from consumers and sells remanufactured products that compete with new products from the manufacturer. Several papers have examined this issue. Majumder and Groenevelt (2001) present a two-period model to explore the effect of competition in remanufacturing. In the first period, only an OEM manufactures and sells new products. In the second period, a fraction of these items are returned for remanufacturing. However, the OEM doesn't get all these returned products, some are used up by a local remanufacturer who competes with the OEM in the consumer market to sell remanufactured products. In this case, the critical trade-offs for the OEM are between the lower cost of remanufacturing in the second period against the threat of higher competition from the remanufacturer. The authors show that competition causes the OEM to manufacture less in the first period and attempt to increase local remanufacturer's cost of remanufacturing. On the contrary, the remanufacturer helps OEM reduce his manufacturing cost. The authors also extend the model to examine the role of a social planner who wants to increase remanufacturing. They show that the social planner can give incentives to the OEM to increase the fraction available for remanufacturing, or reduce his remanufacturing costs.

Ferguson and Toktay (2006) develop models to support a manufacturer's recovery strategy in the face of a competitive threat on the remanufactured product market. They first analyse the competition between new and remanufactured products produced by a monopolist manufacturer and identify conditions under which the firm would choose not to remanufacture its products. They then characterise the potential profit loss due to external remanufacturing competition and analyse two entry-deterring strategies: remanufacturing and preemptive collection. A major finding is that a firm may choose to remanufacture or preemptively collect its used products to deter entry, even when the firm would not have chosen to do so under a pure monopoly environment.

Ferrer and Swaminathan (2006) analyse a two-period model, that is later extended to a multi-period setting, in which a firm produces new products in the first period and uses returned cores to offer remanufactured products, along with new products, in the second period. They extend their focus to the duopoly environment where an independent operator sells remanufactured products in future periods. The authors find that if remanufacturing is very profitable, the original-equipment manufacturer may forgo some of the first-period margin by lowering the price and selling additional units to increase the number of cores available for remanufacturing in future periods. Further, as the threat of competition increases, the OEM is more likely to completely utilise all available cores, offering the remanufactured products at a lower price.

SSCM and marketing strategy

While a large part of the SSCM literature focuses on operational decisions, a small but significant research stream has explored sustainability decisions in a supply chain from a marketing perspective. Two major issues have been examined: (i) How do market characteristics affect remanufacturing incentives? (ii) How do classical marketing decisions such as pricing and segmentation, interface with technology selection and remanufacturing decisions? The following papers provide some answers.

Atasu, Sarvary, and van Wassenhove (2008) examine the remanufacturing environment from a marketing perspective with an emphasis on important characteristics of a remanufactured product such as low-cost, lower valuation, cannibalisation and supply constraints. In addition to analysing the profitability of remanufacturing systems for different cost, technology, and logistics structures, the authors provide an alternative and somewhat complementary approach that considers demand-related issues, such as the existence of 'green' segments, original-equipment manufacturer competition, and product life-cycle effects. For a monopolist, they show that there exist thresholds on the remanufacturing cost savings, the green segment size, market growth rate, and consumer valuations for the remanufactured products, above which remanufacturing is profitable. They also show that under competition, remanufacturing can become an effective marketing strategy, which allows the manufacturer to defend its market share via price discrimination.

Debo, Toktay, and van Wassenhove (2005) visualise remanufacturing as an interplay between pricing, market segmentation and technology selection. In particular, the authors solve the joint pricing and production technology selection problem faced by a manufacturer that considers introducing a remanufacturable product in a market that consists of heterogeneous consumers. The objective is to understand the market and technology drivers of product remanufacturability. They show that 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 technology drivers. The more consumers are concentrated on the lower end of the market, the lower the remanufacturing potential.

While these papers provide a much-needed impetus to research in this domain, many issues remain to be examined. First, we need to identify and critically examine the firm's incentives to invest in product durability in relation to the life-cycle environmental impact of products. Second, more research is needed in designing, pricing and promoting products with specific environmental attributes—such as lowering emissions, reducing amount of waste generated/disposed, and increasing energy efficiency—in much the same way as marketing literature has studied other attributes. Consumer valuation of environmental attributes of products, willingness to pay for new versus remanufactured products, advertising and promotion strategies for 'green' products, sales force compensation and incentives, integration of forward and reverse channels, product line design decisions are all issues that can have tremendous implications on theory and practice of SSCM. Further research into these areas is likely to be influential in shaping our understanding of, as well as guiding managerial decisions in, SSCM.

Decisions at functional interfaces

The discussion above summarises strategic aspects of sustainable supply chain management. We now turn to describing specific managerial decisions and trade-offs firms need to understand in order to incorporate sustainability as an integral part of management practice. In keeping with our integrative perspective, we focus primarily on decisions that cross disciplinary boundaries and span the entire value chain.

For SSCM, managing post-use products along with new products has been a primary focus of researchers and practitioners alike. There are several interesting and challenging issues that the literature has tried to address when considering new and remanufactured products over their entire life-cycles. New products diffuse through markets at different rates, different consumers use the products for various lengths of time before discarding or returning the products, and the rate of product use over a certain length of time varies across individuals. All these characteristics make the timing, quality and quantity of returned product streams variable and unpredictable. This in turn poses challenges for manufacturers in deciding on the pricing of returned products, determining how much to invest in getting better information on returns, and deciding on the type and level of investments to make at the design stage, to make the products more durable or remanufacturable.

Thus, the literature here can broadly be summarised along the following three categories: (i) product design and product life-cycle; (ii) pricing and valuation of returns; and (iii) forecasting, information provision and value of information. We discuss each of these categories below.

Product design and product life-cycle

The crucial design decisions firms face include deciding on the durability of products and/or components, and the level of remanufacturability of products, while accounting for the challenges of an unpredictable return stream, consumer preferences between new and remanufactured products, and supply constraints. The following papers investigate some of these issues.

Debo, Toktay, and van Wassenhove (2006) build a model based on the Bass diffusion model to examine the integrated dynamic management of a portfolio of new and remanufactured products that penetrate a market over the product life-cycle. The authors address the issues of cannibalisation, timing of used product returns, volume of product returns, remanufacturability, diffusion rate, and repeat purchase. The timing of product return is modelled using a residence time construct, which is defined as the duration of one use of the product by a customer; residence time is uncertain and exogenously given. Primarily, the paper contributes to the SSCM literature a way to analyse life-cycle dynamics of new and remanufactured products and investigates the impact of various managerial levers (remanufacturability level, capacity structure and reverse channel responsiveness) on profitability. It also contributes to the diffusion literature by extending the Bass diffusion model to accommodate repeat purchases, substitution behaviour, and an endogenous supply constraint.

Geyer, van Wassenhove, and Atasu (2007) focus on products that have reached the end-of-use phase but still contain significant amounts of value added, such as components that can be reused for manufacturing products with original functionality. In this regard, the authors model the cost-savings potential of production systems that collect, remanufacture and remarket end-of-use products as perfect substitutes while facing the constraints of limited component durability and finite product life-cycles. The product characteristics considered in the model are the lifetime of the product, used product collection rates, and the length of end-of-use period. Moreover, they model the limited durability of reusable components by quantifying the characteristic number of times a component can be used for the same kind of product. The results demonstrate the need to carefully coordinate production cost structure, collection rate, product life-cycle, and component durability to create or maximise production cost savings from remanufacturing. The paper contributes to the SSCM literature by investigating the profitability of product remanufacturing under basic supply-loop constraints such as accessibility of end-of-use products (collection rate), technical feasibility of remanufacturing (durability), and market demand for remanufactured products (life-cycle).

Pricing and valuation of returns

The second set of issues in managing an unpredictable stream of returned products involves decisions related to valuation and pricing of post-use product returns. Some of the many factors that affect pricing of returns are: (i) product durability and remanufacturability, (ii) timing of return, (iii) extent of consumer use, (iv) supply of returns, (v) extent of cannibalisation between new and remanufactured products, (vi) presence of competitors in both new and remanufactured products markets, (vii) effort required to encourage, collect and process returns, and (viii) the reverse supply chain network. While many of these issues remain to be examined, and a comprehensive analysis that includes all of these factors is a complex task, many researchers have looked at some of these issues and provided interesting answers.

Ray, Boyaci, and Aras (2005) study the optimal pricing and trade-in rebate decisions for a profit-maximising firm selling a durable, remanufacturable product. The focus is on decisions of the firm at the particular point in time when it is announcing the trade-in offer. The main features of the model are: (i) durability, (ii) time dependent residual value, (iii) age profile of the products, and (iv) the relative size of the two segments. The authors argue that the replacement decisions are driven not only by the trade-in-prices, but also by the durability as well as age of the existing product in use. The age of the product determines the residual value of the product, whereas durability has a bearing on how this value depreciates over time. They show that if the firm is dealing with a low-durability product, then it is sufficient to know only the average age of the products in use to determine the optimal age-independent rebate. Moreover, this rebate increases with durability.

Guide, Souza, van Wassenhove, and Blackburn (2006) argue that the issue of how to extract more value from the returns stream has been largely ignored. In this regard, they consider the problem of how to design and manage the reverse supply chain to maximise net asset value recovered from the flow of returned products. They explicitly capture the cost of lost product value because of time delays at each stage of the returns process. A queuing theory based network flow model developed for this closed-loop supply chain computes the value of reducing delays in reprocessing of returned products. They show that a centralised efficiency-driven reverse network is no longer always appropriate. Return rate and recoverable product value are scale effects, i.e., they impact the magnitude of the costs of the reverse network, and therefore the profitability of the business. Large and increasing return rates and high recoverable product value influence the structure of the reverse channel. Hence, companies with high return rates and considerable recoverable value should seriously consider redesigning their return networks from a focus on centralisation and efficiency to a focus on responsiveness (speed, decentralisation) when the rate at which their products lose value is high. If, in addition, many returned products are unused, firms should also consider an early product differentiation strategy.

Forecasting, information provision, and the value of information (VOI)

The third category of decisions related to managing uncertainty in return product stream involves information. How and when can better information improve management of returns? What kind of information is more valuable? Is there a trade-off between investing in reducing supplier lead-time and investments made to improve remanufacturing yield information? How can a manufacturer better organise its remanufacturing operations to make use of advanced yield information? The following summary provides the answers.

Ketzenberg, van der Laan, and Teunter (2006) explore the value of information in the context of a firm that faces uncertainty with respect to demand, product return, and product recovery. The objective is to evaluate the VOI from reducing one or more types of uncertainties, where value is measured by the reduction in total expected holding and shortage costs. Starting with a single period model, the authors show that there is no dominance in value amongst the different types of information, and that there is an additional pay-off from investing in more than one type. The authors then extend their analysis to the multi-period case, where returns in a period are correlated with demands in the previous period, and study the value of partial information as well as full information. They demonstrate that the results from the single period model carry-over exactly.

Ferrer and Ketzenberg (2004) address a remanufacturer's problem involving a trade-off between limited information regarding remanufacturing yield and potentially long supplier lead-time. Their results indicate that the yield information is generally quite valuable, while investments in supplier responsiveness provide trivial returns to products with few parts. However, as product complexity increases with large number of target parts, the value of short lead times increases.

Ketzenberg, Souza, and Guide (2003) explore the value of advanced yield information in the context of a mixed assembly-disassembly operation for remanufacturing. The main focus is on determining the best line configuration. Under a parallel configuration, there exist two separate dedicated lines, one for assembly and one for disassembly, that are decoupled by inventory buffers. Under a mixed configuration, the same station is used for both disassembly and assembly of a specific part. The authors investigate the value of advanced yield information on these two different configurations and find that this information generally improves flow-time. They also show that the parallel configuration outperforms the mixed line only when the variability of both arrivals and processing time are significantly higher for disassembly and remanufacturing than for assembly.

Regulation and government policies

In our discussions so far, we have assumed that firms take sustainability as a strategic priority, and have focused on specific actions firms need to take to incorporate sustainability in supply chain decisions. However, government regulation and policies often play an important role in encouraging firms to adopt sustainability practices. Traditional approaches to government regulation adopt a 'command and control' perspective by, for example, mandating levels of environmental taxes (e.g., carbon tax), forcing firms to adopt minimum environmental standards (e.g., mandating a certain percentage of power generation to come from renewable sources), or subsidising certain technologies and industries (e.g., solar and wind power generation). While such approaches can certainly be useful in some circumstances, it is increasingly being recognised that environmental impacts of products over their lifecycle can best be managed through goal-oriented and market-based mechanisms that provide flexibility in choosing compliance levers to the targeted firms or industries. Excellent examples of such market-based approaches include emissions trading programs and extended producer responsibility (EPR). In the US, markets for sulphur-dioxide (SO_2) permits now account for more than USD 8 billion a year in trades; in the EU, the Emissions trading scheme is the cornerstone of the Kyoto Protocol implementation and affects more than 12,000 producers in 25 countries. Moreover, an increasing number of industries, from electronics to automobiles, in countries around the world find themselves responsible for 'closing the loop' on their products, as EPR programs make them responsible for product take-backs post consumer-use. As experience in designing and implementing such mechanisms accumulates, policy makers everywhere are exploring market-based programs to achieve the goals of environmental sustainability in a variety of areas. Such mechanisms are preferred to the traditional command-and-control approach to environmental policy making because of the price signal and the flexibility they provide to the decision-makers, and often lead to environmental goals being realised more efficiently. Proper design of such mechanisms, however, needs to reflect a good understanding of managerial choices and trade-offs that often weigh profit maximisation and economic value of decisions as heavily as social and environmental goals.

We will focus in this section on two market-based mechanisms that have been widely debated and adopted around the world: (i) Extended producer responsibility, and (ii) Cap and trade. We introduce and discuss each of these regulatory mechanisms, outline major issues and trade-offs that academics and managers need to address in adapting to each of these mechanisms, and provide a summary of academic literature that has dealt with the issues outlined below.

Extended producer responsibility (EPR)

EPR is a prime example of a successful market-based approach to sustainability. EPR policies are being applied with two primary objectives: shifting responsibility for life-cycle environmental performance of products towards the producers and away from municipalities, and providing incentives to manufacturers to incorporate environmental considerations into the design of their products (Lindhquist, 1992; Organization for Economic Cooperation and Development (OECD), 2001). EPR is implemented through various instruments such as product take-back and recovery targets (e.g., home appliance recycling in Japan; ordinance on producer responsibility for cars in Sweden making manufacturers responsible for accepting end-of-life vehicles); economic instruments such as disposal fees and material taxes (e.g., more than a dozen states in the US have taxes or fees on the disposal of old tires, EPA, 1991); or design/performance standards such as fuel efficiency laws in the US and Canada. Firms under EPR programs also have a variety of strategies available to make their products and production processes sustainable, including the following:

- Change product design to incorporate end-of-life take-back, disassembly and reuse;
- Rationalise parts and components to decrease material usage, eliminate hazardous substances, and facilitate remanufacturing;
- Change product mix;
- Choose optimal product durability with a view not only to 'planned obsolescence' but 'planned take-backs and replacements' as well;
- Consider alternatives to selling, such as leasing and 'installed base management' in which the manufacturer assumes responsibility for the product replacement decision, and bundles maintenance services along with the sale or lease of its product;
- Consider various contractual arrangements with suppliers and distributors that facilitate joint planning and responsibility over the life-cycle of a product, including the structure of the 'reverse supply chain' to manage product take-backs and remanufacturing.

Evidently, the interactions and trade-offs are complex. Several authors have studied some of these issues and have generated important insights into how EPR policies and firm decisions interact.

Toffel (2003) argues that three objectives of product take-back legislations are: (i) to reduce the amount of hazardous materials heading to landfills, (ii) to increase the availability and reduce the price of recyclable materials relative to virgin materials, and (iii) to prevent pollution by reducing the environmental burden of end-of-life products at their source. The author argues that in addition to deciding on the types of responsibilities to impose, legislators must also decide whether to impose these responsibilities individually on companies or collectively on entire industries, and whether specific fee and pricing mechanisms should be stipulated. The article identifies the potential industries in which take-back legislations can be targeted, analyses the potential impact of such legislations, and discusses alternative product recovery strategies.

The issue of individual versus collective product take-back is analysed by Webster and Mitra (2007) within a two-period manufacturer/remanufacturer competitive model. The authors show that, in some settings, enactment of collective take-back will result in higher manufacturer and remanufacturer profits while simultaneously spurring remanufacturing activity and reducing the tax burden on society. A negative effect is higher consumer prices in the market. In other settings, they find that collective take-back introduces a structural change to the industry, creating an environment where remanufacturing becomes profitable when it is not profitable without a take-back law. With respect to individual take-back, they find that the manufacturer often benefits from allowing the remanufacturer to enter the market, though from a government policy-maker perspective, there are clear risks of monopolistic behaviour. Atasu, van Wassenhove, and Sarvary (2009) show that the efficiency of take-back systems is driven by environmental classification of products, industry structure, and end-user willingness to participate in take-back programs.

Subramanian, Gupta, and Talbot (2009) examine the influence of EPR policy parameters on product design and coordination incentives in a durable product supply chain. The paper models two design attributes of the product: performance and remanufacturability, and considers environmental costs during product use (e.g. emissions) and post-use (e.g., product waste and landfilling). The authors demonstrate how environmental charges during use and post-use can be used as levers to encourage environmentally favourable product design. They also analyse the impact of supply chain coordination on design choices and profit, and outline three contracts that can be used to achieve coordination, both under symmetric and asymmetric information about customer attributes. In particular, the authors show how contracts such as price-replacement interval, two-part tariff and leasing can coordinate supply chains, leading to higher supply chain profitability as well as environmentally superior product design choices.

Plambeck and Wang (2009) investigate the impact of e-waste regulation on a new product. Manufacturers choose the development time and expenditure for each new version of a durable product, which together determine its quality. "Fee-upon-sale" types of e-waste regulation cause manufacturers to increase their equilibrium development time and expenditure, and thus the incremental quality for each new product. As new products are introduced (and disposed of) less frequently, the quantity of e-waste decreases, and even excluding the environmental benefits, social welfare may increase. Consumers pay a higher price for each new product because they anticipate using it for longer, which increases manufacturers' profits. The existing "fee-upon-sale" types of e-waste regulation fail to motivate manufacturers to design for recyclability. In contrast, "fee-upon-disposal" types of e-waste regulation such as individual extended producer responsibility motivate design for recyclability, but in competitive product categories, fail to reduce the frequency of new product introduction.

Cap and trade

In 1990, Title IV of the Acid rain program developed by the Environmental Protection Agency in the US established a cap and trade program for reducing SO_2 emissions from the biggest electricity generating units. The total emissions from all sources were capped, and the units were allocated individual allowances based on their baseline heat input. The units had the flexibility to choose methods to comply with their allocated emission limits through, for example, input substitution, process improvements, abatement or sequestration. Those that achieved larger amounts of reductions than required could then sell their excess permits to firms that had difficulty reducing their emissions levels economically. A market price was thus established for emissions. The program has been widely credited for achieving emission reductions much faster and at costs far below the initial estimates.

The SO_2 program provides an illustration of a successful, market-based approach to environmental improvement that has been replicated in many programs. In February 2005, Kyoto Protocol was ratified by several countries to be the predominant global mechanism with specific targets to reduce greenhouse gas emissions. The Emissions Trading Scheme, adopted by 25 countries in the European Union, is the cornerstone of those countries' strategies to meet their commitments under Kyoto Protocol. The EU ETS remains the largest cap and trade program in the world, covering more than 12,000 facilities, 46% of EU's GHG emissions, and more than USD 60 billion in traded volumes. Several market exchanges have been established to facilitate trades in "carbon-credits" with dominant players such as the Intercontinental Exchange (www.theice.com) and Nasdaq OMX Commodities (www.nasdaqomxcommodities.com) reporting traded volumes of over 5 billion and 45 million tons of CO_2e, respectively (in 2009), including spot and futures trades.[1]

While the United States has been a notable exception to Kyoto Protocol, several regional cap and trade programs in the US for GHG emissions are operational or are being experimented on. These include Regional Greenhouse Gas Initiative (RGGI) in the Northeast; the Western Climate Initiative (WCI) among states in the western United States and several provinces in Canada, including British Columbia, Ontario, Quebec, and Manitoba; and the Midwestern Climate Accord among several states in the Midwest, including Michigan, Illinois, Iowa, and Minnesota. Cap and trade programs are also under consideration in Australia, Japan, and New Zealand.

The proliferation of cap and trade programs around the world poses several challenges for the study and practice of sustainable supply chain management. Among the issues that need to be studied are the following:

- What are the major compliance strategies or levers firms have at their disposal to comply with a cap and trade regime?
- How can firms determine the value of a carbon permit, and internalise that value in making investment decisions?
- How do carbon prices affect product line design decisions when different products require different capacities and have different levels of emissions during production?
- How do different regulatory regimes (such as carbon permits or taxes and subsidies) affect a firm's technology choice decisions?

While economists have extensively studied cap and trade issues, research efforts into incorporating the effects of cap and trade programs within SSCM have been lacking, with the following exceptions.

Subramanian, Gupta, and Talbot (2007) characterise the trade-offs among firms' compliance strategies in an industry facing a cap and trade regime, where a regulator interested in controlling emissions auctions off a fixed number of emissions permits. Firms can invest in pollution abatement, procure permits in an auction that allow them to release a certain amount of pollutants, or decrease output levels, in order to comply with emissions stipulations. The regulator chooses the emissions targets for a particular pollutant, firms in a particular industry or a geographic region. Using a three-stage game theoretic model, the authors show that, contrary to popular beliefs, a tightening of the environmental stipulations through reduction in the available permits can benefit firms, provided the firms are sufficiently 'clean'. Indeed, their results show that a reduction in the number of permits stimulates lower levels of investment in abatement from 'dirtier' industries. This research offers a systematic way for regulators to assess the interactions among observed abatement levels, permit prices in auction-based markets and industry output levels. In addition, the framework offers a way for firms to evaluate trade-offs among different options they have to comply with environmental regulations, and a methodology to derive a bidding strategy in permit auctions based on the firm's marginal value function for a unit of permit.

Drake, Kleindorfer, and van Wassenhove (2010) study the impact of cap and trade and emissions tax regulation on a firm's technology choice and capacity decisions, focussing

[1] CO_2e stands for carbon dioxide equivalent, a standard measure that converts the impact of each greenhouse gas in terms of the amount of carbon dioxide that would cause the same amount of warming.

on heavy process industries such as power generation, cement, and pulp and paper that are often targeted by environmental regulation. The authors develop a two-stage, stochastic model where the firm chooses capacities in two technologies in stage one, demand uncertainty resolves between stages (as does emissions price uncertainty under the cap and trade regime), and the firm chooses production quantities. They characterise solutions under two regimes (cap and trade, and emissions taxes) and compare the resulting technology shares, expected profit, expected emissions, and expected production. The authors find that expected profits are greater and expected emissions are lower under cap and trade, while expected production is greater under an emissions tax, indicating competing welfare effects.

Integrative models and decision support tools

As is apparent from our discussion so far, the connection between a firm's operational decisions and its environmental performance is immediate. Although environmental considerations often impose additional costs and constraints on production systems, they also open up new opportunities that, if properly exploited, can lead to better financial performance while also improving the firm's environmental impact (Subramanian, Talbot, & Gupta, 2010). Joint operational and environmental decision-making requires the understanding and modelling of complex trade-offs, which, in turn, requires a rich and pliable framework capable of treating nonlinear interactions (Bloemhof-Ruwaard, van Beek, Hordijk, & van Wassenhove, 1995). Senior managers in many industries lack such a framework and practical tools that can help them set priorities and make decisions that are both financially and environmentally sound. There is therefore a rich opportunity for researchers and practitioners to collaborate in developing integrative, holistic models that can treat these complex trade-offs and serve as decision support tools for managers. The following efforts cover some distance towards this target.

Stuart, Ammons, and Turbini (1999) present an analytical approach to capture comprehensively measurable corporate environmental impact considerations for the product life-cycle. A mixed integer programming model is developed to select product and process alternatives while considering trade-offs of yield, reliability, and business-focused environmental impacts. In particular, the constraint sets demonstrate a new way to define the relationship between disassembly configurations and assembly activities through take-back rates.

Subramanian, Talbot, and Gupta (2010) develop a nonlinear mathematical programming model from a profit-maximising firm's perspective, which can be tailored as a decision-support tool for firms facing environmental goals and constraints. Although, the model is based on the specific context of diesel engine manufacturing and remanufacturing, it demonstrates how environmental targets and firms' compliance strategies can be modelled effectively with mathematical programming. In particular, the authors incorporate operational elements (e.g., quantities of new and remanufactured products to be produced in each period), environmental elements (e.g., design choices such as performance and remanufacturability), and strategic elements (e.g., pricing and demand management) in a single model.

SSCM considerations in India

Over the last two decades, the Indian economy has witnessed an unprecedented growth in its output, resources consumed, and consequently, environmental impact. The average GDP growth rate for the Indian economy since 2001 has been 7.5 percent, and India now ranks as the fourth largest economy in the world, measured on purchasing power parity (International Monetary Fund, 2011). India's aggregate greenhouse gas emissions have increased from 1.2 billion tons CO_2e in 1994 to 1.7 billion tons CO_2e in 2007,[2] a compound annual growth rate of 2.9%, earning India 5th spot in aggregate GHG emissions in the world (Indian Network for Climate Change Assessment, 2010). However, per capita GHG emissions remain low at around 1.7 tons/person in 2007 compared to a global average of about 4.3 tons/person. A comprehensive report issued by the Government of India, comparing results from five environmental modelling studies, suggests that even with rapid economic growth, India's per capita GHG emissions are expected to remain between 2.77 and 5.00 tons/person in 2031, though aggregate emissions are expected to increase to between 4.0 and 7.3 billion tons (Climate Modelling Forum, 2009).

Many policy initiatives taken post-liberalisation in the country in 1991 require mitigation of greenhouse gases and other air/water pollutants. With growing global competition and increasing emphasis on environmental concerns, firms are increasingly required not only to offer high quality and innovative products with competitive prices, but also to develop supply chains that are sustainable in the long run. Emission and waste reduction, climate change mitigation, and energy conservation sectors in India are therefore likely to see significant growth in the future.

As a 'non-Annex I' country, India does not have binding emissions reduction targets under Kyoto Protocol. Historically, India's participation in international carbon markets has largely been through the Clean Development Mechanism (CDM), a 'flexible mechanism' that allows countries with binding emissions reduction commitments to invest in certain environmental projects in India. Such reductions lead to 'certified emissions reduction' credits, which can be traded in international carbon markets such as the EU ETS, or used by Annex I countries to meet their targets. While India has been the second largest host country for CDM projects to date, lack of a domestic carbon market may have hindered local innovation in clean technologies and a widespread adoption of sustainable practices. However, with post-2012 carbon market uncertainties in the world, Indian policy-makers have been looking at various avenues to curb emissions through schemes such as renewable energy certificates (REC) and perform-achieve-trade (PAT). Based on these schemes, industry experts believe that there is scope for creating a new domestic market for

[2] Including Land Use, Land Use Change and Forestry (LULUCF).

emissions mitigation, which is expected to touch INR 200 billion in the next few years (Singh, 2011).

There is also an emerging consensus that policies and incentive mechanisms promoting market-based approaches are in particular desirable to mobilise Indian businesses to solve environmental problems in a positive way. With per capita income expected to triple over the next two decades, the Indian consumer market is projected to grow by over 32 percent (McKinsey Report, 2007). This dramatically changing retail sector demands immediate and drastic changes in policies addressing production and marketing concerns, such as types of products/components produced, product life-cycle, end-of-life disposal, and distribution channels adopted by firms. In this regard, absence of sustainable supply chains and insufficient government incentives have been identified as some of the most important issues the industry is facing today (CII-ATKearney Report, 2006).

In addition to regulatory initiatives, IT/ITeS can also enable firms to better design and coordinate activities in their supply chains with an emphasis on reduced environmental impacts. For example, Cognizant Inc. (2008) suggests several possible actions for incorporating sustainability in various supply chain activities of firms: (i) focussing on efforts reducing packaging and in-transit damage; (ii) performing life-cycle analysis in helping choose products/solutions with minimum environmental impact; and (iii) aligning green initiatives with the strategic objectives of the firm. The burgeoning Indian IT/ITeS sector can certainly play an important role here in pioneering sustainable supply chain solutions and helping diffuse these solutions throughout the world.

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