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Product Reuse Economics in Closed-Loop Supply Chain Research

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This paper provides a critical review of analytic research on the business economics of product reuse inspired by industrial practice. Insights and critical assumptions are provided for each paper. We further classify the research into four streams: industrial engineering/operations research, design, strategy, and behavioral, and present a framework linking these streams. We find that some modeling assumptions risk being institutionalized, and suggest a renewed exploration of industrial practice. Future research should also include empirical work on consumer behavior, product diffusion, and valuation of returns.

Key words: closed-loop supply chains; remanufacturing; reverse logistics; reuse economics
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Introduction

Closed-loop supply chains (CLSCs) can generate profits by taking back products from customers and recovering the remaining added value. Depending on the economics of a particular situation, recovery processes may reuse the entire product, selected modules, components, and/or parts. CLSCs represent a rapidly growing industrial activity characterized by a lack of formal systems and procedures to guide management decision making. There has also been a recent surge in academic research interest.

CLSC management may be defined as *the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with the dynamic recovery of value from different types and volumes of returns over time* (Guide and Van Wassenhove 2006). This definition has evolved from the strictly technical understanding of remanufacturing, prevalent when we began research in this area 15 years ago. Indeed, remanufacturing started as product life extension for large capital goods, such as locomotive engines and airframes (Lund 1984). Over the years, CLSC research has evolved from this narrow technical focus to a full-fledged subarea of supply chain management (Guide and Van Wassenhove 2007).

Product returns are an increasing concern to industry. Large retailers can have return rates in excess of 10% of sales, and manufacturers such as Hewlett-Packard report product return costs that exceed 2% of total outbound sales. At present, only a small percentage of the value is being recovered. Many firms still view product recovery activities as a nuisance, and this prevents them from recognizing potential value creation activities.

This paper offers an in-depth discussion of CLSC analytic research that takes a business economics focus and was inspired by practice. Our motivation is simple: academic research should be focused on industrially relevant problems to create impact. We identified research papers by consulting our colleagues, and relying on our own research experiences over the last 15 years, to guide us in selecting influential research, or research that we believe will be influential (Table 1). Our focus on practice-driven analytic research on business economics does not imply that other CLSC research is not influential but that these other research streams are simply outside the scope of this paper. We readily admit that the final selection was a somewhat subjective decision made in consultation with our colleagues in this area. We also point out how these papers influenced recent research with similar focus. Our objective is to provide a framework for understanding how the research has evolved and to point out important future research issues.

Table 1 CLSC Analytic Research with a Business Economics Focus

CLSC research stream	Analytic papers discussed
IE/OR	van der Laan et al. (1999) Toktay et al. (2000) Fleischmann et al. (2001)
Design	Geyer et al. (2007) Guide et al. (2003) Savaskan et al. (2004) Guide et al. (2006)
Strategy	Majumder and Groenevelt (2001a) Ferguson and Toktay (2006) Debo et al. (2005) Debo et al. (2006) Atasu et al. (2008)
Behavioral	Ferguson et al. (2006) Guide and Li (2007)

The purpose of the paper is not to provide an exhaustive review of the vast literature on remanufacturing, CLSCs, environmental operations, or sustainable business. A quick search on Google Scholar revealed more than 10,000 articles. We readily admit that we omit works that could well be considered "classics"; however, these works fall outside of the criteria we established for the research considered in this work. For the interested reader we include Table 2 as a global introduction to CLSCs. We also suggest that readers with a broader interest in operations and the environment consult the feature issues edited by Corbett and Kleindorfer (2001, 2003).

Foundations of CLSC Reuse Economics Research

To set the foundations of this business economics approach, we begin by discussing three early thought-piece papers that were anchored in industrial practice. These papers outlined a set of suggestions for investigation, which subsequently drove a great deal of academic work and provided the basis for the analytic research we discuss.

Strategic Issues in Product Recovery Management (Thierry et al. 1995). This paper contains perhaps the first examination of product recovery as a value-added set of activities from a general management perspective. It discusses the introduction of a green copier line at Xerox and the subsequent changes. It became apparent that the introduction of this new remanufacturable line of copier affected all the business functions at Xerox. This research led the authors to eight important managerial implications.

1. There were significant problems in obtaining the required information flows to support managerial decision making because information was scattered among many groups, if available.
2. The selection of the most profitable option depended on technological feasibility, sufficient sources of used products, markets for recovered goods, and legislation.
3. The use of specific material reuse targets is beneficial to focus managerial attention.
4. Product redesign is most often necessary.
5. More cooperation is required among the different supply chain actors.
6. There are opportunities to cooperate with competitors in developing reverse supply chains.
7. Companies wanting to develop capabilities in product recovery must be able to manage the supply of used products (product acquisition) and develop markets for recovered products and materials (remarketing).
8. Product recovery activities will have a profound influence on production, operations, and logistics management.

The research by Thierry et al. (1995) laid the foundation for a general understanding of how product recovery activities influence the firm, and established the need for in-depth research into a number of important topics.

Table 2 Suggested Readings in CLSC

Dekker et al. (2004)
Flapper et al. (2005)
Guide and Van Wassenhove (2003a)
Guide and Van Wassenhove (2003b)
Guide and Van Wassenhove (2004)
Guide and Van Wassenhove (2006)
Kleindorfer et al. (2005)

Production Planning and Control for Remanufacturing: Industry Practice and Research Needs (Guide 2000). The second thought-piece paper was based on years of industrial experience with capital goods remanufacturing firms, many of them dealing with complex military asset remanufacturing. This research established how remanufacturing shops are different from traditional manufacturing operations and explores the research issues from an industrial engineering/operations research (IE/OR) perspective. Managers of remanufacturing facilities must effectively cope with the inherently higher amount of variability. This variability can require different managerial processes (e.g., product acquisition management to obtain the right quality of used products) and/or new tools to plan and control. It also suggests numerous analytic and empirical research opportunities based on current industrial practice. Guide (2000) also recognizes the need for researchers to take a broader business perspective on remanufacturing when designing subsystems (e.g., production planning and control).

Managing Product Returns for Remanufacturing (Guide and Van Wassenhove 2001). The final thought-piece paper blends the general management view of Thierry et al. (1995) with the IE/OR view of Guide (2000) into a business perspective on CLSCs with a strong focus on profitability. This paper provides a framework for analytic research taking a business process view. It shows the value of eliminating all the process bottlenecks to unleash the hidden profitability of CLSCs. These bottlenecks can be technical or cost-related, but most often we find them in product return acquisition or remarketing processes. This research shows that product acquisition (1) determines whether remanufacturing is a value-creating activity for a firm, (2) is a key driver to maximize profits, (3) influences facility design, and (4) helps uncover the market potential for remanufactured goods. The authors use an economic profit approach to explore the drivers that can unleash the hidden value and how managers can influence these drivers.

To summarize, these three thought-pieces, Thierry et al. (1995), Guide (2000), and Guide and Van Wassenhove (2001), were based on industrial reality and carefully explored how product reuse affects the firm. They also outlined a research agenda that called for studies examining the overall business model. These papers heavily influenced much of the analytic work that followed.

Four CLSC Research Streams

CLSC research can be broken down into four major streams (Table 1). Early researchers took the traditional *IE/OR* approach to analyze the new problems specific to remanufacturing. This stream deals with familiar OR themes, such as forecasting return rates, dual sourcing inventory control, and reverse logistics network design.

A second stream of research pursued a more holistic *design*, recognizing that industry was struggling with getting the larger business issues right and identifying the drivers of profitability. Researchers in this stream addressed problems in product acquisition management, time value of product returns, durability choices, diffusion of new and remanufactured products over the life cycle, and the link between durability, return rates, and product life cycle.

The third stream takes a more *strategic* competition focus, considering the viability of an original equipment manufacturer (OEM) introducing remanufactured products on the market. This research focuses on issues such as reverse channel design (i.e., who should collect used items), how an OEM can compete with third-party remanufacturers, and how introducing remanufactured products can be a deterrence to the entry of low-cost competitors.

The final stream addresses *behavioral* problems related to commercial product returns and customer perceptions of remanufactured goods. Research shows that manufacturers can, by setting the right incentives, motivate resellers to reduce false failure product returns. Consumer perception research focuses on how companies and consumers value remanufactured products, i.e., what is the willingness to pay (WTP) and how do remanufactured products cannibalize (or may be substituted for) new product sales.

It should be clear that any categorization is somewhat arbitrary. We readily acknowledge that some papers may fit into more than one stream, and the decision on where to place a particular paper was, in part, a subjective one. The following sections elaborate on influential papers in the four research streams outlined above.

CLSC IE/OR Stream Papers

Much of the initial research into remanufacturing took a technical IE/OR focus using the familiar OR toolkit (e.g., queueing, inventory control, and facility location models) to obtain managerial insights. Although the three papers discussed below may, strictly speaking, not have a business economics focus, they were heavily inspired by industrial reality and strongly influenced later work.

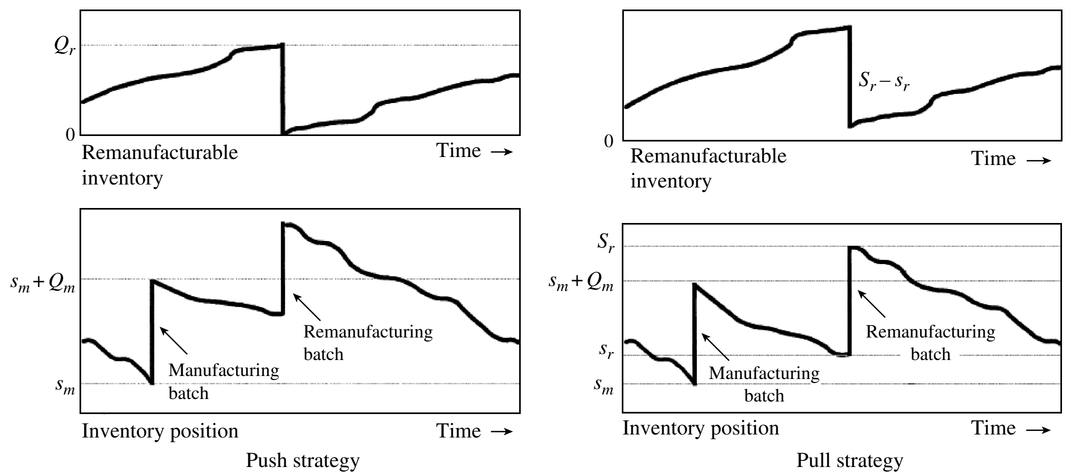
Inventory Control in Hybrid Systems with Remanufacturing (van der Laan et al. 1999). This paper provides an elegant analytic investigation of dual sourcing inventory systems using product returns under a (Q, R)-type of continuous review ordering policy. The main question is how to best manage the returned products. This research was motivated by problems at Xerox and IBM. Two logical strategies are considered (Figure 1): *Push*, where the returned products are remanufactured as early as possible, and *Pull*, where the returned products are remanufactured as late as possible. In the Push strategy, as soon as the returned product inventory reaches Q_r, a remanufacturing batch is triggered. The remanufactured items are then added to the serviceable inventory. Conversely, under the Pull strategy, when the remanufacturing reorder point, s_r, is reached, and the returned product inventory is sufficient, a remanufacturing batch $S_r - s_r$ will be pulled. The main contribution of the paper is comparing the traditional systems with hybrid systems and identifying conditions under which Pull (Push) is superior.

***Critical Assumptions*:**

—Perfect substitution; i.e., customer does not distinguish between new and remanufactured items.

—Continuous review policy with Push or Pull policy for returned products, and full backordering.

Figure 1 Push and Pull Strategies (from van der Laan et al. 1999)



Source. Reprinted by permission. Copyright 1999 INFORMS. Figures 2 & 3 in van der Laan, E., M. Salomon, R. Dekker, L. N. Van Wassenhove. 1999. Inventory control in hybrid systems with remanufacturing. *Management Science* 45(5) 733–747, the Institute for Operations Research and the Management Sciences, 7240 Parkway Drive, Suite 300, Hanover, Maryland, 21076.

—Single product and unlimited capacity with fixed lead times.

—Coaxian-2 demand and return distributions.

***Insights*:**

—The expected system cost with remanufacturing may be higher than without remanufacturing. Indeed, the additional costs of return variability could offset the savings from using recovered products instead of new products.

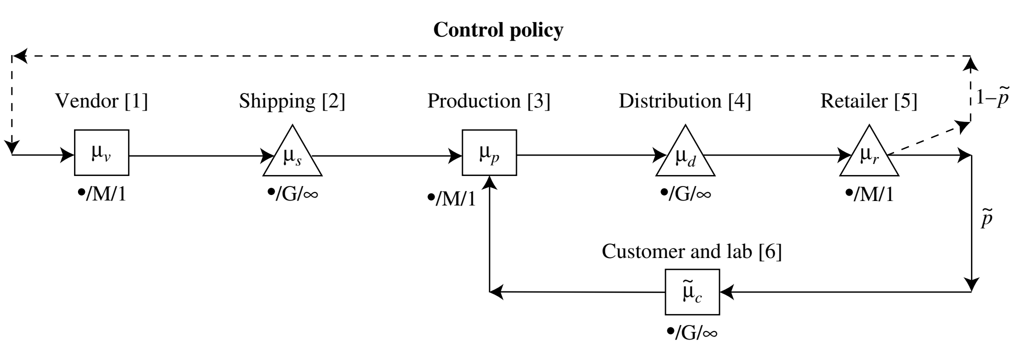
—The Pull strategy outperforms the Push strategy when holding returned products is much cheaper than holding remanufactured products. The Push strategy may dominate when there is little difference in the holding costs.

—Reducing returns uncertainty by keeping track of correlations between sales and returns may yield significant cost savings.

Inventory Management of Remanufacturable Products (Toktay et al. 2000). The next paper in the CLSC IE/OR stream also deals with dual sourcing inventory management using returned products, and was inspired by the example of Kodak's single-use cameras. Manufacturers using returned products face uncertainty from the supply side as well as the demand side. Moreover, the supply of returned products is limited by sales in previous periods (supply constraint). This paper, using a closed queueing network, which takes into account used products with customers, finds an ordering policy that minimizes the total expected costs over time (in Figure 2, note that $\tilde{p}$ denotes the proportion of reusable products returned).

The inventory control policy is basically an ordering rule for new products. There are two major issues that complicate the analysis of the queuing network: what percentage of products sold will be returned, and when. The authors use a distributed lag model with dynamic information updating for estimating return flows. The paper provides a complete solution via a very rigorous analytic treatment, and its strength lies in the analytic part.

Figure 2 Closed Queueing Network (from Toktay et al. 2000)



Source. Reprinted by permission. Copyright 2000 INFORMS. Figure 1 in Toktay, B., L. Wein, S. Zenios. 2000. Inventory management of remanufacturable products. *Management Science* 46(11) 1412–1426, the Institute for Operations Research and the Management Sciences, 7240 Parkway Drive, Suite 300, Hanover, Maryland 21076.

***Critical Assumptions*:**

—Perfect substitution of new and remanufactured products.

—Stationary, Poisson demand.

—Base stock-type policy with lost sales and no fixed costs.

***Insights*:**

—Accurate estimation of return flows results in significant cost savings.

—Estimating return probabilities and the amount of products with the customer; i.e., unobservable inventories have significant impacts.

—Information intensive monitoring of products results in significant cost savings especially for low sales volumes. Under high sales volumes, cost savings from monitoring decrease.

The Impact of Product Recovery on Logistics Network Design (Fleischmann et al. 2001). Our final paper in the CLSC IE/OR stream investigates the reverse logistics network design problem. The key research questions are whether to integrate the reverse logistics network with the forward network, and what parameters drive this decision. The paper extends classic facility location models to include reverse flows in the mixed-integer linear programming formulation. It provides guidelines for recovery network design by incorporating a number of case studies into the analysis.

***Critical Assumptions*:**

—Exogenous and deterministic demand, return and reusability rates.

—Return rates are less than demand rates.

***Insights*:**

—When the production and consumption are in the same geographic region, return flows have little or no impact on the optimal distribution network structure.

—Conversely, when production and consumption patterns are geographically different, the optimal reverse logistics network structure may differ significantly from the optimal forward logistics network structure.

—If return flows are relatively substantial, jointly optimizing forward and reverse networks is recommended.

Comments on CLSC IE/OR Research Stream

Several other papers followed the path opened by these influential papers. Other substantive research work with an CLSC IE/OR perspective includes investigation of shop floor operations for remanufacturing (Ketzenberg et al. 2003), hybrid manufacturing/remanufacturing systems coordination (Aras et al. 2006), value of return information for inventory control (Ketzenberg et al. 2006), optimal ordering quantities between generations (Bhattacharya et al. 2003), lot sizing for remanufacturing (Atasu and Cetinkaya 2006, Tang and Teunter 2006), and inventory control for assembly systems (DeCroix and Zipkin 2005).

Almost all papers in this stream of literature, including our first two, assume perfect substitution between new and remanufactured goods. Although this assumption makes for analytic tractability and perhaps a reasonable first approach, it unfortunately holds true for a small number of industrial cases (e.g., single-use cameras and toner cartridges). Another key issue is the relationship between product sales and returns and the corresponding uncertainties in quantity, quality, and timing of returns. Toktay et al. (2000) cleverly use past sales and returns information to forecast future return rates, whereas both Fleischmann et al. (2001) and van der Laan et al. (1999) are less sophisticated in modeling the return process.

The product life cycle is ignored by the majority of papers in this stream. Obviously, sales, returns rates, and return quality depend on the stage of the product life cycle. In some stages of the product life cycle, return rates may well exceed demand rates. A final characteristic of papers in the CLSC IE/OR stream is their focus on local cost minimization. In some instances, value decay may be more important than cost minimization; i.e., time is money.

CLSC Design Stream Papers

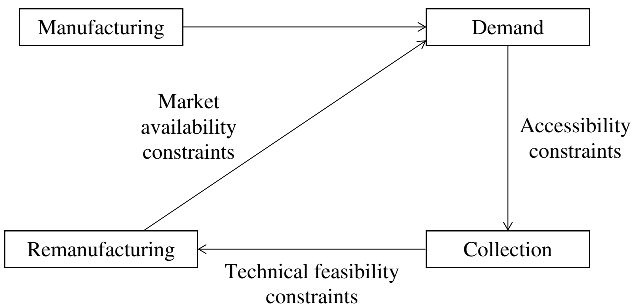
This second stream of research takes a larger scope, business model approach, seeking to uncover the drivers of profitability.

The Impact of Limited Component Durability and Finite Life Cycles on Remanufacturing Profit (Geyer et al. 2007). This paper, inspired by Kodak's single-use camera, models and quantifies the cost-saving potential of production systems that collect, remanufacture, and remarket end-of-use products as perfect substitutes. The results clearly demonstrate the need to carefully coordinate production cost structure, collection rate, product life cycle, and component durability to create and maximize production cost savings from remanufacturing. Figure 3 explains the main idea of the paper. To satisfy demand with remanufactured products, one has to be able to collect used products (accessibility). These products must still be remanufacturable; i.e., the products are durable and remanufacturing is technically feasible. Finally, there must be a demand for remanufactured products (market availability, life cycle).

***Critical Assumptions*:**

—Deterministic setting in which all parameters are assumed to be known, i.e., demand profile over life cycle, collection rate, and the time a product spends with the customer.

Figure 3 Fundamental Constraints on Profitable Remanufacturing (Adapted from Geyer et al. 2007)



Note. Adapted with permission from Geyer, R., L. N. Van Wassenhove, A. Atasu, The economics of remanufacturing under limited component durability and finite product life cycles, *Management Science*, volume 53, number 1, January 2007. Copyright 2007, the Institute for Operations Research and the Management Sciences, 7240 Parkway Drive, Suite 300, Hanover, Maryland 21076.

—Costs and collection rates are stationary.

—Single-product life cycle and perfect substitution.

***Insights*:**

—Demonstrates how to coordinate the basic drivers of CLSC design: production and remanufacturing cost structure, collection rate, product life cycle, and component durability.

—Provides a simple analytic model to evaluate the impact of managerial actions on one of the drivers; e.g., what is the potential economic benefit of encouraging consumers to return products quicker?

Matching Supply and Demand to Maximize Profits from Remanufacturing (Guide et al. 2003). This second paper in the CLSC design stream attempts to match product return acquisition decisions with remanufactured product sales opportunities and is motivated by work with a mobile telephone remanufacturer (see Guide and Van Wassenhove 2001). The authors consider a scenario in which a remanufacturer needs to buy the optimal combination of remanufacturable products with varying quality levels. Less expensive remanufacturable products are of poorer quality and are more costly to remanufacture because all products must be brought to a common standard. Demand for the remanufactured product decreases linearly with selling price. The paper illustrates that effective product recovery management should consider market demand, remanufacturing costs, and product return acquisition simultaneously. The impact of product acquisition decisions on the profitability of CLSCs has hardly been analyzed in previous academic research.

***Critical Assumptions*:**

—There is no uncertainty about the (nominal) quality level of the acquired products, or their supply.

—Acquired products are remanufactured to a single, common quality standard.

—Return rates are independent of sales (single-period model).

***Insights*:**

—Product acquisition management is a significant driver of remanufacturing profitability.

—When supply and demand curves are linear, a simple graphical rule provides the optimal solution.

Closed-Loop Supply Chain Models with Remanufacturing (Savaskan et al. 2004). The third paper in the CLSC design stream explores the problem of who should collect used products. It considers a two-echelon supply chain structure with a manufacturer and a retailer and compares the profitability of different collection modes observed in industry (Figure 4): (1) manufacturer (M), (2) retailer (R), and (3) an independent third-party collector (3P). These decentralized systems are compared with a centralized supply chain (C).

***Critical Assumptions*:**

—Perfect substitution between new and remanufactured products.

—Single period, single manufacturer/remanufacturer—single retailer—single third-party collector monopoly.

—Collection cost structure independent of collecting agent. Collection rate is quadratically increasing in the collection effort. Collection systems already exist.

—Demand decreases linearly with price.

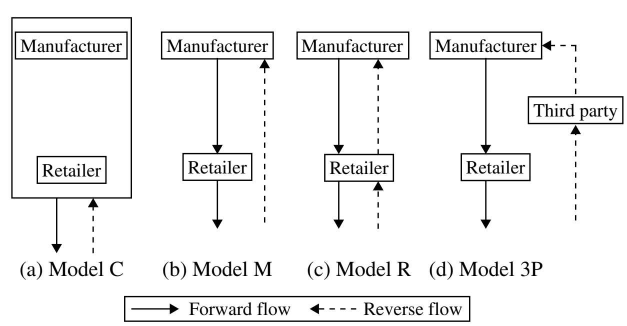
—Manufacturer acts as a Stackelberg leader.

***Insights*:**

—The preferred collecting agent is the retailer (R), followed by the manufacturer (M), and the third-party (3P), respectively.

—In the decentralized supply chains, prices increase with strategies R, M, and 3P, respectively, as one would expect with double marginalization. A similar argument holds for retailer and manufacturer profits, which are declining for R, M, and 3P, respectively.

Figure 4 Four Product Collection Scenarios (from Savaskan et al. 2004)



Source. Reprinted by permission. Copyright 2004. INFORMS. Figure 1 in Savaskan, C., S. Bhattacharya, L. N. Van Wassenhove. 2004. Closed-loop supply chain models with product remanufacturing. *Management Science* 50(2) 239–252, the Institute for Operations Research and the Management Sciences, 7240 Parkway Drive, Suite 300, Hanover, Maryland 21076.

—A two-part tariff coordination mechanism, under the retailer collects strategy, can achieve the centralized supply chain results. The variable part of the two-part tariff control increases with the collection rate.

Time Value of Commercial Product Returns (Guide et al. 2006). The final paper in the CLSC design stream focuses on selecting the best design (i.e., degree of responsiveness) for the reverse supply chain to maximize profits. The authors model the problem as a queueing network. The study is motivated by the commercial returns problem of two firms, one with products with a high marginal value of time (Hewlett-Packard) and the other with low marginal value of time products (Bosch Power Tools). Figure 5 illustrates the main idea. Because the value of returned products decreases over time, a more responsive system may maximize profits. On the other hand, a responsive system may have higher costs. Trading off the increased sales revenues of a more responsive system with the higher operational costs allows the system to be designed for optimal responsiveness (optimal speed).

***Critical Assumptions*:**

—Constant marginal costs of transportation and handling over time. No learning or scale effects.

—Products can be returned only once.

—Remanufacturing-related facilities are modeled by M/M/1 queues.

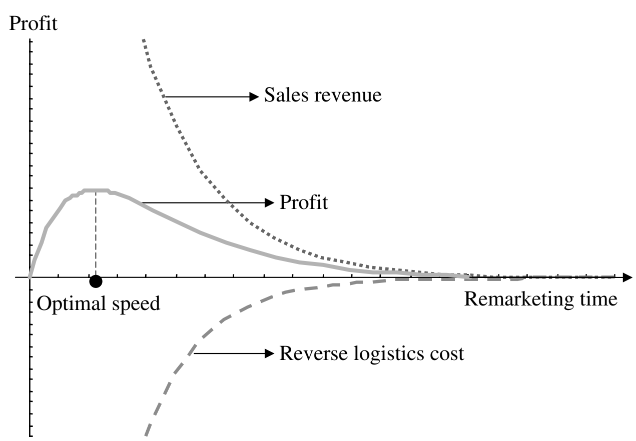
***Insights*:**

—There is an optimal network responsiveness level.

—The drivers for network design are product value, price decay, return rate, and proportion of unused returns. High values favor a more responsive network.

—Product preponement, the early determination of the condition of the returned product, allows for higher levels of value recovery. For example, with preponement, unused products can be returned to the market faster.

Figure 5 Selecting the Optimal Speed in a Reverse Supply Chain (Adapted from Guide et al. 2006)



Note. Adapted with permission from Guide, Jr., V. D. R., G. Souza, L. N. Van Wassenhove, J. D. Blackburn, Time value of commercial product returns, *Management Science*, volume 52, number 8, August, 2006. Copyright 2006, the Institute for Operations Research and the Management Sciences, 7240 Parkway Drive, Suite 300, Hanover, Maryland 21076.

Comments on CLSC Design Research Stream

The papers in this stream take a broader perspective on CLSC design, as suggested by Guide and Van Wassenhove (2001). For instance, Geyer et al. (2007), while still assuming perfect substitution, no longer focus on local cost minimization, as much of the IE/OR stream does. They show it is not sufficient that remanufacturing is cheaper than new product manufacturing for a CLSC to be profitable. The latter requires careful balancing of costs, used-product collection rate, durability, and product life cycle. Similarly, Guide et al. (2003) builds on Guide and Van Wassenhove (2001) by analytically showing the importance of product acquisition management (quality of returns) and of matching acquisition with remarketing in secondary markets.

Savaskan et al. (2004) acknowledge the fact that in practice, reverse supply chains typically do not have centralized control. Consequently, they revisit the problem of reverse logistics network design studied by Fleischmann et al. (2001) in a decentralized context. This allows them to determine which supply chain actor should manage used product collection activities and how best to coordinate the reverse supply chain.

Guide et al. (2006) take the CLSC network design problem studied by Fleishmann et al. (2001) and Savaskan et al. (2004) a step further by moving away from the conventional cost minimization perspective. They maximize the value of recovery over the product life cycle and introduce the notion of time value. Their research shows that current industrial practice, focusing on centralized recovery networks, and exploiting economies of scale, is not necessarily optimal for fast clockspeed products.

Other substantive research that addresses design issues has recently appeared. Savaskan and Van Wassenhove (2006) extend Savaskan et al. (2004) by considering the case of competing retailers. Debo et al. (2006) complement Geyer et al. (2007) by studying the joint life-cycle dynamics of new and remanufactured products, while Georgiadis et al. (2006) study the impact of a product life cycle on capacity planning with remanufacturing. Galbreth and Blackburn (2006) discuss the impact of product sorting and acquisition policies for remanufacturing under random yield, following Guide et al. (2003). Zikopoulos and Tagaras (2008) further explore the potential benefits of product sorting prior to disassembly. Bakal and Akcali

(2006) embed the pricing options when remanufacturing operations face random yield. Finally, Vorasayan and Ryan (2006) extend the queuing models by Toktay et al. (2000) and Guide et al. (2006) to consider pricing decisions.

Although papers in the design stream extend the boundaries of the IE/OR stream by taking a broader business process design perspective, they still ignore the realities of competition.

CLSC Strategy Stream Papers

This third stream introduces strategic competition issues in a CLSC context.

Competition in Remanufacturing (Majumder and Groenevelt 2001a). To the best of our knowledge, this is the first paper to explicitly consider remanufacturing competition. The authors model the case where an OEM, who also remanufactures, competes with a local remanufacturer. The limited number of product returns are split between the OEM and local remanufacturer using a number of exogenous allocation mechanisms. The two firms decide on their product prices given the availability of used products. A two-period model allows the authors to capture the dynamics of the problem (Figure 6). New product sales occur in period one and define the amount of products available for remanufacturing in period two (supply constraint). Competition in period two is between the OEM's new products, the OEM's remanufactured products, and the local remanufacturer.

***Critical Assumptions*:**

—Perfect substitution between the OEM's new and remanufactured products, but customers distinguish between remanufacturer and OEM's products.

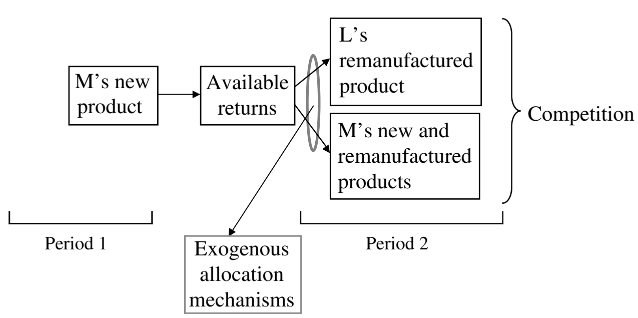
—Given allocation mechanisms for returned products with no collection effort.

—Two-period model, two-player game, single-product type, given Bertrand-type demand curves.

***Insights*:**

—Recognition of the potential strategic role of OEM remanufacturing when faced with a local remanufacturer.

Figure 6 Competition in Remanufacturing (Adapted from Majumder and Groenevelt 2001a)



—The choice of the returned product allocation mechanism does not affect the equilibrium structure.

—Reducing remanufacturing costs for the OEM lowers the average price of their product and benefits the customer. However, higher sales translate to more returns, which benefit the local remanufacturer.

The Effect of Competition on Recovery Strategies (Ferguson and Toktay 2006). This second paper in the CLSC strategy stream builds on Majumder and Groenevelt (2001a) by exploring the strategic role of OEM remanufacturing as an entry deterrent to local remanufacturers (Figure 7). A monopolist may not wish to offer remanufactured products out of the fear that they will cannibalize new product sales. In this case the monopolist has no incentive to collect returns because it is expensive. However, this opens the door for a local remanufacturer to collect used products and introduce a remanufactured version of the monopolist's product. This paper analyzes this strategic problem and derives conditions under which the OEM only manufactures new products, also collects used products, or uses the collected products to offer a remanufactured version.

***Critical Assumptions*:**

—Similar to Majumder and Groenevelt (2001a), but with a more general cost structure and endogenous returned product allocation mechanisms.

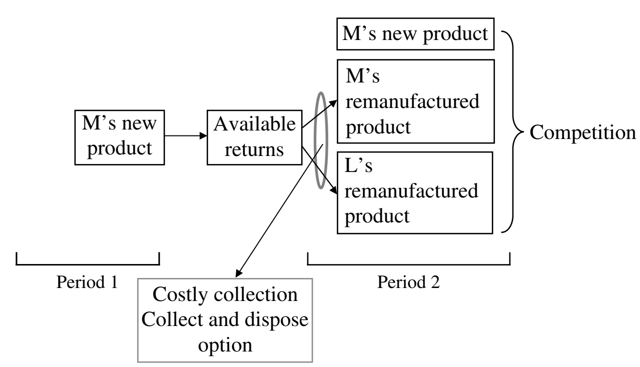
—Differentiable new and remanufactured products. There is competition between the new and remanufactured products where the consumer WTP for a remanufactured product is lower.

***Insights*:**

—OEM remanufacturing may be a viable strategic option to deter the entry of local remanufacturers into the market, even if remanufacturing in itself is not attractive to a monopolist OEM.

—Remanufacturing is not the only strategy to deter competitor entry. Collection without remanufacturing can be attractive when the cost to collect is relatively small compared with remanufacture.

Figure 7 The Effect of Competition on Recovery Strategies (Adapted from Ferguson and Toktay 2006)



Market Segmentation and Production Technology Selection for Remanufacturable Products (Debo et al. 2005). This third paper in the CLSC strategy stream adds the element of investing in reusability to increase the likelihood that a product return is remanufacturable. This paper deals with simultaneous pricing of new and remanufactured products, together with the selection of the appropriate investment in reusability. It explicitly considers the dependence between new and remanufactured products because the supply of remanufacturable product returns depends both on past sales of new products and investment in product durability. Using an infinite period dynamic programming model, the paper investigates the impact of cost parameters, consumer profiles, technology choice, and industry structure on the profitability of remanufacturing.

***Critical Assumptions*:**

—Infinite-horizon model with identical periods.

—Monopoly in the new product market.

—Products can be remanufactured only once.

—There is competition between the new and remanufactured products where the consumer WTP for a remanufactured product is lower.

***Insights*:**

—The dual impact of new product on remanufacturing profit. New and remanufactured products are substitutes but also complements, as one needs a used product to be able to sell a remanufactured one. When the new product price increases, the profit potential from remanufacturing increases. However, with higher prices, new product sales may decrease, which in turn reduces the number of products available for return, resulting in lower profit potential from remanufacturing.

—The impact of consumer profile on profitability. Because remanufactured products are targeted at lower valuation consumers, one would expect to have higher remanufacturing profit under a high concentration of lower valuation consumers. However, this reduces new product sales and hence limits the supply of remanufacturable products. Thus, remanufacturing is more profitable when consumers are more concentrated on the high valuation end. This decreases the risk of cannibalization while also increasing the supply of remanufacturable products.

—The impact of consumer profile on technology choice. Investing in durability makes sense when there are more low valuation customers, especially if the cost of increasing remanufacturability is relatively low.

Life-Cycle Dynamics for Portfolios with Remanufactured Products (Debo et al. 2006). The fourth paper in the CLSC strategy stream extends the ideas in Geyer et al. (2007) and Debo et al. (2005) using a multiperiod model with product differentiation, explicit consideration of the product life cycle, and capacity management issues. It also investigates the market penetration of competing new and remanufactured products. This paper is the first to consider the joint life-cycle dynamics of new and remanufactured products. Explicit consideration of diffusion allows the authors to understand (1) how diffusion affects the profitability of remanufacturing, (2) how the capacity requirements for new production and remanufacturing evolve over the product life cycle, and (3) the value of flexible capacity and reverse channel responsiveness.

***Critical Assumptions*:**

—Similar to Debo et al. (2005).

—A Bass-like diffusion model with repeat purchases adapted to a remanufacturing context.

—Diffusion is propagated by new products only because remanufactured products do not create a word-of-mouth effect.

—Probabilistic product residence time with the customer.

—Explicit consideration of capacity extension costs.

***Insights*:**

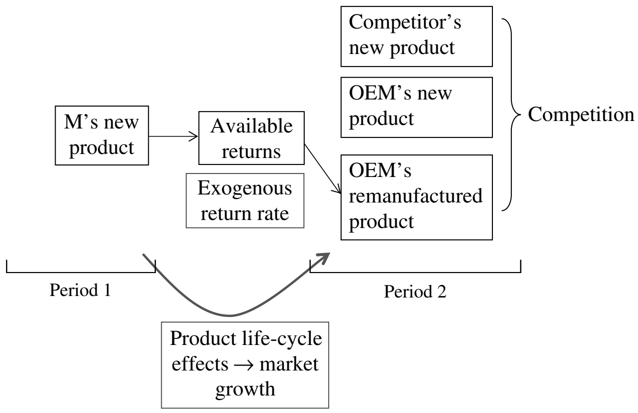
—Remanufacturing is more attractive for slowly diffusing products.

—Repeat purchases increase the profitability of remanufacturing.

—High sales of new products may lead to high sales of the remanufactured product in a subsequent period, causing oscillating sales patterns between the two. This makes flexible capacity more valuable, especially with fast diffusion and repeat sales.

Remanufacturing as a Marketing Strategy (Atasu et al. 2008). The final paper in the CLSC strategy stream is the first to simultaneously look at cannibalization, OEM competition, and product life-cycle interaction in a remanufacturing context. It acknowledges the existence of different consumer segments with diverse remanufactured product valuations. The paper studies the effect of the timing of the remanufactured product introduction and the use of remanufacturing to compete against low-cost OEM competitors. That is, it considers the use of remanufacturing as a marketing strategy. As such, it differs from other papers in this stream that solely address competition between an OEM and a remanufacturer. The analysis uses a two-period model, where in the first period the OEM sells new products only. In the second period, the OEM has the option to sell remanufactured products, and a low-cost manufacturer enters the market (Figure 8). The paper shows that the viability of remanufacturing depends on the market growth, or decline, rate from period one to period two. Even if the remanufacturing option is not profitable in a monopoly situation, depending on the timing in the product life cycle, it may be an effective

Figure 8 Remanufacturing as a Marketing Strategy (Adapted from Atasu et al. 2008)



Note. Adapted with permission from Atasu, A., M. Sarvary, L. N. Van Wassenhove, Remanufacturing as a marketing strategy, *Management Science*, forthcoming. Copyright 2008, the Institute for Operations Research and the Management Sciences, 7240 Parkway Drive, Suite 300, Hanover, Maryland 21076.

marketing strategy against a low-cost OEM competitor entering the market.

***Critical Assumptions*:**

—Two-period model, where the second-period models the entry of a low-quality product OEM and the opportunity for the high-quality product OEM to introduce a remanufactured version.

—Deterministic and known parameters. Exogenous market growth.

—Remanufacturability rate is constant over the product life cycle.

—Unit remanufacturing cost is given, independent of product life cycle and product quantity.

***Insights*:**

—Illustrates the interaction between competition, product life cycle, and cannibalization in determining the profitability of remanufacturing.

—Increased understanding of how cannibalization works between a high quality new product, a remanufactured product, and a low-cost competitor product.

—Shows how the remanufacturing option can also be used as a marketing strategy against potential low-cost copycats, depending on when the latter enter the market during the product life cycle.

Comments on CLSC Strategy Research Stream

Majumder and Groenevelt (2001a) are the first to consider competition in a simplified context. In their two-period model, a manufacturer sells new products in period one and a mixture of perfectly substitutable new and remanufactured products in period two. In period two the manufacturer faces competition from a local remanufacturer. Ferguson and Toktay (2006) build on this model, relaxing the assumption of perfect substitution and exogenous product return allocation. They show that even if the manufacturer has no interest in offering remanufactured products, it may be wise to collect used products to prevent them from being remanufactured by a third party. Debo et al. (2005) offer further extensions to the previous papers by integrating the pricing of new and remanufactured products with the required investment in reusability. Indeed, remanufactured product supply depends on durability, and pricing subsequently determines the potential for cannibalization of new product sales. The paper also relaxes the two-period model restriction by considering an infinite horizon. Debo et al. (2006) continue to refine the complex interactions between new and remanufactured products by using a multiperiod diffusion model to explore joint life cycle dynamics. Finally, Atasu et al. (2008) look at cannibalization, OEM competition, and product life-cycle interaction in a remanufacturing context. They extend the previous competition models by introducing a low-cost competitor and a more generic market structure. They show that depending on the timing of entry, a remanufactured product may be an effective way to cannibalize the low-cost competitor's sales.

Several other recently published papers and working papers contribute to the emerging stream of CLSC strategy research. Majumder and Groenevelt (2001b) extend Majumder and Groenevelt (2001a) by allowing for competition in the acquisition of product returns between a manufacturer and a remanufacturer. Ferrer and Swaminathan (2006, 2007) extend the work by Majumder and Groenevelt (2001a) by considering finite, multiple-horizon models with, and without, product differentiation and identifying the impact of remanufacturer competition. Ray et al. (2005) discuss the revenue generation potential of trade-in rebates through remanufactured products.

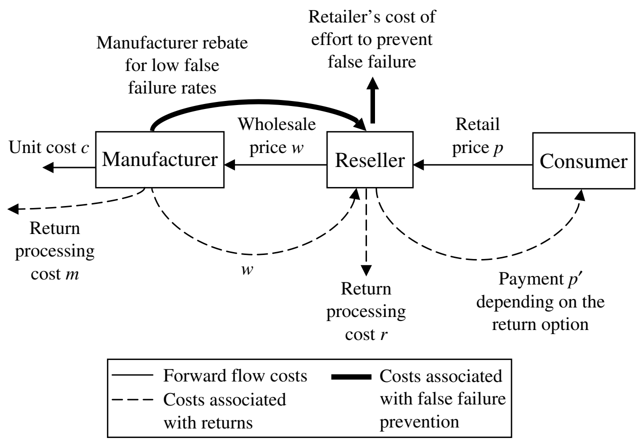
The strategy CLSC research stream, while introducing competition, diffusion, and durability issues, makes simple and yet untested assumptions about consumer perceptions of remanufactured products.

CLSC Behavioral Stream Papers

This last research stream deals with behavioral issues related to the return quantities and consumer perceptions of remanufactured products.

Supply Chain Coordination for False Failure Returns (Ferguson et al. 2006). The first paper in this stream is not behavioral research per se but applies contracting to influence behaviors of actors in a CLSC. The problem is motivated by a manufacturer wanting to reduce false failure product returns (i.e., a returned product with no physical defect). However, a reseller does not have an incentive to spend more time with customers to ensure the best product is selected to match their needs. Additionally, the reseller's efforts cannot be directly observed. The

Figure 9 Target Rebates for False Failure Returns (Adapted from Ferguson et al. 2006)



paper proposes a return target rebate contract to coordinate the reverse supply chain, using a simple stylized model (Figure 9). However, target rebates do not necessarily coordinate both the forward and reverse supply chains.

***Critical Assumptions*:**

—The cost of the reseller's effort is convex and known, and can be captured by a single variable.

—Single-period model.

—False failures are included in the reseller's sales personnel evaluation system.

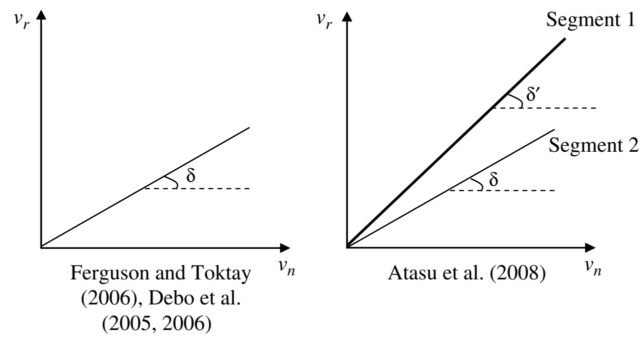
***Insights*:**

—Target rebate contracts are Pareto-improving for the majority of cases tested.

—Target rebate contacts combined with other sales contracts help reduce gaming (sending back unsold units as consumer returns) by the reseller.

The Potential for Cannibalization of New Product Sales by Remanufactured Products (Guide and Li 2007). The second paper in the behavioral CLSC stream is, to the best of our knowledge, the first attempt to empirically examine cannibalization between new and remanufactured products. The fear of cannibalization prevents many OEMs from introducing remanufactured products. As a result the OEMs may forgo increased market share and profits. Most academic research ignores cannibalization by assuming perfect substitution, or secondary markets, for remanufactured products. Analytic papers modeling competition between new and remanufactured products use stylized models with assumptions that have not been empirically tested. They typically assume consumer valuations for the new product to have a specific distribution and valuations for the remanufactured products to be a fraction of that. The left hand part of Figure 10 shows this common assumption in the case where consumer valuations for the new product, V_n are uniformly distributed, as

Figure 10 Market Segmentation and Customer Valuation



are the valuations for the remanufactured products, V_r. The right hand graph illustrates the market structure used by Atasu et al. (2008) where consumers are segmented in terms of their valuations for the remanufactured products. They show that this kind of segmentation can have a significant impact on pricing decisions and the attractiveness of the remanufacturing option.

Guide and Li (2007) use Internet auctions to empirically investigate consumer valuation differences for new and remanufactured products. Two products were auctioned, a consumer good (a power hand tool) and a B2B (business-to-business) product (an Internet security appliance). The authors identify the price points and bidding behavior for new and remanufactured products to help determine the extent, if any, of cannibalization. In a sense, Atasu et al. (2008) and Guide and Li (2007) complement each other, the first paper modeling the cannibalization-segmentation interaction and the second empirically testing it.

The experiments support the proportional WTP assumption used in the CLSC literature. They also show a segmentation pattern in consumer WTP for the remanufactured product.

***Critical Assumptions*:**

—Bidding behavior in a winner-takes-all (eBay.com) auction setting.

—The use of average winning bids allows an accurate estimation of consumer WTP.

—The auctions for new and remanufactured products are symmetric.

***Insights*:**

—Remanufactured product market segmentation patterns differ by product category.

—Cannibalization may hurt in the case of B2B products while it appears far less harmful for B2C (business-to-consumer) products.

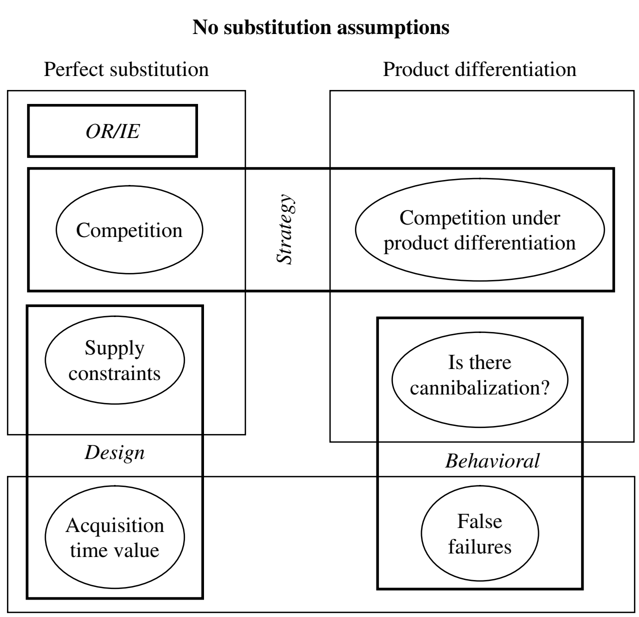
—Consumers value new products higher than their remanufactured counterparts. This is true despite the fact that remanufactured goods are often more reliable, especially for electronic products.

Comments on CLSC Behavioral Research Stream
The fact is that research in CLSC behavioral issues is barely in its infancy, as evidenced by the dearth of research in this area. Unfortunately, industry has long operated under "common wisdom" rather than careful consumer behavior studies. Therefore, researchers cannot simply base their modeling assumptions on industry observation. There is a strong need for empirical work in cooperation with industry to enable the development of more sophisticated and relevant models that incorporate consumer behavior. This is why we decided to identify behavioral research as a stream of its own.

Discussion

Figure 11 superimposes some basic assumptions used in product reuse economics research onto our four CLSC research streams, i.e., IE/OR, design, strategy, and behavioral. It shows that CLSC research can also be segmented into different streams with respect to product differentiation assumptions. According to Figure 11, a dominating assumption in part of CLSC research has been the requirement of *perfect substitution* between new and remanufactured products, while other researchers considered situations in which new and remanufactured *products can be differentiated*. Perfect substitutes are typically container products; the customer is more interested in the content/service than the container. For example, the buyer of a single-use camera wants to take pictures. There is a sustainable development argument to be made for industry to move to *servicizing*, where customers buy the service provided by the product instead of the product itself (see Yadav et al. 2003 for a discussion of trucking fleet tires). However, we are a long way from this becoming common practice. In reality, today there are relatively few products where the assumption of perfect substitution can be justified. Nonetheless, as can been seen in Figure 11, perfect substitution has been a critical assumption in the IE/OR, design, and, to a lesser extent, strategy research streams. Although perfect substitution is an obvious first-cut modeling assumption, product differentiation must be acknowledged in future research to maintain industrial relevance.

Figure 11 A Framework for CLSC Research



The challenge with introducing product differentiation concepts in our models is that little is known about consumer perceptions of remanufactured products, or how those products are valued when compared with new versions of the product. Marketing has not studied this issue specifically and most operations management researchers have scant training in this area. Consequently, analytic CSLC research has used simple assumptions about consumer preferences, such as (1) consumer valuations for remanufactured products would be a fraction of their valuations for new products, and (2) consumer valuations are heterogeneous and distributed uniformly on a given scale. Although such assumptions are useful in creating first-order managerial insights and modeling important trade-offs, these assumptions need to be tested empirically. Our experiences with companies suggest that industry itself knows surprisingly little about how consumers value remanufactured goods. Frequently, marketing and sales groups hold very emotional views that remanufactured products will heavily *cannibalize* new product sales. These views are often instilled by misaligned sales incentives, rather than by market research. Companies lack data to objectively assess remanufacturing profitability as well as the expertise necessary for consumer behavior research in this area. There is a similar lack of understanding related to reseller returns and consumer returns.

In the end, major problems seem to stem from a lack of knowledge about valuing product returns and the misaligned incentives that prevent companies from researching these issues. We need to go into the field to better understand consumer behavior toward remanufactured products. Improving our understanding of behavioral issues seems to be the most important future development of research in terms of its industrial relevance. Untested assumptions about remanufactured product valuation hold the risk of reducing the potential industrial impact of research.

Another important industrial reality that has been largely ignored in academic research is that products have life cycles. The new product *diffusion* process influences the used product returns process. In addition, the remarketing process may influence the new product diffusion process. The two processes could be interrelated and form a dynamic version of the supply constraint discussed earlier. This new dynamic supply constraint considers product life-cycle effects.

Introducing diffusion elements into models is an enormous mathematical challenge, just as studying cannibalization introduces the sizeable challenge of establishing empirical research in this area. Classical OR/IE approaches to CLSC may not be the best tools to resolve this. There is a need to introduce techniques that are much more widespread in fields such as marketing (empirical methods) or physical sciences (diffusion). On a related subject, our experiences with industry show that companies use widely varying methods to *value returned products*. Clearly, this has a significant impact on their perception of remanufacturing profitability, as well as the results of modeling efforts. This indicates there is a need to include management accounting in CLSC research.

The above comments have one thing in common. This discipline started with a solid anchor in industrial reality, as the three thought-piece papers discussed in the second section illustrate. Researchers subsequently used these descriptions of industrial practice to motivate their modeling assumptions, at least in the beginning. These early papers often used simplifying assumptions as a first approximation to obtain first-order managerial insights. Not unexpectedly, academic researchers then continued to build on these early papers, thereby institutionalizing some assumptions, e.g., perfect substitutability. We would like to warn that there are limits to this behavior. It can, in the extreme, lose all connection with industrial reality. While we appreciate the beauty of elegant mathematical models and the need for simplicity, it would be lamentable if a field that was, at one point, ahead of industrial practice in terms of insights became irrelevant. We acknowledge that this concern is not unique to CLSC research, but we strongly believe that much of the research we discuss here is far ahead of industrial practice. In our experience, this puts us (i.e., CSLC researchers) in the unique position of being able to do more than offer benchmarking studies of current practice, or solutions to problems that do not exist in practice. This concern is justified based on the fact that this exact pathway is being taken in other fields. For instance, a huge body of flexible manufacturing systems (FMS) research continued to use assumptions drawn from early empirical descriptions of a few industrial FMS examples, instead of reflecting the subsequent rapid technological and industrial evolution of such systems.

This paper offers interested researchers a roadmap to understanding analytic CLSC literature with a business economics focus but also signals that this may be the right time to return to the field's roots, i.e., to explore how industry is evolving and what its pressing problems are. Prominent among those problems are certainly the issues of cannibalization, diffusion, and valuation.

The future may accelerate new issues that, although noticeable today, have not received much attention from industry or research. For instance, extended producer responsibility legislation, such as the European Union Directive on Waste Electrical and Electronic Equipment (WEEE), may introduce conflict between material recycling and product reuse. It may also lead to competition for product returns to comply with mandated recycling targets. Finally, while technological advances favor short life cycles, limiting reuse, legislation may push exploration of reuse opportunities across product life cycles. In short, there is a trend toward a more integrated view of sustainability, combining profit with people and planet (Kleindorfer et al. 2005).

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References

Aras, N., V. Verter, T. Boyaci. 2006. Coordination and priority decisions in hybrid manufacturing/remanufacturing systems. *Production Oper. Management* **15**(4) 528–543.

Atasu, A., S. Cetinkaya. 2006. Lot sizing for optimal collection and use of remanufacturable returns over a finite life cycle. *Production Oper. Management* **15**(4) 473–487.

Atasu, A., M. Sarvary, L. N. Van Wassenhove. 2008. Remanufacturing as a marketing strategy. *Management Sci.* Forthcoming.

Bakal, I. S., E. Akcali. 2006. Effects of random yield in remanufacturing with price-sensitive supply and demand. *Production Oper. Management* **15**(3) 407–420.

Bhattacharya, S., V. D. R. Guide, Jr., L. N. Van Wassenhove. 2003. Optimal order quantities with remanufacturing across new product generations. *Production Oper. Management* **15**(3) 421–431.

Corbett, C., P. Kleindorfer, eds. 2001. Environmental management and operations. Special issue. *Production Oper. Management* **10**(2&3).

Corbett, C., P. Kleindorfer, eds. 2003. Environmental management and operations management. Special issue. *Production Oper. Management* **12**(3).

Debo, L., B. Toktay, L. N. Van Wassenhove. 2005. Market segmentation and production technology selection for remanufacturable products. *Management Sci.* **51**(8) 1193–1205.

Debo, L., B. Toktay, L. N. Van Wassenhove. 2006. Life-cycle dynamics for portfolios with remanufactured products. *Production Oper. Management* **15**(4) 498–513.

DeCroix, G., P. Zipkin. 2006. Inventory management for an assembly system with product or component returns. *Management Sci.* **51**(8) 1250–1265.

Dekker, R., M. Fleischmann, K. Inderfurth, L. N. Van Wassenhove, eds. 2004. *Reverse Logistics*: *Quantitative Models for Closed-Loop Supply Chains*. Springer-Verlag, Berlin.

Ferguson, M., B. Toktay. 2006. The effect of competition on recovery strategies. *Production Oper. Management* **15**(3) 351–368.

Ferguson, M., V. D. R. Guide, Jr., G. Souza. 2006. Supply chain coordination for false failure returns. *Manufacturing Service Oper. Management* **8**(4) 376–393.

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

Ferrer, G., J. Swaminathan. 2007. Managing new and differentiable remanufactured products. Working paper, Kenan-Flagler School of Business, University of North Carolina, Chapel Hill.

Flapper, S. D. P., J. van Nunen, L. N. Van Wassenhove, eds. 2005. *Managing Closed-Loop Supply Chains*. Springer-Verlag, Berlin.

Fleischmann, M., P. Beullens, J. Bloemhof-Ruwaard, L. N. Van Wassenhove. 2001. The impact of product recovery on logistics network design. *Production Oper. Management* **10**(2) 156–173.

Galbreth, M., J. D. Blackburn. 2006. Optimal acquisition and sorting policies for remanufacturing. *Production Oper. Management* **15**(3) 385–392.

Georgiadis, P., D. Vlachos, G. Tagaras. 2006. The impact of product lifecycle on capacity planning of closed-loop supply chains with remanufacturing. *Production Oper. Management* **15**(4) 514–527.

Geyer, R., L. N. Van Wassenhove, A. Atasu. 2007. The economics of remanufacturing under limited component durability and finite product life cycles. *Management Sci.* **53**(1) 88–100.

Guide, Jr., V. D. R. 2000. Production planning and control for remanufacturing: Industry practice and research needs. *J. Oper. Management* **18**(4) 467–483.

Guide, Jr., V. D. R., K. Li. 2007. The potential for cannibalization of new product sales by remanufactured products. Working paper, Smeal College of Business, The Pennsylvania State University, University Park.

Guide, Jr., V. D. R., L. N. Van Wassenhove. 2001. Managing product returns for remanufacturing. *Production Oper. Management* **10**(2) 142–155.

Guide, Jr., V. D. R., L. N. Van Wassenhove, eds. 2003. Closed-loop supply chains. Special issue. *Interfaces* **33**(6).

Guide, Jr., V. D. R., L. N. Van Wassenhove, eds. 2003. *Business Aspects of Closed-Loop Supply Chains*. Carnegie Mellon University Press, Pittsburgh.

Guide, Jr., V. D. R., L. N. Van Wassenhove, eds. 2004. Closed-loop supply chains. Special issue. *California Management Rev.* **46**(2).

Guide, Jr., V. D. R., L. N. Van Wassenhove, eds. 2006. Closed-loop supply chains. Special issue. *Production Oper. Management* **15**(3&4).

Guide, Jr., V. D. R., L. N. Van Wassenhove. 2007. The evolution of closed-loop supply chains. *Oper. Res.* Forthcoming.

Guide, Jr., V. D. R., R. Teunter, L. N. Van Wassenhove. 2003. Matching supply and demand to maximize profits from remanufacturing. *Manufacturing Service Oper. Management* **5**(4) 303–316.

Guide, Jr., V. D. R., G. Souza, L. N. Van Wassenhove, J. D. Blackburn. 2006. Time value of commercial product returns. *Management Sci.* **52**(8) 1200–1214.

Ketzenberg, M., G. C. Souza, V. D. R. Guide, Jr. 2003. Mixed assembly and disassembly operations for remanufacturing. *Production Oper. Management* **12**(3) 320–335.

Ketzenberg, M., E. van der Laan, R. H. Teunter. 2006. Value of information in closed loop supply chains. *Production Oper. Management* **15**(3) 393–406.

Kleindorfer, P., K. Singhal, L. N. Van Wassenhove. 2005. Sustainable operations. *Production Oper. Management* **14**(4) 482–492.

Lund, R. T. 1984. *Remanufacturing*: *The Experience of the United States and Implications for Developing Countries*. World Bank, Washington, D.C.

Majumder, P., H. Groenevelt. 2001a. Competition in remanufacturing. *Production Oper. Management* **10**(2) 125–141.

Majumder, P., H. Groenevelt. 2001b. Procurement competition in remanufacturing. Working paper, Duke University School of Business, Durham, NC.

Ray, S., T. Boyaci, N. Aras. 2005. Optimal prices and trade-in rebates for durable, remanufacturable products. *Manufacturing Service Oper. Management* **7**(3) 208–228.

Savaskan, C., L. N. Van Wassenhove. 2004. Reverse channel design: The case of competing retailers. *Management Sci.* **52**(1) 1–14.

Savaskan, C., S. Bhattacharya, L. N. Van Wassenhove. 2004. Closed-loop supply chain models with product remanufacturing. *Management Sci.* **50**(2) 239–252.

Tang, O., R. H. Teunter. 2006. Economic lot scheduling problem with returns. *Production Oper. Management* **15**(4) 488–497.

Thierry, M., M. Salomon, J. A. E. E. van Nunen, L. N. Van Wassenhove. 1995. Strategic issues in product recovery management. *California Management Rev.* **37**(2) 114–135.

Toktay, B., L. Wein, S. Zenios. 2000. Inventory management of remanufacturable products. *Management Sci.* **46**(11) 1412–1426.

van der Laan, E., M. Salomon, R. Dekker, L. N. Van Wassenhove. 1999. Inventory control in hybrid systems with remanufacturing. *Management Sci.* **45**(5) 733–747.

Vorasayan, J., S. M. Ryan. 2006. Optimal price and quantity of refurbished products. *Production Oper. Management* **15**(3) 369–384.

Yadav, P., D. Miller, C. Schmidt, R. Drake. 2003. McGriff treading company implements service contracts under shared savings. *Interfaces* **33**(6) 18–29.

Zikopoulos, C., G. Tagaras. 2008. On the attractiveness of sorting before disassembly in a remanufacturing facility. *IIE Trans.* **40**(3) 313–323.