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Closed-Loop Supply Chains with Remanufacturing

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Abstract In this tutorial I present an overview of closed-loop supply chains, which are supply chains where there are flows of products (postpurchase) back to manufacturers. Examples include supply chains with consumer returns and leasing options. I start by defining basic terms: differences with respect to forward chains, sources of product returns, disposition options for product returns (scrap, recycling, reuse, cannibalization for spare parts, and remanufacturing), strategic, tactical, and operational issues, along with regulatory and legislative issues. I then provide a brief overview of current practices, particularly regarding the state of remanufacturing in select industries: personal computers and peripherals, B2B information technology equipment, tires, and construction equipment (Caterpillar). I review the extant academic literature on closed-loop supply chains, particularly as it regards to business and management aspects, with less of a focus on environmental practices. Finally, I conclude with some directions for future research.

Keywords closed-loop supply chains; remanufacturing; reverse logistics; sustainable operations

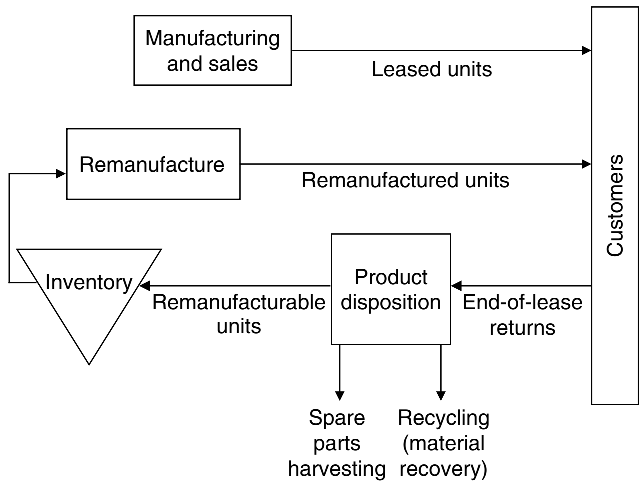
1. Introduction

In forward supply chains the flow of material is unidirectional, from raw material suppliers to manufacturers to distributors to retailers, and to consumers. In closed-loop supply chains there are (reverse) flows of used products (postconsumer) back to manufacturers. An example of a closed-loop supply chain, taken from Ferguson et al. [23], is given in Figure 1. Pitney Bowes is an original equipment manufacturer (OEM) based in Stamford, Connecticut, producing large-scale mailing equipment that matches customized documents to envelopes, weighs the parcel, prints the postage, and sorts mail by zip code. Pitney Bowes derives about 90% of its revenues from leasing its new products, with the remaining 10% from sales. The length of a typical leasing contract is four years. At the end of the lease, if the customer upgrades to a newer technology equipment (when available), end-of-lease products are returned from customers to a central facility where they are tested and sorted, and a final disposition is made: recycling (for raw material recovery), spare parts harvesting (to recover parts for use in service), or remanufacturing, which restores the used product to a common aesthetic and operating standard. Remanufactured products are then sold to customers at a discount compared to the price of purchasing a new unit of the same model.

There are essentially three types of returns in closed-loop supply chains:

• *Consumer returns*: These returns are primarily a consequence of liberal return policies by powerful retailers, and they are more prevalent in North America. Consumer returns are typically current, from a technology perspective, and have only been lightly used by the customer, if they have been used at all. In many cases, they are not defective; for example, 80% of returned printers at Hewlett-Packard (HP) are not defective upon arrival (Ferguson et al. [22]). Consumer returns represent 5%–6% of sales for printers, 2%–3% for power tools, and up to 35% for fashion products (Ferguson et al. [22]).

FIGURE 1. Closed-loop supply chain for Pitney Bowes (Ferguson et al. [23]).



• *End-of-use returns*: These products have been fully used by the customer, and as a result, they are typically one technological generation or more behind current new products; however, they still may be fully functional. Examples include cell phones (many users upgrade to new phones every 1–2 years), end-of-lease equipment such as Pitney Bowes, and product trade-ins.

• *End-of-life returns*: These returns have reached the end of their useful life, and, for the most part, their appropriate disposition decisions are landfilling, incineration, or recycling (see below). An exception is a worn-out tire, which is no longer functional but can be remanufactured (retreaded).

In some industries, returns are referred to as *cores*. In general, disposition decisions for product returns include:

• *Landfilling*: This option is illegal for some products in some countries/states.
• *Incineration*: This option implies energy recovery.
• *Recycling*: This option implies materials recovery.
• *Parts harvesting*: This option implies recovering selected parts from returns for use in service (spare parts).
• *Resale* (*as-is*): An example of this option is IBM, who sells some of their used information technology (IT) equipment recovered from end-of-lease to certified brokers.
• *Internal reuse*: This option implies light or no refurbishing: containers are an example.
• *Remanufacturing/refurbishing*: This is the most comprehensive and value-added disposal option.

Scraping or recycling typically occurs for products with limited or no value remaining, so mostly for end-of-life and in some cases end-of-use returns. For end-of-life returns, an example where recycling occurs is for a product with no value remaining due to technological obsolescence such as very old personal computers (PCs); these products are shredded and materials (plastics, precious metals, steel) are separated and then recovered. For end-of-use returns, an example of recycling at Pitney Bowes is a product that has been heavily used by the customer (with many worn out components, implying expensive remanufacturing), or a product severely damaged during use or transportation. Even consumer returns may face recycling, due to a limited profit margin for resale coupled with high reverse logistics costs; an example is low-end printers at Hewlett-Packard (Guide et al. [39]). Recycling can also be mandated by legislation; an example is the European directive on Waste of Electrical and Electronic Equipment (WEEE), which mandates 65% recycling of collected electrical and electronic used products (by weight). This percentage is scheduled to increase over time.

Some authors distinguish remanufacturing from refurbishing. For example, Hauser and Lund [44] define remanufacturing as an extensive process of restoring used products to "like-new" condition, which includes disassembly, cleaning, replacing worn-out parts with new ones, reworking some parts, and reassembly. Refurbishing would then be classified as "light" remanufacturing. I do not make this distinction in this tutorial (it becomes more difficult in industries such as electronics), and I use the terms remanufacturing and refurbishing interchangeably. According to Hauser and Lund [44], the size of the remanufacturing sector in the United States is $53 billion, with over 70,000 firms and 480,000 employees; if refurbishing is also included as being remanufacturing, these numbers will be larger.

In this tutorial, I focus on closed-loop supply chains that include some level of remanufacturing, as remanufacturing is a value-added operation that provides, in addition to economic benefits, environmental benefits due to extension of the product useful life, and reduced energy and material consumption (Hauser and Lund [44]). Most components and/or products, however, can only be remanufactured a finite number of times (this is a technical constraint) even if there is no technological obsolescence; this is addressed by Geyer et al. [32]. The focus of this tutorial is thus on the *management of remanufacturing operations*; I do not focus on other environmental management practices (e.g., pollution prevention, reduction of energy consumption, and other sustainability practices); for a discussion of these other practices, please see Corbett and Klassen [12], Sroufe [69], and Rajaram and Corbett [61] for an overview.

Closed-loop supply chains with remanufacturing present the following complicating characteristics, with respect to forward chains:

1. The input to the remanufacturing process—product returns—is uncertain in quality, quantity, and the timing of arrival. The network for collecting returns may be different than the forward distribution network.
2. Returns with different quality grades have different remanufacturing processing times, costs, and capacity usage. Some returns are found to be unfit for remanufacturing, and they must be scrapped or recycled. Alternatively, the firm can also salvage returns for spare parts.
3. Consumers generally view remanufactured products as imperfect substitutes for new products, so they need to be priced accordingly.

Those characteristics have many implications for supply chain management. I divide the discussion in terms of strategic, tactical, and operational decisions. Strategic decisions (such as plant location) impact the firm's operations for many years. Tactical decisions (such as production planning) impact the firm's operations for weeks or months. Finally, operational decisions (such as scheduling) are made on a day-to-day basis and do not impact the firm's operations in the future. Table 1 provides an overview of decisions in closed-loop supply chains; I comment on the research, and particularly on the structure of some of the basic models, in §3. Although I comment briefly on operational issues, such as disassembly, scheduling, and dispatching, I focus the tutorial on strategic and tactical decisions, because these seem to be the target of most of the recent research in the area. Strategic decisions, such as remanufacturing strategy (should the OEM remanufacture?), pricing, network design, collection strategy, and so forth, also drive most of the profits and environmental impacts and are therefore where most improvements and influence in practice can be made.

2. Industry Practice

Remanufacturing practice, both in terms of strategic and tactical issues, varies considerably across industries. This is illustrated in the comprehensive survey by Hauser and Lund [44], who poll 274 remanufacturing firms in the United States in six different industries: automotive, electrical equipment, furniture, machinery, tires, and toner cartridges. The competitive environment, relationship with OEMs, remanufacturing cost drivers, pricing, source of returns, and so forth, can differ significantly across different industries. For example,

TABLE 1. Strategic, tactical, and operational issues in closed-loop supply chains.

Level	Decisions and issues
Strategic	• Network design: location and size of collection centers, aggregation centers, recycling centers, remanufacturing facilities, etc. • Network design: Should the firm combine reverse and forward flows to decrease handling and transportation costs? • Collection strategy: should customers return products to retailers or directly to OEMs? • Should the OEM remanufacture? • Pricing of remanufactured products (versus new) • Leasing or selling? • Use of trade-in and buy-back programs to guarantee steady supply of cores or to diminish secondary market (by OEM) • Supply chain coordination: contracts and incentives
Tactical	• Acquisition of product returns (cores): how many, when, and of which quality? • Production planning for remanufacturing, considering uncertain return stream, and different quality grades (implying different capacity usage) for returns • Use/modifications of material requirement planning (MRP) for remanufacturing • Inventory management with product returns
Operational	• Disassembly planning: sequence and level of disassembly (depth) • Dispatching rules (release mechanisms) to the floor after disassembly • Routing of products in the shop floor • Priority rules in the shop floor when remanufacturing products whose serial number parts should match (e.g., turbines) • Lot sizing

remanufactured toner cartridges are virtually undistinguished from new ones. Some OEMs (such as Lexmark and HP) derive a significant profit from the sale of new cartridges, so they engage in practices to prevent third parties from remanufacturing used cartridges: collecting empty cartridges and scrapping them, using electronic chips that prevent refilling, etc. In contrast, Ford actively engages in remanufacturing of engines and transmission through a selected network of certified third-party remanufacturers.

In this section, I provide a snapshot of remanufacturing practice in a few select industries: IT networking equipment, PCs and printers, and retreaded tires. I also illustrate Caterpillar's practices because it has a large remanufacturing operation and it remanufactures engines and transmissions for other firms (e.g., Ford). Information was collected through interviews with managers during plant visits and from available public information (e.g., white papers available on the home page of some trade associations, white papers by research firms, and the business press in general). I organize the information along 10 dimensions, shown in Tables 2 and 3.

First consider the technology of remanufactured products. In industries where technology evolves quickly (e.g., IT equipment, PCs, printers), remanufactured products rarely belong to the same generation as new products. Exceptions include consumer returns (for PCs), demo products (IT equipment), or products lightly damaged during transportation. In industries where products have long life cycles, such as tires and engines, remanufactured products are, for the most part, technologically on par with new products. Remanufactured products almost always sell at a discount relative to new products, primarily because of customer perceptions. For example, remanufactured engines at Caterpillar carry a like-new warranty, yet they are still sold at 40%–60% off the price of a new engine. There are (considerably) fewer examples of industries where remanufactured and new products are perfect or near perfect substitutes (i.e., consumers do not distinguish between the two): toner cartridges, single-use cameras, or remanufactured components in Xerox copiers are frequently

TABLE 2. Remanufacturing practice: IT networking and retreaded tires.

Dimension	Secondary IT networking industry	Retreaded tire industry
Technology	Typically, remanufactured and new products do not belong to the same generation, but they may (e.g., product returns)	Remanufactured and new products belong to the same generation
Use of remanufactured products	Cheaper and quicker full replacement for new products, network expansion, redundancy, spare parts, testing, and training	Used as a full replacement for new tires for commercial fleets. There are some laws against using retread tires on the steering axle
Pricing	Between 10% and 95% off a new product's list price. An OEM (Cisco) offers remanufactured products at 25%–30% off new	Between 45% and 75% off new
Market size	According to UNEDA (trade association): US$2 billion	About half of all replacement tires purchased by commercial trucking fleets
Channels	Online channels; larger firms have dedicated sales agents	Many independent tire retreaders who license (and buy equipment and training) from one of the OEMs (Michelin, Bridgestone, and Goodyear)
Sources of returns	Technology upgrades, asset sales of firms who have gone out of business	Automatic upon a tire replacement
Acquisition cost	Remanufacturers offer "cash or trade" programs to firms wanting to sell their network equipment. Market prices exist, at least for the most popular equipment	Varies, because of the service contracts. Retreaders occasionally purchase old tires to supplement the ones recovered through service contracts
Remanufacturing cost	5%–20% of cost of new equipment	About 25% of the cost of a new tire
Competitive landscape	Cisco has a limited (outsourced) remanufacturing program, but there are many third-party providers (in excess of 300 firms)	Many small- to medium-sized retreaders that use one of the technologies developed by three large OEMs
Reasons for OEM remanufacturing	According to Cisco, to provide more choices for customers, to sell more equipment, and to increase revenue from services (tech support). Some analysts say Cisco is trying to "protect the turf"	OEMs have the best technology for retreading but do only a small portion of it themselves. Instead, they sell their technology to independent shops

used examples. This is also the case when the firm sells a service contract as opposed to the product. For example, in the tire industry, commercial fleet companies have contracts with tire shops (who are also retreaders) for them to provide good tires for a certain number of miles; these retreaders naturally prefer to use retreaded tires rather than new tires to cut down on costs.

Remanufactured products may be sold as a cheaper alternative to new products, sometimes even sharing the same channel (e.g., Caterpillar's exclusive dealer networks, some Oreck vacuum cleaner stores). For IT equipment and consumer electronics, however, this is rarely the case because remanufactured products are sold in outlet stores (including direct online channels), separately from new products. Our interactions with marketing managers in these industries clearly indicate a fear of cannibalization. In general, Hauser and Lund [44]

Table 3. Remanufacturing practice: PCs, printers, and Caterpillar.

Dimension	PCs and printers	Caterpillar
Technology	Some refurbished PCs and printers originate from consumer returns, so their technology is similar to new products. Some outlets sell older technology such as off-lease products (e.g., www.tigerdirect.com)	Caterpillar's remanufactured products carry a like-new warranty; technology is similar to that of new products
Use of remanufactured products	Near-perfect substitute for new products for newer technology; older technology can be used in non-profits and emerging markets	Near-perfect substitute for new products; similar reliability and warranty
Pricing	Between 10% and 25% off a new product's list price for newer technology; up to 80% off new for older technology	Between 40% and 80% off a new product's list price
Market size	For every two new PCs shipped to mature markets, one PC is resold in the secondary market (Escherich [20])	About US$1 billion
Channels	Online and offline outlet stores	Sold exclusively at Caterpillar parts distribution network
Sources of returns	Consumer returns, end-of-lease returns	Dealers return used parts to Caterpillar as a result of incentives: buy-back guarantee for unsold inventory, a core deposit fee for remanufactured parts, and a voluntary take-back of surplus used products at a price above the scrap value
Acquisition cost	A consumer return is sent back to OEM, who issues a full credit to retailer	Core deposit fee; transportation is significant part of cost
Remanufacturing cost	Low (<10% of cost of new product); mostly testing, cosmetic remanufacturing, replacing a single malfunctioning component, or software update	About 30% of cost of new equipment (about 70% of cost of a new product is for the components)
Competitive landscape	OEMs offer refurbished products to recover significant value from consumer returns. Thousands of third parties offer refurbished products of unknown origin	Caterpillar has acquired most of its competitors
Reasons for OEM remanufacturing	To increase profitability from recovering value in consumer returns	To expand market penetration, as it attracts a customer who cannot afford to buy a new product (although it decreases the market for new products, decreasing economies of scale)

report that 64% of remanufactured products across industries are sold directly to the end user, with about 18% sold to installers and 15% through retailers and distributors.

For the most part, there is considerable fragmentation in most remanufacturing industries, with many small independent remanufacturers; one exception is Caterpillar, which has acquired many of its smaller competitors. Given this fragmentation, Hauser and Lund [44] argue that a remanufacturer's (or seller's) reputation is a key competitive weapon, and this is supported empirically by Subramanian and Subramanyam [70]. They show, using data from eBay auctions, that a buyer's willingness to pay for a remanufactured product decreases (nonlinearly) in the seller's reputation. Remanufacturing cost is a fraction of a new product's manufacturing cost, often in the range 5%–30%, and as a result, remanufacturing is for the most part profitable. Regarding remanufacturing's main input, returns, they sometimes come naturally (e.g., consumer returns, off-lease equipment); sometimes, however, it is necessary to provide incentives (buy-back, trade-in credit) to customers so that the firm has a sufficient number of cores (e.g., automotive engines).

There are significant differences across industries in the level of competition between new and remanufactured products. Caterpillar firmly believes that their remanufactured products expand their customer base by providing a cheaper branded and certified product to a customer who otherwise would not be able to afford a new Caterpillar product. So, in essence, Caterpillar believes that there is no significant cannibalization of their new product sales by remanufactured products. In the IT networking equipment industry, Cisco only offers a limited range of remanufactured products but faces significant competition from (many) third-party remanufacturers, as budget-strained IT managers look for cheaper (and faster, from a delivery lead time standpoint) alternatives when facing network expansion. For the case of PCs and printers, OEMs remanufacture consumer returns themselves (although remanufacturing—as well as new product manufacturing—is typically outsourced to contract manufacturers such as Flextronics and Solectron); thus, they do not face direct competition from independent remanufacturers, who offer, for the most part, older technology products. In this case, remanufacturing for the OEMs is a value recovery strategy in what is considered an annoyance they have to deal with (consumer returns). Hauser and Lund [44] report that for remanufactured products in the automotive parts industry, the strongest competition comes from other remanufactured products; for office furniture, electrical equipment (e.g., power tools, motors, generators, pumps), and tire remanufacturers, however, the strongest competition comes from new products. Having presented a snapshot of industry practice in a few select industries, I now proceed with decision models from the academic literature for approaching the issues faced by OEMs and remanufacturers.

3. Modeling Closed-Loop Supply Chains

In this section, I review the literature on closed-loop supply chains, present some basic models, and comment on extensions of these basic models. Given the ambitious scope of this tutorial, the review is not meant to be exhaustive; when appropriate I point the reader to other surveys in specific areas. I divide the presentation into strategic, tactical, operational, and regulatory issues. To the extent possible, I maintain a consistent notation throughout.

3.1. Strategic Issues in Closed-Loop Supply Chains

3.1.1. Competition and Pricing. A significant stream of research has developed recently that studies competition between new and remanufactured products. Remanufactured products may or may not compete directly with new products; competition is more likely to arise if the remanufactured product's technology is not significantly older than the new product's. Many issues arise: Should the OEM engage in remanufacturing its own used products? Under which conditions (e.g., availability of used products for remanufacturing by third parties, remanufacturing costs, etc.) should it do so? If remanufacturing is an option, which programs (e.g., leasing, trade-ins, take-back incentives, etc.) can the OEM put in place to guarantee a steady supply of good quality returns? Should the OEM take into account remanufacturability of a product in the design stage? How should the OEM price its new and/or remanufactured product(s)? How should third parties remanufacturers price their remanufactured products? The basic framework for answering these questions is similar in the literature, and it uses vertical differentiation models widely used in economics and marketing. I review the basic modeling framework here, which is based on Assumptions 1 and 2 below.

Assumption 1. *Consumer willingness to pay* (*the* maximum *amount a consumer will pay*) *for a new product is heterogeneous and uniformly distributed in the interval* $[0,1]$.

The highest willingness to pay for a new product, whose market is being modeled, is normalized to one. This represents a consumer with extraordinarily high utility for the product. The lowest willingness to pay for a new product is from a consumer who essentially has no use for that product, and is therefore zero. A consumer of type $\theta \in [0,1]$ has a willingness-to-pay θ for the new product, and as a result, her utility from purchasing is $\theta - p_n$, where p_n is the new product's price. Under a monopoly market (with no remanufactured products) with size normalized to one, if the firm prices at p_n, then only customers with willingness-to-pay $\theta > p_n$ have a positive utility from the new product, and will therefore purchase it. Thus, the quantity sold, given the uniform distribution and the unit market size, is $q_n = 1 - p_n$, which is the demand function.

Assumption 2. *A consumer's willingness to pay for a remanufactured product is a fraction* δ, $0 \le \delta \le 1$ *of her willingness to pay for the new product* θ, *independently of* θ.

Under Assumption 2, a consumer with a willingness-to-pay θ for a new product has a willingness to pay of $\delta\theta$ for the remanufactured unit. If $\delta = 0$, the consumer does not consider the remanufactured price as a substitute, regardless of prices. This could be the case, for example, for certain medical supplies that have contact with human tissue; even upon sterilization, some consumers may perceive them as unsafe. If $\delta = 1$, remanufactured and new products are perfect substitutes. This would be the case for retreaded tires for commercial fleet companies, as seen in the previous section; another example is the often-mentioned single-use camera example. Most markets fall in between these two extremes, with $0 < \delta < 1$; in this case, consumers prefer the new over the remanufactured product if they have the same price, which is the vertical differentiation case. There is considerable evidence that consumers perceive remanufactured products to be of lower quality than new products. For example, most remanufactured products are sold at a lower price than new products (see §2); Hauser and Lund [44] report 35%–55% *average* discounts for a remanufactured product relative to new (i.e., δ ranges between 0.45 and 0.65), although this number varies considerably across industries. Guide and Li [35] empirically derive δ for power tools and Internet routers using online auctions; in their study, both remanufactured and new products are of the same technological generation, and they find $\delta \sim 0.85$. In another empirical study, Subramanian and Subramanyam [70] compare prices of new products with prices for identical remanufactured products (including very similar or identical warranties) and find that δ varies from 0.60 (for video game consoles) to 0.85 (some consumer electronics).

Consider a monopolist OEM selling both new and remanufactured products. For simplicity, assume constant marginal costs of production for new and remanufactured products at c and c_r, respectively (this assumption is revisited later for remanufactured products). The firm decides on the prices of new p_n and remanufactured p_r products to maximize per-period profit. Assume that each consumer consumes one unit of the product per period. Then, the firm solves the basic optimization problem:

$$\max_{p_n, p_r} \Pi = (p_n - c)q_n + (p_r - c_r)q_r \quad \text{s.t.} \quad q_n, q_r \ge 0. \tag{1}$$

Assumptions 1 and 2 allow us to determine q_n and q_r as a function of p_n and p_r as follows. A customer of valuation $\theta < p_n$ obtains a negative utility from the new product, but a $\delta\theta - p_r$ utility from the remanufactured product, which is positive for $\theta > p_r/\delta$. A customer with valuation $\theta > p_n$ has positive utilities for both products, but for $\theta > (p_n - p_r)/(1-\delta)$ the new product's utility is higher than the remanufactured product's. Thus, $q_n = 1 - (p_n - p_r)/(1-\delta)$ and $q_r = (p_n - p_r)/(1-\delta) - p_r/\delta$, which can be substituted into (1) to solve for p_n and p_r. Notice that we have a linear demand curve for both new and remanufactured products; this is a result of the uniform distribution for θ—a different distribution for willingness to pay (e.g., logistic) yields a different shape for the demand curve (e.g., the S-shaped logit curve); see, e.g., Phillips [57] and Debo et al. [14]. If the OEM only sells the new product, and a third-party remanufacturer offers the remanufactured product, then we have a game where the OEM maximizes the first term and the entrant maximizes the second term in (1).

This basic setup is present in a number of papers. Debo et al. [14] consider that the firm also optimizes the level of remanufacturability of a new product (which impacts the remanufacturing cost c_r), and they use an infinite-horizon model where sales of new products in a period constrain the amount of remanufacturing in future periods. Ferguson and Toktay [21] consider both the cases where the OEM offers remanufactured and new products in a monopoly, as well as the case where the remanufactured product is offered by a third-party remanufacturer. Their model is a two-period setting where remanufacturing in the second period q_2 is constrained by the number of cores available, which is the quantity of new products produced in the first period (i.e., q_1). They show how remanufacturing can be used as a strategy by the OEM to deter the entry of third-party remanufacturers. Ferrer and Swaminathan [26] also consider a multiperiod problem, however, they assume that the OEM's new and remanufactured products are perfect substitutes (e.g., single-use camera, printer toner cartridges), but a third-party offers a remanufactured product with an inferior quality; this same competitive scenario is considered by Majumder and Groenevelt [55], who do not model consumer utility directly as above but assume linear demand curves (which is equivalent). In Atasu et al. [4], the OEM offers both new and remanufactured products but faces competition from a low-cost producer of *new* products. This situation is particularly relevant for OEMs in the auto industry (e.g., Ford) that offer both new and remanufactured parts, but are now facing competition from "cheap imports" from Asia.

Vorasayan and Ryan [74] use the basic demand framework above for a monopolist selling new and remanufactured products, however, they explicitly consider uncertainty in demand and production/remanufacturing when setting the optimal prices (as they impact quantities) in a capacitated setting through the use of a queuing network model. Oraiopoulos et al. [56] explore the case (in the IT equipment industry) where the OEM (e.g., Sun) can control the margins of third-party remanufacturers by charging a relicensing fee for software (e.g., operating system) for used equipment; a higher relicensing fee makes remanufacturing less attractive by a third party (reducing cannibalization), but it also decreases the demand for the OEM's new products because consumers are strategic and they realize the lower future resale value for their products when making a purchasing decision.

Trade-in programs as a source of returns for remanufacturing have been explored by two papers: Ray et al. [62], and Agrawal et al. [1]. Ray et al. [62] assume that trade-in products can be remanufactured and that consumers also have a feel for the value of their used product; they suggest the optimal trade-in discount to be offered to the customer as a function of the used product's price, and they compare this policy against a policy that offers a standard discount for a trade-in independent of the product's age. Agrawal et al. [1] explore the case where the OEM offers a trade-in program when it introduces a new generation of products; the trade-in program allows the OEM to perfectly price discriminate (i.e., give the minimum discount possible for a trade-in such that the customer upgrades) the segment of customers in the market who do not consider the remanufactured product, which belongs to an older technological generation.

One important part of Assumption 2 is that consumer's willingness to pay for the remanufactured product relative to the new, δ, is independent of her type θ. This assumption has been relaxed by Jin et al. [51] by assuming that the willingness to pay for the remanufactured product is a function of the customer's type $g(\theta)$. The general insights are preserved under this more general form; thus, parsimony and tractability are important advantages of Assumption 2.

3.1.2. Reverse Network Design. In forward supply chains, facility location models provide the optimal configuration for the chain. For example, suppose the firm wants to determine the optimal number and location of warehouses, given existing customer and plant locations, that minimizes distribution costs. The answer to this question can be obtained through the well-known fixed-charge facility location problem (see, e.g., Chopra and Meindl [10]). In a closed-loop supply chain, the firm also has to locate consolidation centers for returns and reprocessing facilities (remanufacturing, recycling, or disposal). These consolidation centers aggregate returns from various sources (customers), test them to decide upon the appropriate disposition decision, and then ship them to appropriate reprocessing facilities.

Systematic reviews of reverse network design models are provided by Ammons et al. [2] and Fleischmann et al. [30]. I illustrate the modeling framework and issues involved with the general formulation presented by Fleischmann et al. [28]. It includes four separate levels: (i) plants, where new products are made and/or reprocessing takes place; (ii) warehouses, for distribution of products (new and/or reprocessed) to customers; (iii) consolidation centers, where returns are sent to be tested and/or disassembled; and (iv) customers. The flow is as follows: new and/or recovered products are shipped to customers via warehouses, whereas returns are shipped to plants (or disposal) via consolidation centers. As an example of reverse network, Hewlett-Packard has a returns consolidation and testing center for printers and PCs in Tennessee (Guide et al. [39]) to which all consumer returns across the United States are sent. After testing, returns are sent from there to different remanufacturing or recycling facilities in North America.

Indexes
- i Plant locations, $i \in I$; $I_0 = I \cup \{0\}$, where $i = 0$ is the disposal option.
- j Potential warehouse locations, $j \in J$.
- k Fixed customer locations, $k \in K$.
- l Potential consolidation center locations $l \in L$.

Variables
- X^f_{ijk} Fraction of customer k's demand served from plant i through warehouse j.
- X^r_{kli} Fraction of customer k's returns returned to plant i through consolidation center l.
- U_k Unsatisfied fraction of customer k's demand.
- W_k Uncollected fraction of customer k's returns.
- Y^p_i Indicator variable for opening plant i (Y^w_j and Y^r_l similarly defined).

Costs
- c^f_{ijk} Unit cost (transportation, production, handling) of serving k from i via j.
- c^r_{kli} Unit cost of returns (transportation, handling) from k to i via l.
- c^r_{kl0} Unit disposal cost (including collection, transportation, handling) for k via l.
- c^u_k Unit penalty cost for not serving customer k's demand.
- c^w_k Unit penalty cost for not collecting customer k's returns.
- f^p_i Fixed cost for opening plant i (f^w_j and f^r_l similarly defined).

Parameters
- D_k Demand for customer k.
- R_k Returns from customer k.
- γ Minimal disposal fraction.

The firm solves the following mixed-linear integer program (MILP) to optimally design its network of plants, warehouses, and consolidation centers:

$$TC = \min \sum_{i\in I} f_i^p Y_i^p + \sum_{j\in J} f_j^w Y_j^w + \sum_{l\in L} f_l^r Y_l^r + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ijk}^f D_k X_{ijk}^f + \sum_{k\in K}\sum_{l\in L}\sum_{i\in I_0} c_{kli}^r R_k X_{kli}^r + \sum_{k\in K}(c_k^u D_k U_k + c_k^w R_k W_k) \tag{2}$$

$$\text{s.t.} \sum_{i\in I}\sum_{j\in J} X_{ijk}^f + U_k = 1 \quad \forall k \tag{3}$$

$$\sum_{l\in L}\sum_{i\in I_0} X_{kli}^r + W_k = 1 \quad \forall k \tag{4}$$

$$\sum_{k\in K}\sum_{l\in L} R_k X_{kli}^r \le \sum_{j\in J}\sum_{k\in K} D_k X_{ijk}^f \quad \forall i \tag{5}$$

$$\gamma \sum_{i\in I_0} X_{kli}^r \le X_{kl0}^r \quad \forall k,\ \forall l \tag{6}$$

$$\sum_{j\in J} X_{ijk}^f \le Y_i^p \quad \forall i,\ \forall k \tag{7}$$

$$\sum_{i\in I} X_{ijk}^f \le Y_j^w \quad \forall j,\ \forall k \tag{8}$$

$$\sum_{i\in I_0} X_{kli}^r \le Y_l^r \quad \forall k,\ \forall l \tag{9}$$

$$Y_i^p, Y_j^w, Y_l^r \in 0,1 \quad \forall i,\ \forall j,\ \forall l \tag{10}$$

$$0 \le X_{ijk}^f, X_{kli}^r, U_k, W_k \le 1 \quad \forall i,\ \forall j,\ \forall k. \tag{11}$$

The objective function minimizes fixed and variable costs of operating the network. Constraints (3)–(4) represent flow balancing constraints for demand and returns at each customer. Constraint (5) represents flow balancing constraints at each plant; the gap between outgoing and incoming products represents new production. Constraint (6) requires that disposal be a minimum percentage of all returns; this is necessary because, from a technical standpoint, not all returns can be reused (remanufactured or recycled). Constraints (7)–(9) ensure that flows from a facility only happen if the facility is open.

Constraints (5)–(6) are not present in “forward chain” facility location models. As discussed by Fleischmann et al. [28], this formulation is very general and captures many different problems. For example, if the firm decides to pursue separate network configurations for forward and reverse chains, then it can solve two different problems, one where $R_k = 0$ and the other where $D_k = 0$. If there are no regulatory constraints on collection amounts (e.g., Realff et al. [63], Jayaraman et al. [50]), then $c_k^w = 0$; otherwise, it can be made as large as desired (e.g., Spengler et al. [68]). Through the value of c_{ijk}^f relative to c_{kli}^r and c_k^u, plants can be dedicated solely to recovery or to new product manufacturing (e.g., Barros et al. [7]). Sahyouni et al. [64] propose a Lagrangian relaxation-based algorithm to solve the network design problem and present computational results.

Other reverse network design issues have been approached from a different perspective than the MILP optimization models discussed above. Guide et al. [39] use queuing networks to demonstrate (and optimize) the value of speed in recovery—which is not captured in the MILP models above — on profitability for time-sensitive products. Their model applies to time-sensitive commercial returns (products with short life cycles), where a significant value in returned products exist, but value deteriorates quickly with time. Wojanowski et al. [76] use a continuous model for network design (where population is represented by a *density*) to study the effectiveness of a deposit-refund scheme in increasing a firm’s collection rate in a reverse network—increasing the used product's collection rate is particularly important when there are mandated collection targets, such as in some types of take-back legislation (I discuss take-back legislation further in §3.4). They show that a deposit-refund scheme increases the firm's collection rates for products with a high return value. Another example of network design issue regards the collection strategy: should used products be collected by the OEM, the retailer, or a third party? This issue, which involves coordination of different decision makers, is analyzed in the next subsection.

3.1.3. Incentives, Contracts, and Coordination in Closed-Loop Supply Chains. The literature on incentives and coordination in closed-loop supply chains approaches different problems arising from the strategic interaction of multiple parties in decentralized reverse supply chains. I illustrate this line of research with the model addressing the coordination issue of reducing "false failures" returns by Ferguson et al. [22]; for a more complete review, please see the corresponding chapter in Dekker et al. [18]. False failures are nondefective returns, returned to the manufacturer due to liberal return policies ("no questions asked") by powerful retailers. For example, about 80% of returned Hewlett-Packard printers in the United States are false failures. Ferguson et al. [22] present industry data suggesting that a considerable fraction of false failure returns can be avoided through retailer effort in the sales process, such as spending more time with the customer to suggest a product that best fits his or her needs; however, most of the benefits of reduction accrue to the manufacturer, who incurs most reverse logistic costs.

Specifically, consider a supply chain comprised of a manufacturer and a retailer under a single-period setting. If the retailer exerts a (sales) effort $\rho \geq 1$ at a cost $a\rho^2/2$, then the number of false failure returns is $X(\rho)$, a random variable with $E[X(\rho)] = \beta/\rho$; $\rho = 1$ is the baseline effort level such that β is the baseline expected number of false failures in the period. Avoiding one false failure return (through some retailer effort ρ) implies a profit increase to the manufacturer π_m, which is a combination of the return's processing cost (logistic cost, refurbishing if necessary, and remarketing cost) and the expected foregone margin (there is a probability that the consumer does not exchange the false failure with a product from the same manufacturer). For the retailer, avoiding a false failure implies a profit increase of $\pi_r < \pi_m$, which is a combination of the retailer's processing cost and the expected foregone margin (there is a probability that the consumer walks away after returning the product). If the retailer and manufacturer are vertically integrated (i.e., a centralized supply chain), the retailer's optimal effort level is found by

$$\max_{\rho} \Pi(\rho) = (\pi_r + \pi_m)\left(\beta - \frac{\beta}{\rho}\right) - \frac{a\rho^2}{2}. \tag{12}$$

The solution to this problem is $\rho^C = [(\pi_r + \pi_m)\beta/a]^{1/3}$. If the retailer and manufacturer are separate parties, then the retailer's optimal effort is given by solving (12) under $\pi_m = 0$, which yields $\rho^D = (\pi_r\beta/a)^{1/3}$. Clearly, $\rho^D < \rho^C$, so the retailer does not exert the system-optimal level of effort. To coordinate the supply chain, Ferguson et al. [22] propose a target rebate contract, where the manufacturer pays the retailer a fixed amount u per return below a set target T. The retailer's profit under the contract is $\Pi_r(\rho) = \pi_r(\beta - \beta/\rho) - a\rho^2/2 + uE_X[T - X(\rho)]^+$, where the last term is the additional payment by the manufacturer for false failures under the target T. Similarly, the manufacturer's profit is $\Pi_m(\rho) = \pi_m(\beta - \beta/\rho) - uE_X[T - X(\rho)]^+$. The values or (u, T) are chosen such that the supplier's optimal effort level ρ^*, found through $\partial\Pi_r(\rho)/\partial\rho = 0$, results in the centralized solution; that is, $\rho^* = \rho^C$. Ferguson et al. [22] show that this contract is Pareto improving in a wide range of scenarios for normal and uniform distributions of $X(\rho)$.

Corbett and DeCroix [11] also consider a model of effort coordination. The context is the auto industry supply chain, where effort by a supplier of indirect material—typically a hazardous chemical (e.g., solvent, paint)—as well as by the OEM can decrease this material's consumption, translating into savings for consumers and the environment. However, the supplier needs an additional incentive to act in consumption reduction, because otherwise it will cut into her profits. Corbett and DeCroix [11] show how a shared savings contract, where the OEM pays the supplier a fixed fee plus a variable amount depending on consumption, provides an incentive for the supplier to increase her consumption reduction effort (e.g., by reformulating the product), and thus improve the performance of this supply chain.

Savaskan et al. [66] investigate the strategic interactions between an OEM and a retailer in setting a collection strategy. They assume that new and remanufactured products are perfect substitutes; the retailer is able to collect used products and transfer them to the OEM for remanufacturing through a unit transfer price b; another alternative is for the manufacturer to collect used products herself; finally, another alternative is for the OEM to hire a third party to collect the used products. This scenario fits well the examples of single-use cameras and toner cartridges. Savaskan et al. [66] find that the retailer is the most appropriate agent for collecting used products. Savaskan and Van Wassenhove [65] extend these results to the case of competing retailers and find that retailer collection is still preferred for products where retailers compete on prices; manufacturer collection is preferred, however, for products where retailers have less of an impact on prices (e.g., toner cartridges).

3.2. Tactical Issues in Closed-Loop Supply Chains

As seen in Table 1, most tactical issues in closed-loop supply chains revolve around returns acquisition, remanufacturing planning, and inventory management. Remanufacturing planning has the peculiar characteristic of nonuniformity of inputs (returns), which has several implications: the firm needs to separate returns into different quality categories; this leads to an uncertain mix of inputs in each period, as quantity, quality, and timing of returns are typically uncertain. More importantly, different quality grades may have different cost and processing requirements (which has capacity implications), and graded returns can be salvaged/disposed of at potentially different salvage values depending on their quality. Some returns are unfit for remanufacturing and need to be disposed of. There is a growing body of literature addressing remanufacturing planning. I present here some of the more basic models and discuss some of the variations and extensions analyzed in the literature. For comprehensive overviews, see Inderfurth et al. [48], Inderfurth and Teunter [46], Guide [34], and Fleischmann et al. [29]. I divide the discussion in three parts: single-period inventory and returns acquisition models, multiperiod inventory management models, and multiperiod production planning models.

Single-period inventory management models are (typically) variations of the Newsvendor model, used mostly for deriving insights into such issues as the impact of remanufacturing yield, remanufacturing cost structure, return stream, and/or demand uncertainty into the optimal remanufacturing or return acquisition quantity for a given period. They are by nature myopic models. There is a considerable stream of research in continuous-time or multiperiod inventory management with remanufacturable items, and these are reviewed separately from multiperiod production planning models because these models are for the most part uncapacitated, and/or assume stationary distributions of demand and returns, although they deal with demand and/or return uncertainty. Multiperiod (nonstationary) production planning models assume a capacitated, nonstationary environment and allow for carrying inventory of both returns and remanufactured units across periods; however, they are, for the most part, deterministic mathematical programming approaches that use as an input *expected values* of demand and returns per period.

3.2.1. Single-Period Inventory Models, Optimal Acquisition Plan. These papers are concerned with the optimal acquisition plan (i.e., how many returns to acquire) and/or optimal remanufacturing plan (i.e., how many units to remanufacture) in a single period, where there is some source of uncertainty. Some papers assume only two categories of returns (good or bad); good units are remanufactured *at the same cost*, whereas bad units are salvaged (e.g., Zikopoulos and Tagaras [77], Ferrer [24]). Other papers assume more granularity in the quality of incoming returns, which implies different remanufacturing costs, and focus on the optimal *acquisition* plan for product returns (e.g., Galbreth and Blackburn [31], Bakal and Akcali [6], Guide et al. [42]). I illustrate some of the underlying issues here with the model by Zikopoulos and Tagaras [77] and comment on extensions.

Assume the firm has collected R returns and the sorting procedure produces r remanufacturable returns (thus, $R-r$ returns are nonremanufacturable and should be disposed of at a unit cost c_d). Out of the r remanufacturable returns, the firm decides upon the remanufacturing quantity $z_r \le r$ to meet stochastic demand D, which has cumulative distribution function (cdf) $F(\cdot)$. Unit sales revenue is p_r, remanufacturing cost is c_r, shortage cost is c_P, and disposal cost for unsold refurbished items is c_{d1}. The optimal solution to the unconstrained version of this problem is given by

$$F(z_r^*) = \frac{p_r - c_r + c_P + c_d}{p_r + c_P + c_{d1}}. \tag{13}$$

Equation (13) is the familiar Newsvendor formula (see, e.g., Chopra and Meindl [10]), where unit underage cost is $p_r - c_r + c_P + c_d$ (margin plus shortage cost plus opportunity cost of disposing an extra unit that could have been used to meet demand), and unit overage cost is $c_{d1} - c_d + c_r$ (difference in disposal costs plus remanufacturing cost). Given (13), the optimal solution to the constrained version of the problem is quite simple: if $r \ge z_r^*$, then remanufacture z_r^* and dispose $r - z_r^*$; if $r < z_r^*$, then remanufacture all r units. This is the first part of the decision process. The firm should also decide upon the amount of returns to collect R. Zikopoulos and Tagaras [77] assume that returns originate from two collection sites. Site i, $i=1,2$, has stochastic yield (percentage of remanufacturable returns) q_i; these random variables are correlated with a joint distribution $g(q_1,q_2)$. The firm then determines the amount to collect from each site r_i (such that $R = r_1 + r_2$, and $r_1 q_1 + r_2 q_2 = r$). They show that in some cases it is optimal to collect from a single site, and in others it is optimal to collect from both sites. Zikopoulos and Tagaras [78] consider the case where there are inaccuracies in the sorting operation, so there is a probability α that a (good) remanufacturable item is thrown away, and a probability β that a nonremanufacturable unit is sorted as good and it is further disassembled at a cost. They determine conditions under which setting up a sorting operation before disassembly is optimal. In Ferrer [24], demand D is deterministic; there is a single source for returns, but the firm also has the possibility of meeting demand by sourcing (more expensive) new parts from an outside supplier (this is called a *hybrid* system, which I discuss in more detail below). He shows that the optimal solution is generally not mixed, that is, the firm either sources only new parts or only remanufactured parts *if* the supply of returns is large enough.

A stream of research considers the optimal acquisition strategy for remanufacturing (in a single period) when returns have varying quality levels. Consider the basic framework of Guide et al. [42]. There are N quality categories for returns; category i has remanufacturing cost c_{ri}. To improve the quality of returns, the firm decides upon the acquisition price a_i for quality category i and realizes a corresponding return rate $R_i(a_i)$, where $R_i(\cdot)$ is increasing in a_i. Because the supply of returns, which is determined by a_i, constrains the amount of products that can be remanufactured, the firm should set (optimally) the price of remanufactured products p_r^* such that supply meets demand. The demand function (quantity sold) is $D(p_r)$, so the firm sets p_r^* such that $D(p_r^*) = \sum_{i=1}^N R_i(a_i)$, or $p_r = D^{-1}(\sum_{i=1}^N R_i(a_i))$. Thus, the firm's optimization problem is

$$\max_{a_1,\ldots,a_N} \Pi(a_1,\ldots,a_N) = D^{-1}\left(\sum_{i=1}^N R_i(a_i)\right)\sum_{i=1}^N R_i(a_i) - \sum_{i=1}^N R_i(a_i)(a_i + c_{ri}). \tag{14}$$

In (14), the decision variables are the values of the acquisition prices a_i for each quality category i. Note that remanufacturing yield is not considered in (14). Bakal and Akcali [6] consider a single acquisition price a and a single-unit remanufacturing cost c_r, but model the resulting quality of acquired returns such that yield rate (fraction of units fit for remanufacturing out of all units collected) is $t(a)q$, where $t(\cdot)$ is a concave function (so that a higher acquisition price implies a higher yield), and q is a random variable. Thus, the total amount of remanufacturable units is $R(a)t(a)q$. The firm then decides on a and the remanufactured product's price p_r, with the firm facing a linear demand curve $D(p_r) = \alpha - \beta p_r$. (Due to the random yield, the firm cannot set prices to exactly match supply and demand, as in Guide et al. [42].) Galbreth and Blackburn [31] consider an exogenous acquisition price a, but assume that total remanufacturing cost (excluding acquisition cost) decreases in the total quantity of returns acquired R (the decision variable) such that the firm minimizes $TC(R) = aR + \int_{x=0}^{c_r^U} xg(x)\,dx$, where $g(x)$ is the probability density function for remanufacturing cost (with cdf $G(\cdot)$), and $c_r^U = G^{-1}(D/R)$, so that the firm meets demand D from the acquired R units. The trade-off is the higher the total amount of returns collected R, the higher the acquisition cost, but the total remanufacturing cost is lower because there are more returns of better quality in the pool of acquired returns.

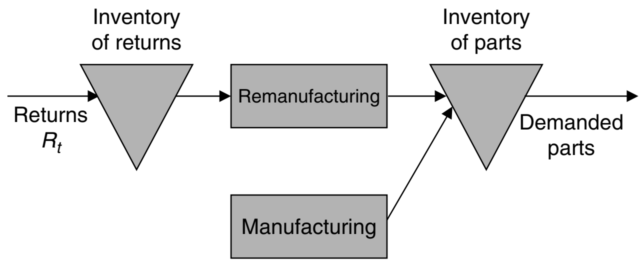
3.2.2. Multiperiod/Continuous-Time Inventory Management Models. In multiperiod or continuous-time inventory management models, there is more than one opportunity to order/produce. Two broad streams exist (Fleischmann et al. [29]): (i) repair systems, where there is a significant correlation between demand and return streams, in that the total number of parts in the system is constant (every return—defective part—triggers a demand for repaired part), and (ii) recovery (remanufacturing) systems, where, due to the long time lags between buying a new product and its end of use, return and demand streams can be assumed to be independent. Again, the focus here is on remanufacturing systems; see Cho and Parlar [9] for a tutorial and review on repair systems.

I briefly present here the periodic-review model by Inderfurth et al. [47] to illustrate some of the dynamics. There are n reuse options for stochastic product returns R_t at period t. Different reuse options could be, e.g., disassembly for spare parts, light remanufacturing, and comprehensive remanufacturing. Reuse option j faces stochastic demand D_{jt} at time t, has processing lead time λ_j, unit processing cost c_{rj}, and unit shortage cost b_j. Unit holding cost for returns is h, and holding cost for an option-j-processed unit is h_{rj}. The firm then decides on the disposal quantity v_t and reuse quantities z_{jt} at time t. Denoting by α the one-period discount factor, the firm solves the following stochastic optimization problem:

$$TC = \min_{v_t, z_{1t}, \ldots, z_{nt}} E\Bigg[\sum_{t=1}^{T} \alpha^{t-1}\Bigg[c_d v_t + \sum_{j=1}^{n} c_{rj} z_{jt} + h\Bigg(u_{t-1} - v_t - \sum_{j=1}^{n} z_{jt} + R_t\Bigg) + \sum_{j=1}^{n} h_j (y_{j,t-1} + z_{j,t-\lambda_j} - D_{jt})^+ + \sum_{j=1}^{n} b_j (D_{jt} - y_{j,t-1} - z_{j,t-\lambda_j})^+\Bigg]\Bigg]. \quad (15)$$

In (15), the expectation is taken with respect to $R_t, D_{1t}, \ldots, D_{nt}$; u_t and y_{jt} are the ending inventory of returns and processed units for option j at time t, respectively; they satisfy the balancing equations $u_t = u_{t-1} - v_t - \sum_{j=1}^{n} z_{jt} + R_t$ and $y_{jt} = y_{j,t-1} + z_{j,t-\lambda_j} - D_{jt}$. The optimal solution structure for (15) is fairly complex, but Inderfurth et al. [47] show how a heuristic policy with a simpler structure—a base-stock policy for returns coupled with base-stock policies for each of the reuse options—perform well under a linear allocation rule for returns to the different reuse options. (A base-stock policy for an option j maintains inventory position of processed units constant at z_j^*, where inventory position is defined as inventory on hand minus backorders plus in-processing, or in transit, inventory.)

FIGURE 2. *Hybrid* inventory control system with remanufacturing and manufacturing sourcing.



Many models in the literature consider a *hybrid* system, where demand can be met by remanufacturing a returned item or by manufacturing (procuring) a new item from a supplier (see Figure 2); these two options have different lead times and costs. Hybrid systems are particularly appropriate for managing inventory of spare parts, or in products such as Xerox photocopiers and Kodak single-use cameras, where some parts are obtained from remanufacturing used products. There are two broad types of models: continuous-review and periodic-review systems. van der Laan et al. [73] derive optimal inventory policies for push systems (where remanufacturing is initiated as early as possible—as soon as there are enough returns for a batch) and for pull systems (where remanufacturing is initiated as late as possible, depending on forecasts, current inventory positions, etc.) in a continuous-review setting with fixed remanufacturing costs. Toktay et al. [72] study a hybrid system with continuous review and no fixed ordering cost and propose a base-stock policy for managing the manufacturing of new components; their biggest contribution is to provide a methodology for estimating the demand parameters, which depend on the products' sojourn time with the customer and the probability that a customer returns a used product. Aras et al. [3] also consider a continuous-time setting with no fixed remanufacturing costs, but they consider two types of stochastic (Poisson) returns: returns of higher quality have a lower remanufacturing lead time than returns of lower quality.

In terms of periodic-review systems, Inderfurth [45] shows how the hybrid system is quite complex if the two sourcing options—remanufacturing and manufacturing—have different (positive) lead times. Thus, one needs heuristic approaches; some are provided by Kiesmueller [53] and Teunter et al. [71]. Ferrer and Ketzenberg [25] numerically extend the hybrid one-period model by Ferrer [24] (see §3.2.1) to a multiperiod setting. Ketzenberg et al. [52] provide an estimate for the value of information in a hybrid system, where value of information is defined as reduction in inventory costs (holding and shortage) as a result of reducing uncertainty in demand, returns, and remanufacturing yield. In a series of papers, DeCroix and his coauthors study *multiechelon* inventory policies for hybrid systems under periodic review in multistage supply chains. DeCroix et al. [17] study a serial supply chain where product returns join new products directly in stock, without the need for remanufacturing. They show that an echelon base-stock policy is optimal. An echelon base-stock policy maintains echelon inventory position at stage j constant at z_j^*, where the echelon inventory position at j is defined as inventory on hand at j and at all downstream stages $j-1,\dots,1$ minus backorders at stage 1 plus in-transit inventory to j. DeCroix and Zipkin [16] study complex assembly systems where there can be returns of end products; these returns are disassembled, and a fixed subset of the recovered parts join existing inventory of those parts for future assembly. They propose some heuristic inventory policies and show that they perform well. DeCroix [15] extends the single-stage hybrid system with remanufacturing of Inderfurth [45] to a serial multiechelon supply chain. DeCroix [15] shows that if product recovery occurs at the most upstream stage, then the optimal policy at that stage is similar to that of Inderfurth [45], with three parameters: remanufacture-up-to, order-up-to, and dispose-down-to levels, evaluated in terms of the echelon inventory position as defined above; the optimal policy for downstream stages is a simple echelon base-stock policy.

Periodic-review or continuous-time inventory management approaches assume unlimited capacity, a stationary environment (in most cases), and a single-product case; the vast majority of these papers also assume that returns come in a single quality, and thus, unit remanufacturing cost is a constant. These assumptions can be relaxed with mathematical programming approaches, which we review next, although these models also have their shortcomings (in particular, most models are deterministic).

3.2.3. Multiperiod Nonstationary Planning Models. In multiperiod production planning, the firm matches supply of returns, remanufacturing capacity, and demand in a nonstationary environment. Some papers consider extensions of the material requirement planning (MRP) approach to remanufacturing planning (e.g., Ferrer and Whybark [27]). The MRP approach incorporates many complexities, such as component commonality, variable yield per part, and a detailed bill of materials; it is focused on disassembling an appropriate number of returns and remanufacturing the appropriate number of each part (or purchasing new parts from a vendor) to meet demand for remanufactured products. However, the MRP system cannot optimize the production plan if there are capacity constraints or if variable quality of returns (different quality grades for returns) is considered, other than yield. Finally, the MRP system does not consider alternative revenues from other disposition options (e.g., spare parts, recycling).

In terms of optimization models, the literature generally considers the *expected value* of demand and returns in each period and, similarly to regular (forward) production planning problems, suggest a rolling horizon approach as a practical way of dealing with uncertainty. I present here a basic (aggregate) optimization problem with linear remanufacturing costs and multiple quality grades for returns, taken from Ferguson et al. [23]. Then notation is shown below:

Indexes
i Quality category, $i=1$ (worst), $\ldots, I$ (best).
t Time period, $t=1,\ldots,T$.

Parameters
D_t Demand for remanufactured products at period t.
R_{it} Quantity of quality-i returns at period t.
c_{rit} Unit remanufacturing cost for quality-i returns at time t.
s_{it} Unit salvage value for quality-i returns at time t.
h_{it} Unit holding cost for quality-i returns at time t.
h_r Unit holding cost for a remanufactured product.
b Unit backlogging cost per period.
C_t Available remanufacturing capacity in period t.
g_i Unit remanufacturing resource usage for quality i returns.

Variables
z_{it} Quantity of quality-i returns remanufactured at period t.
v_{it} Quantity of quality-i returns salvaged at the end of period t.
u_{it} Inventory of quality-i returns at the end of period t.
y_t Inventory of remanufactured products at the end of period t.

The aggregate production planning problem under deterministic demand and returns can be formulated as a linear program:

$$\min_{z_{it},\, v_{it}} \quad TC=\sum_{t=1}^{T}\left\{\sum_{i=1}^{I}(c_{rit}z_{it}-s_{it}v_{it}+h_{it}u_{it})+h_r y_t^{+}+b y_t^{-}\right\} \tag{16}$$

$$\text{subject to} \quad (y_{t-1}^{+}-y_{t-1}^{-})-(y_t^{+}-y_t^{-})+\sum_{i=1}^{I}z_{it}=D_t, \quad \forall\, t \tag{17}$$

$$z_{it}+u_{it}-u_{i,\,t-1}+v_{it}=R_{it}, \quad \forall\, I;\ \forall\, t \tag{18}$$

$$\sum_{i=1}^{I} g_i z_{it} \leq C_t, \quad \forall t \tag{19}$$

$$y_t^+, y_t^-, z_{it}, v_{it}, u_{it} \geq 0, \quad \forall I;\ \forall t. \tag{20}$$

Notice that the formulation (16)–(20) assumes a demand stream for remanufactured products that is *separate* (and independent) from that of new products, so this is not a hybrid system. It is also an *aggregate* plan in that quantities are not broken down at the component level and there is essentially one product family, although it can be easily extended to multiple product families by adding another index to the decision variables, demands, and returns.

Ferguson et al. [23] derive analytical properties for the solution of (16)–(20), but the focus of their research is on finding the value of grading returns into a finite number of quality categories (as opposed to all returns going into a single pile), and the "optimal" number of quality categories. They find that most benefits are derived from using five quality categories (e.g., worst, bad, average, good, best) for categorizing returns. Guide et al. [37] provide a framework and formulation for hierarchical remanufacturing planning, when there are multiple products, although they do not conduct a comprehensive numerical study. Golany et al. [33] do not consider multiple quality grades, but they assume that demand can also be met with new products (a hybrid system), and they consider a fixed cost to remanufacture in a period. Denizel et al. [19] consider the case where the outcome of the grading process (that is, the number of returns obtained for each quality grade) is random in each period, and thus, (16)–(20) is reformulated as a multistage stochastic program. They demonstrate the advantages of the stochastic programming formulation, as it detects infeasibilities that are not possible in the deterministic formulation. For example, returns with worse quality grades consume more capacity; if the firm realizes "bad" outcomes (many returns have bad quality) a few periods in a row, then the problem may be infeasible if backlogs are not allowed or restricted, even though, in expectation, the firm has enough capacity.

3.3. Operational Issues

In this section, I offer a (very) short summary of the types of operational issues that are peculiar to remanufacturing. The focus is primarily on remanufacturing shops—operations that have low volume and where products have nonstandard routings; incidently, this tends to be the case of most remanufacturing operations due to the nonstandard input. There are examples of high-volume remanufacturing operations with more standard routings, for example, toner cartridges; these operations have more of an assembly line structure. However, most of the literature deals with remanufacturing shops. Many remanufacturing shops, particularly those where the product under consideration has mechanical components, can be divided into three separate areas: disassembly of the product into components, remanufacturing (where value-added operations are performed, such as cleaning, repair, and replacement), and reassembly. Many issues arise here, which are divided into disassembly sequencing, release mechanisms (from the disassembly area), priority rules at remanufacturing stations, and routing.

3.3.1. Disassembly Sequencing. There is a vast literature on the general topic of disassembly planning and sequencing. A considerable amount of attention is devoted to the topic of finding a disassembly plan—sequence of disassembly of subassemblies and parts—that maximizes disassembly net revenue (or minimizes disassembly time). The problem is combinatorial in nature. Consider a product with 10 parts. There are 1,023 possible disassemblies and 314.7 million disassembly sequences (of which 34.5 million are complete). A commonly held early assumption is that the optimal disassembly sequence is simply the inverse of the assembly, but that is not often the case. To find the optimal disassembly sequence, researchers have employed graph theory and mathematical programming approaches. For a survey, please see Lambert [54] and Gungor and Gupta [43].

3.3.2. Release Mechanisms. Should the firm release disassembled parts from the shop as soon as they are available? Should the firm release them only after a signal from downstream, e.g., the completion of a job at a certain station? Or, should the firm use a time-phased mechanism for releasing parts, much like MRP? The answer to these questions would, a priori, depend on several factors, such as the configuration of the shop (i.e., number of machines, routing, processing times) and the bill of materials of the products. So, such questions have been tackled using simulation (e.g., Guide et al. [40], [41]). The basic insight is that simple release rules—such as the order of disassembly—perform reasonably well and are recommended due to their simplicity.

3.3.3. Priority Rules. The issue here regards priority rules for different parts of different products at different remanufacturing work centers. Given that parts are then rejoined at a reassembly center, priority rules for parts at different remanufacturing centers impact the flow time of a product in the remanufacturing shop. Again, most of the research uses discrete-time simulation, where the performance of a reasonably complex shop and product structure is studied. In two studies, Guide et al. [40], [41] analyze different bill of materials (i.e., product structure trees) in a job shop with disassembly, 10 remanufacturing stations, and reassembly; in their study there are also serial-number-specific products, where all parts in a remanufactured product must be the same ones disassembled earlier (i.e., they all have the same serial number). They find that earliest-due-date type of scheduling rules perform well, although product structure impacts performance. Guide et al. [38] present a stylized analytic model with a simple queuing network: two products are disassembled; product 1 has a single component that goes to a station that is shared with component A of product 2, and component B of product 2 goes to a separate station. After the components are remanufactured, they are assembled at another station. Guide et al. [38] show that a simple first-come first-served scheduling rule at the shared station (station A) performs reasonably well in terms of weighted average flow times.

3.3.4. Routing. Here, the issue concerns routing of parts or products at the different work centers, if there is flexibility. Using queuing networks, Souza et al. [67] model a job shop, based on remanufacturing of cell phones, where incoming products can be remanufactured at different work centers; each work center is specialized at a particular product but can remanufacture other products less efficiently. They solve a nonlinear program for assigning products to work centers to maximize long-run profitability subject to a service-level constraint on average flow times through the shop (lead time is a critical competitive weapon in many remanufacturing industries). They then propose different heuristics for routing products in real time depending on the state of the queues in the shop, such that long-run profitability is achieved.

3.4. Regulatory Issues

There is an extensive literature on environmental economics (see, e.g., the survey by Cropper and Oates [13]); however, the interests here are on the impacts of legislation on closed-loop supply chain management, and most of the contributions in this domain are quite recent. Of particular interest is the impact of extended producer responsibility (EPR) laws, where brand OEMs (e.g., Hewlett-Packard, Sony), not municipalities and government, have the responsibility for collection and appropriate disposal (often including recycling targets) of end-of-life products from consumers. An EPR law of particular impact is the European directive on WEEE—appliances, consumer electronics, medical equipment, telecommunications equipment, and so forth (in essence, all equipment that is dependent on electrical currents or electromagnetic fields). This directive mandates a minimum recycling target of (roughly) 65% of collected waste; there was a collection target per household per year of 4 kg in 2006. In a nutshell, manufacturers (and importers) are responsible for recycling and treatment of collected waste, bearing all relevant costs (sorting, transportation, recycling, disposal) from collection points established by local governments; the responsibility is given to each manufacturer according to its market share.

Given its impact across the European Union, the WEEE directive has sparked a significant level of interest among researchers. In particular, given its focus on recycling, as opposed to remanufacturing or reuse, some researchers have studied the environmental and business impacts of the WEEE directive. Williams [75] shows that 75% of all electricity consumed during a PC's lifecycle (from raw materials production until recycling) occurs during the production phase. Thus, one wonders whether recycling is the most appropriate disposal decision for a PC from an environmental standpoint. Quarigasi Frota Neto et al. [60], in fact, suggest (using available data on energy consumption) that reuse and remanufacturing are the most appropriate disposition decisions for PCs and TV sets, whereas recycling makes sense for appliances such as refrigerators. This is because 96% of a refrigerator's consumption of energy (during its life cycle, from raw materials to recycling) occurs during the usage phase. Given that refrigerators have long life cycles and that newer-generation appliances consume significantly less energy, there is a significant energy consumption reduction from switching to newer appliances. Bloemhof-Ruwaard et al. [8] and Fleischmann et al. [28] use the network design optimization model described in §3.1.2 to argue that uniform recycling targets for paper in the European Union do not make sense; this is because most of the production of virgin paper pulp occurs in the Scandinavian countries, whereas most consumption of paper occurs in the high-population countries of Western Europe. Thus, it makes sense, from an economical (transportation costs) and environmental (emissions) perspective, to produce paper mainly containing virgin pulp (and thus a low recycled content) in the Scandinavian countries, while producing paper with a high recycled content in central Europe.

EPR laws typically require the brand manufacturer (OEM) to have full responsibility for reverse logistics and recycling costs, so other members of the supply chain (e.g., the OEM's suppliers) are not typically directly impacted. Jacobs and Subramanian [49] study the impact of recycling and collection targets on supply chain profits and environmental impacts when responsibility for EPR costs are shared across supply chain members; they show, using simple economic models similar to those in §3.1.1, that implementing regulation that requires some cost sharing may reduce environmental impacts. Plambeck and Wang [59] study the impact of EPR on the frequency of new product introductions and find conditions under which EPR legislation can actually increase the pace of new product introductions. Plambeck and Taylor [58] study how testing of competitive products by an OEM can improve regulatory compliance. Atasu et al. [5] consider the design of take-back legislation to improve environmental and economic performance.

4. Conclusion

In this tutorial I have presented closed-loop supply chains, where I define the basic terminology, present an overview of industry practice in a few select industries, and review existing academic research by presenting basic modeling frameworks and commenting on extensions. (The review is not exhaustive, so the reader is pointed to more comprehensive reviews of the academic literature in select areas, such as in Dekker et al. [18] and Guide and van Wassenhove [36].)

I start by defining the various types of product returns in closed-loop supply chains (consumer returns, end-of-use returns, and end-of-life returns) and the types of disposition decisions (disposal, incineration, recycling, reuse, spare parts, and remanufacturing), and by differentiating the activities of a closed-loop supply chain from a forward supply chain. Specifically, the main input in a closed-loop supply chain (returns) is variable in terms of quality, quantity, and timing, requires varying capacity usage, and implies different remanufacturing costs depending on quality. Furthermore, consumers generally perceive remanufactured products to be of lower quality than new products; this requires remanufactured products to be priced at a discount. I have divided the review of the academic literature into strategic, tactical, operational, and regulatory issues.

In terms of strategic decisions, research has focused on competition of remanufactured and new products (including pricing of remanufactured products), reverse network design (i.e., location and size of facilities such as collection centers), and, to a lesser extent, on incentives and coordination among self-interested parties in the reverse supply chain. Research in tactical decisions has focused on acquisition strategy for returns (when, how much, of which quality), remanufacturing planning, and inventory management in general. A significant stream of research has been developed in hybrid inventory management systems, where remanufactured and new products are perfect substitutes (that is, the firm has two sourcing options—remanufacturing and manufacturing); these systems, however, are not as prevalent in practice as systems where remanufactured and new products are imperfect substitutes. Finally, a stream of literature has focused on operational issues, such as disassembly planning, dispatching, and scheduling. Regulatory issues are an important reality in closed-loop supply chains, so recent academic literature has studied the impact of EPR laws into supply chain performance.

There are many fertile areas for future research. One area is an analytical and empirical examination of the impact of retailer return policies on supply chain performance. More liberal return policies have a positive impact on sales but a negative impact on costs, so the design of such policies is an important issue. More empirical research is welcome, particularly on documenting acquisition and collection costs, remanufacturing costs, and pricing for remanufactured products (vis-à-vis new products) for different industries. The impact of legislation (e.g., recycling targets) on economic and environmental performance of closed-loop supply chains is a nascent area of research.

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