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ABSTRACT

The management of commercial product returns is an area where there are significant opportunities to build competitive advantages from the appropriate choices in reverse supply chain design. In this paper we use a simple queuing network model to provide managerial insights into the marginal value of time in the product returns stream. We illustrate our approach with actual examples from two companies in different industries and show how industry clockspeed affects the choice between an efficient and a responsive returns network.

1 Introduction

In a perfect world manufacturers would never have to deal with product returns. Supply would meet demand, and consumers would be satisfied with their purchase. In reality, manufacturers and their distributors must cope with an increasing flow of returned products from their customers. Stimulated by returns from growing on-line sales, the value of commercial product returns--which we define as products returned for any reason within 90 days of sale—has been increasing rapidly and now exceeds US $100 billion annually (Stock, Speh and Shear 2002). The reverse supply chain of returned products represents a sizeable flow of potentially-recoverable assets for manufacturers.

In most reverse supply chains only a fraction of the potential value is extracted by manufacturers; a large proportion of the product value erodes away in the returns process and never reaches the bottom line. The reasons why so much of the potential value is lost in the returns stream are historical: most returns processes in place today were developed for an earlier environment in which return rates were low and the value of the asset stream was insignificant. The goal of the returns process was usually cost efficiency; collection networks were constructed to minimize the logistics costs of handling returned products and to minimize the need for managerial oversight. For example, Stock, Speh and Shear (2002) describe Sears' cost-effective transportation networks serving three central returns processing centers.

The returns' environment has changed, but most returns processes have not. Although cost-efficient logistics processes may be desirable for retrieval and disposal of products when returns rates are low and of low value, this approach can actually limit a firm's profitability. Narrowly focusing on minimizing operating costs in the reverse supply chain can create time delays that limit the options available for reuse or disposition. These observations, based on our studies of returns processes for a number of manufacturers, imply that substantial asset value is lost through time delays; for short life cycle, time-sensitive products these losses can exceed 30% of product value. The loss in product value due to time delays is a cost that is unseen, and often ignored, by managers of the reverse supply chain in pursuit of process cost efficiency. There is a need for design strategies for product returns that emphasize asset recovery in addition to operating costs, and that need motivates this research.

To that end, we consider the problem of how to design and manage the reverse supply chain to maximize net asset value recovered from the flow of returned products—that is, the total value of product value extracted from returns minus losses in product value and operating costs. This issue is relatively unexplored in theory and rarely considered in practice. In practice, most reverse supply chains are designed for cost efficiency, not asset recovery. In theory, unlike forward supply chains, no principles of design strategy for returns processing have been established. To address these deficiencies, we evaluate alternative reverse supply chain designs by building network models to capture the effects on costs and revenues of different ways to process the returns flows and make disposition decisions.

Our alternative network designs are derived from two sources: observations of emerging practices in returns processing and the research on design strategies for forward supply chains. Fisher [] has proposed a simple design taxonomy of forward supply chains in which the spectrum of designs ranges between two extremes: *physically efficient* and *responsive*; he argues that the design choice depends on specific product characteristics. Viewed through Fisher's lens, we find that most existing returns networks are physically efficient, with centralized processing and disposition. However, we also observe some manufacturers developing more responsive networks by decentralizing and moving disposition decisions closer to the source of return. To capture these effects, we propose a framework for reverse chains that is similar to Fisher's: at one extreme we propose a traditional, *centralized* model built for processing efficiency, and at the other end, a *decentralized* model that trades scale and efficiency for responsiveness in disposition decisions: returns decisions are made as close as possible in space and time to the point of product return.

The decentralized network structure is called the *preponement* model to differentiate it from the principle of postponement that Lee [] and others have established as part of forward supply chain strategy. Unlike postponement, in which product differentiation actions are taken as late in the process as possible, preponement implies the opposite: early product differentiation. For returns, early product differentiation (restockable, refurbishable, or salvage) helps extract the maximum value from a reusable product whose value is dropping rapidly.

We establish basic design principles by building, and comparing, mathematical models of the different network structures. Our models are built and validated using data collected through in-depth studies of the returns processes at two manufacturers: Hewlett-Packard (HP) and Robert

Bosch Tool Corporation (Bosch). These two organizations capture, in microcosm, the essential issues of returns' network design. Although the reverse supply chains in both organizations were set up to achieve cost efficiency, the increasing flow of returns and an awareness of the cost of time delays has prompted a need to review returns' processing strategy. However, the two firms' products exhibit significant differences in processing costs and delay costs, and we show that these differences lead to different network designs, offering useful insights into how product factors influence the desired design. Subsequent to our analysis of the generic design problem, we examine these two cases to illustrate the application of our principles of network design and management.

To analyze alternative design structures, we develop closed form expressions to capture the expected discounted return from operation of the supply chain for a given returns network structure. Based on our studies of existing returns processes, our analytical models capture product return rates and revenue, the time-value of products (subject to their condition), processing speeds, and operating costs. Our network models must not be limited to just the flows in the reverse logistics network because revenue from reusable product is obtained from, and influenced by, the flow to customers in the forward supply chain. To incorporate these effects, the models we construct are "closed-loop" supply chains: integrated flow models of the forward and reverse supply chain. By calculating the effects on system revenues and costs of different reverse supply networks, we evaluate network designs in terms of their incremental expected profitability in the total distribution network. By comparing the net asset value recovered from the proposed closed-loop networks, we derive a set of fundamental design principles for reverse supply chains. These principles specify the conditions under which a given network design structure—centralized or decentralized—is most appropriate.

The analytical models also provide important insights into optimal operating policies for a given network design—that is, how to manage the network, once designed. Basically, these operating policies involve the selection of processing speeds at the individual nodes of the return network where products are evaluated, refurbished or repaired. We use the expressions developed for net asset value to evaluate the "value of time" in a given network—that is, the loss rate in asset value for the product. Using the value of time, we show that the operating decision at a given node involves a tradeoff between processing speed and cost efficiency and that, given product conditions and flow rates, optimal processing speeds can be determined.

The results establish important fundamental principles of design strategy for returns networks. The principles are similar in form to those developed by Fisher [ ] for forward supply chains. We demonstrate that two variables influence the selection of the appropriate design network: (1) the proportion of new, restockable product in the return flow; (2) the product's time value. Increasing the proportion of restockable product in the return stream makes the decentralized, preponement model more desirable; increasing the value of time produces a similar effect.

By capturing the loss of asset value due to time delays and therefore the economic benefits of faster response in a returns network, our models demonstrate that the product's "time value" is a pivotal element in reverse supply chain strategy. The benefits of faster response are well-established for other business processes through studies of time-based competition [], and it should not be surprising to find that these time-based effects are also central to returns network design strategy—the centralized, cost-efficient model loses some appeal when the "unseen" costs of lost asset value are included. These results also reinforce the importance of "clockspeed" that Fine[] and others have introduced in the study of forward supply chains. One measure of clockspeed is the pace of change in an industry: industries that operate at higher clockspeeds require different processes than slow ones. With the product's time value as a proxy for clockspeed, the concept also applies to reverse supply chains. For products with a low time value—relatively stable prices with long life cycles—then the cost-efficient, centralized model provides superior performance. However, for high time value products, time delays are critical--value erodes rapidly—and the decentralized, responsive design dominates.

This paper is organized as follows. In §2, we present a review of the relevant literature. In §3, we present an overview of the product returns system for two manufacturers, Hewlett-Packard Company (HP) and Robert Bosch Tool Corporation (Bosch), which serves as a motivation for the model. In §4, we present the model, and theoretical results. In §5, we study ways to improve network responsiveness. In §6, we analyze a partially decentralized network for handling product returns. In §7, we apply the results to HP and Bosch, using empirical data from these manufacturers. Finally, we conclude in §8.

2 Literature Review

Although manufacturers have a growing interest in extracting value from commercial product returns, there has been little research on how to design the reverse supply chain for this purpose. However, extensive research has been conducted on managing product return flows for the recovery of products at their end-of-use (EOU) or end-of-life (EOL), where products are prevented from entering the waste stream via value and materials recovery systems. Fleischmann (2001), Guide (2000) and Guide and Van Wassenhove (2003) offer comprehensive reviews of the remanufacturing, reverse logistics, and closed-loop supply chain research on EOU/EOL returns' processes. Because the recoverable asset value of EOU/EOL products tends to be low, processing speed is not a priority, and the objective of most studies of these processes is either cost-efficient recovery or meeting environmental standards. This literature has focused on operating issues (e.g., inventory control, scheduling, materials planning) and the logistics of product recovery, but has not considered the product return problem from the business perspective of how to make such operations profitable (see Guide, Teunter and Van Wassenhove 2001 for a complete discussion).

Much of the previous research on commercial product returns has been descriptive: it documents the return rates of different product categories and the cost of processing returns. This research finds that return rates vary widely by product category, by season and across global markets. For example, product return percentages can vary from 5-9% for hard goods and up to 35% for high fashion apparel (Toktay 2003); market research studies have found higher return rates following the holiday season across all categories of consumer products. Other research has found that, due to differences in customer attitudes and retailers' return policies, the proportion of returned product tends to be considerably higher in the North American consumer market. Many US retailers permit returns for any reason within several months of sale; return policies are much more restrictive in Europe and, consequently, return rates are markedly lower (although return rates are rising in Europe due to new EU policies concerning sales through the internet and other direct channels) Additionally, companies have seen an increase in commercial returns disguised as defects from large resellers in the UK (Helbig 2002). With an increased flow of returns comes increased cost, and a number of publications have documented the cost of processing returns. Recent studies reported in the trade literature reveal that returns may cost as much as three to four times the cost of outbound shipments (Andel and Aichlmayr 2002). Although these reports have raised management's awareness of the problem of product returns, the issue of how to extract more value from the returns stream has been largely ignored.

Another thread of research treats returns' policies from a marketing perspective: how do returns policies affect consumer purchase probability and return rates? In one recent study, Wood (2001) found that more lenient policies tended to increase product returns, but that the increase in sales was sufficient to create a positive net sales effect. Other research has focused on the problem of setting returns policy between a manufacturer and a reseller and the use of incentives to control the returns flow (Padmanabhan and Png 1997 1995, Pasternack 1985, Davis, Gerstner and Hagerty 1995, Tsay 2001). Chow, Li and Yan (2004) study the effect of an e-marketplace on returns policy in which internet auctions are used to recover value from the stream of product returns.

Because our research is focused on how to extract value from the reverse supply chain, our analytical models of the process are largely influenced by three research streams external to the literature on product returns: research on design and operating strategies for traditional, forward supply chains; research on closed queueing models; research on the value of time in supply chains. The relevant research from these streams is summarized below.

Supply Chain Design Strategy

A number of researchers have contributed to the development of design strategy for forward supply chains, and the alternative models that we build for reverse supply chains are motivated by this work. A survey of models for traditional supply chains is provided by Swaminathan and Tayur (2003). In a conceptual piece Fisher (1997) proposes two basic designs for forward supply chains-- efficient and responsive—and argues that the appropriate design choice is determined by product characteristics: whether the product is functional or innovative. In an analytical piece, Lee and Whang (1999) examine the tradeoff between two design structures for multi-echelon supply chains--centralized and decentralized—and specify conditions under which each structure is desired. Interestingly, we note that the design structures analyzed in this paper differ primarily in terminology. When we apply these concepts of design structure to the reverse supply chain, we observe that a (cost) efficient returns network equates to a centralized structure and a responsive network equates to decentralized. In this paper we are able to confirm a set of design principles for reverse supply chains similar to those outlined by Fisher. The concept of *postponement*, or delayed product differentiation (Lee and Tang, 1998), is also a significant contribution to supply chain strategy. Numerous examples have been have been described (for example, see Feitzinger and Lee 1997) that show how firms have reduced their supply chain costs by holding generic product and moving the commitment to product variety further down the supply chain. In our analysis of returns processes, we find that, as a design strategy, it is early, not delayed, product differentiation that enhances profitability. We call this concept of early product identification *preponement* to distinguish it from postponement, and in this study we derive conditions under which a preponement strategy increases net asset recovery.

Closed-Loop Queuing Networks

We use closed-loop queuing network models to evaluate alternative reverse supply chain design strategies. Because we are concerned with net asset value recovered, it is important to model the returns process as part of a closed-loop system that integrates the flows of the traditional forward chain with the reverse chain. Conceptually, our model is based on the queuing model that Toktay, Wein and Zenios (2000) use to analyze a specific problem in the remanufacturing of disposable cameras. In our research we show that the closed-loop queuing model is a powerful tool that can be used to develop principles of reverse supply chain design that are applicable to a broad range of commercial products.

Valuing Time in Supply Chains

A significant difference between our model and previous research on reverse supply chains is that we explicitly capture the cost of lost product value due to time delays at each stage of the returns' process. Studies of time-based competition (Blackburn 1991) have demonstrated that faster response in business processes can be a source of competitive advantage, and other studies have shown how to quantify the effect of time delays in traditional make-to-stock supply chains (Blackburn 2001). In his book *Clockspeed*, Fine (1998) shows that the effects of speed vary across industries and product categories, and he uses these concepts to link supply chain strategies to product architecture. This earlier work provides the motivation for our models that specifically incorporate the cost of time delays and its effect on asset recovery. Using these models we are able to show clearly the relationship between a product's time value and the appropriate reverse supply chain structure.

3 Commercial Returns at HP and Bosch

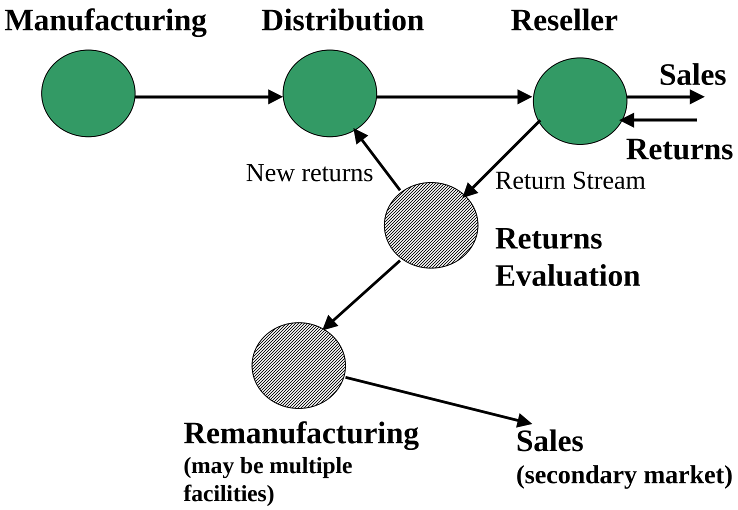
Product returns arise for many reasons, the most powerful being liberal returns policies on the part of resellers. Customers may return products for a variety of reasons, many of which may be classified as non-defective. These returns are driven by convenience; for manufacturers doing business with North American resellers the associated costs can be enormous. HP estimates the cost of product returns at 2 percent of total outbound sales for North America alone (Davey 2001). Figure 1 shows the flow for product returns in generic terms.

In the sections that follow we provide an overview of two product returns processes at HP and Bosch Tools. We selected these two firms since their products' characteristics provide representative examples of fast and slow clockspeed products. Our experience with product returns in many industries suggests that our results can be generally applied.

3.1 Case 1: Hewlett-Packard Inkjet Printers

HP uses a centralized returns center in Smyrna, TN, outside of Nashville. The product returns strategy is focused on recovering maximum value from the returns and developing capabilities that would put HP in a position of competitive advantage. As of 2001, HP had managed to recover approximately 50% (on average) of the dollar value in a returned printer (as measured by the standard cost of a printer), but this is still short of the target goal of 75% recovery (Davey 2001).

Figure 1: Product returns process flows



Product acquisition

Product returns are driven by the increasing power of resellers; see Table 1 for a listing of why customers return products, percentages and disposition after receipt. Most resellers make little effort to determine why a customer returned a product and this may cause delays since the actual reason for the return is important with respect to disposition. After customers return products to the reseller, the reseller stores the products until they arrange for transportation to the HP returns depot where credit is issued. The time that elapses from a customer return to the reseller arranging for transportation to HP's returns depot can vary drastically from reseller to reseller. No hard data is available on how long the products spend waiting at the reseller after a customer return, but managers believe products could spend as long as 4 weeks waiting for transportation, or that the returns are stored in areas where they are ‘out-of-sight, out-of-mind’ (Davey 2001).

HP’s inkjet printer division handled over 50,000 returns per month in North America in 1999 (Davey 2001). This number has been increasing and the most recent trend estimates showed a 20% increase in terms of the volumes of total units returned. Inkjet printers have a relatively short lifecycle, with a new model being introduced every 18 months on average.

Reverse logistics

Resellers return HP products to a central returns depot in Smyrna TN. Ink jet printers are delivered via truck and are unloaded and stored in holding areas to await disposition. The time required for transportation ranges from 6 to 13 days depending on the distance to be traveled.

Table 1: Breakdown of reasons for commercial product returns of HP printers

Reason for return	**Description**	**% of returns**	**Procedure after return**
Product defective	A truly defective product – it simply does not function as intended	20.0%	Product is tested, remanufactured (low or high touch) and sold to a secondary market (sell as remanufactured).
Could not install	The customer could not install the product correctly. Box opened, but product was never used.	27.5%	Product is tested for number of pages printed; if this number is below a threshold value, then the product is re-boxed and shipped back to the forward distribution center to be sold as new. Otherwise it is shipped to appropriate remanufacturing facility.
Performance not compatible with user needs	The product did not meet the user’s needs. Print quality was too low, printing speed was too slow, etc.	40.0%	
Convenience returns	The product was returned for a host of reasons (remorse, rental, better price, etc.)	12.5%	

Test and disposition

Credit issuance, which involves crediting the appropriate reseller, is done by a third-party vendor on site. The receipt and credit issuance take an average of 4 days. After credit issuance, returns are sorted by product line; products other than inkjet printers are sent to the specialized HP recovery facility. Inkjet printers are tested, evaluated, and sent to one of several facilities (see "Remanufacturing" below). All HP printers have an electronic counter that allows a technician to determine how many copies have been printed – there is a threshold of allowable pages before the unit is considered 'used'. In theory, resellers could have access to the data port that would allow them to determine if the unit can be considered new.

Remanufacturing

HP monitors the remanufacturing processes and is responsible for warranty fulfillment. Printers that require mainly cosmetic remanufacturing, referred to as 'low-touch', are done on-site by an HP contractor (Table 2). Printers requiring more extensive remanufacturing operations, or "high-touch", are refurbished in Mexico or salvaged for spare and warranty parts. Presently, the average remanufacturing time is 40 days, but this is an aggregate measure across remanufacturing sites. Low end (inexpensive) products lines are remanufactured by a supply chain partner.

Table 2: Action taken after credit issuance

Action	Percentage
As-is new returns	33%
Low touch remanufacturing	40%
High touch remanufacturing	20%
Dispose	7%

Distribution and remarketing

All remanufactured HP inkjet printers are sold in secondary markets under the direction of a dedicated sales representative.

3.2 Case 2: Robert Bosch Tool Corporation

The current product returns process is a result of the 90-day returns policy, which is meant to attract customers. Bosch sells two different product lines in North America: the Skil line is aimed at the consumer market and the Bosch line is aimed at the professional market. Skil tools are reasonably priced and have smaller profit margins due to the competitive nature of the market. Bosch professional tools command a premium price since reliable and durable tools are highly sought after by the professional market. In the description below, we limit our discussion to the consumer segment since these returns represent the largest volume and concern for Bosch.

Product acquisition

Customers return products directly to resellers. The major difference from HP inkjet printers is the life cycle of power tools, which is much longer, averaging 6 years. The return rates are very stable from year to year, with some seasonality (after Christmas and Father's Day). Table 3 shows the primary reasons customers return products (Wolman 2003). The reseller holds the returned tools by depositing the return in a RTV (return-to-vendor) cage. This inventory is held until a Bosch salesperson is available to perform disposition on the product. The period of time between receipt of product and disposition is highly variable, depending on the workload of the salesperson, with times ranging from one to four weeks (Valenta 2003).

Table 3: Returns classifications for power tools

Reason for return	**Percentage of returns Consumer tools**
Product defective	60%
Poor performance – does not meet user expectations	15%
Improper marketing of tool	10%
Buyer remorse	10%
Tool used for a specific purpose then returned (rental)	5%

Test and disposition, and reverse logistics

A Bosch salesperson makes disposition decisions about each returned product. This is done on-site at every reseller. The products are sent to one of two locations: if a product is deemed to be a straightforward and uncomplicated remanufacture, it is sent to Walnut Ridge, AR. If the problem appears more technical in nature, the product is sent to Addison, IL. Products are transported in bulk via trucks to the appropriate remanufacturing facility. Bosch treats each returned item as if it has been used by the consumer and remanufactures 100% of returns.

Remanufacturing

At both locations, products are diagnosed by technicians and remanufactured when possible. Products are discarded if reconditioning is not possible or likely to be very expensive.

Distribution and remarketing

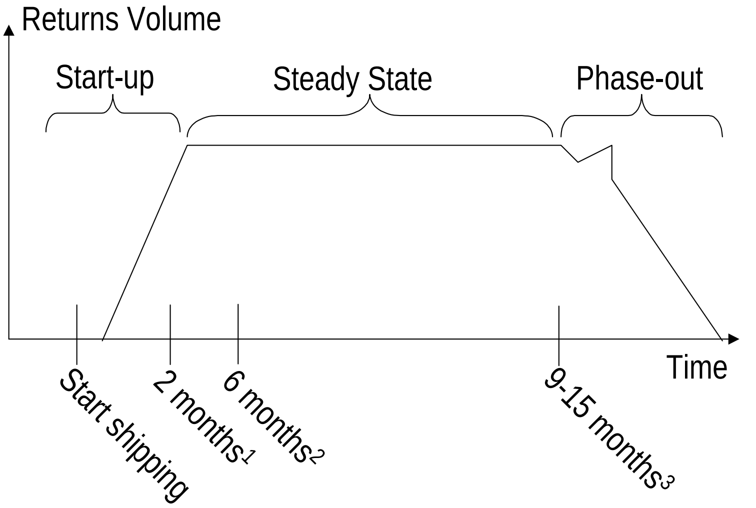
The reconditioned products are sold mainly to liquidators at an average of 15% below the retail price for the new product.

4 A Simple Analytical Model for the Time-Value of Product Returns

In this section, we present an analytic model that computes the value of time in a closed–loop supply chain. We provide closed–form expressions that allow a manager to quickly compute the value of reducing delays in the various links in the supply chain. Managerial actions aimed at reducing delays are not without a cost, so a natural question arises as to what is the *optimal* level of reduction in delays. In §5, we discuss specific actions aimed at reducing delays in the network, for example, increasing processing speed at a facility, and compute the optimal level of responsiveness given assumptions for the underlying cost functions.

Empirical evidence gathered at HP and Bosch suggests that the rate of commercial returns follows a curve similar to the product life cycle, shifted to the right in the time axis, with a long steady state period. Figure 2 shows the returns life cycle for an inkjet printer, which has a typical life cycle of 18 months; the steady state period varies from 7 to 13 months. For Bosch power tools, a typical life cycle is 6 years, with a steady state period of 5 years. In this research, we focus on profit maximization for the steady state period of the returns life cycle, due to the high volumes involved, the long time frame, and the primary use of returns in the steady state period for remanufacturing and sales at a secondary market. In the ramp-up period of the life cycle, most returns are used for warranties (i.e., instead of repairing defective products in the field, the firm uses refurbished products originated from convenience returns to replace these defective products), whereas in the ramp-down period their primary use is for spare parts, after disassembly (Davey 2001).

Figure 2: Returns lifecycle for a typical inkjet printer



1 – Product returns increasing rapidly to stable volumes
2 – Refurbished products available
3 – End of product life, followed by a large number of stock adjustment returns

We model a closed-loop supply chain as shown in Figure 3, where the notation is defined in Table 4. The facilities in the closed-loop supply chain include factory, distribution center, retailer, customer, central evaluating facility for returns, remanufacturing, and the secondary market, where remanufactured products are sold. We represent facilities by nodes, and the flow of products through the nodes is indicated in Figure 3, and described in detail below. To avoid unnecessary confusion, our notation uses parenthesis for grouping terms, and square brackets for denoting functions, e.g., $r(1 - p)$ denotes r times $(1- p)$, and $c[a]$ denotes c as a function of a.

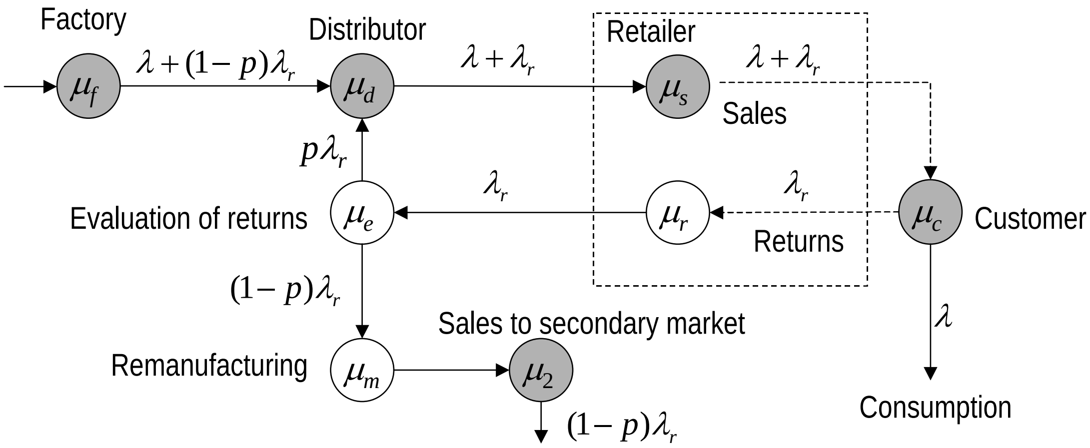
Table 4: Notation

i, j	Subscripts for nodes: f (factory), d (distributor), s (retailer sales), r (retailer returns), c (customer), e (central evaluating facility), m (remanufacturing), 2 (sales outlet at secondary market)
λ	Net new sales rate at the primary market
λ_r	Total steady state rate of returns
p	Proportion of new returns from total returns
μ_i	Average processing rate of products (new/returns) at node i
λ_{ij}	Product flow rate between nodes i and j
τ_{ij}	Average transportation time between nodes i and j
W_{ij}	Expected flow time between the beginning of processing at node i and end of processing at node j
α	Continuous–time price decay at primary market (i.e., % price decay per unit time)
α_m	Continuous–time price decay at secondary market
β	Continuous–time discount rate
ϕ	Continuous-time variable production cost decay parameter
ϕ_m	Continuous-time remanufacturing cost decay parameter
$P[t]$	Unit price for new product at primary market at time t
$P_m[t]$	Unit price for remanufactured product at secondary market at time t;
$v[t]$	Variable production cost at time t
$v_m[t]$	Variable remanufacturing cost at time t
c_{ij}	Unit transportation cost between nodes i and j
$h_i[\mu_i]$	Handling cost per unit at node i as a function of processing rate at node i; $i \in \{e, r\}$
$\pi[t]$	Expected profit rate at time t
Π	Total expected discounted profit over steady–state period

Similarly to Toktay, Wein and Zenios (2000), and for ease of exposition, we consider a single retailer. In §7 we show how the model can be easily extended to multiple retailers when we apply it to HP. Also similarly to Toktay et al., nodes are modeled as either M/M/1 or M/G/∞ queues. We choose to model the facilities and processes of interest (those on the return path—return at retailers, evaluation of returns, and remanufacturing) as M/M/1 queues to capture the significant congestion effects observed in practice, whereas the processes on the forward network (factory, distributor and retailer sales), which realize little congestion, are modeled as M/G/∞ queues. In addition, there are transportation delays τ_{ij} between each pair of nodes i and j in Figure 3, except to and from the customer.

Time $t = 0$ is defined as the beginning of the steady state period for returns (sales are already in steady state at that time), and $t = T$ is the end of steady state for sales and returns (whichever is earlier); thus all queues are in steady state for the period of analysis. The flow rates between each pair of nodes λ_{ij} are defined in Figure 3, i.e., $\lambda_{fd} = \lambda + (1-p)\lambda_r$, $\lambda_{ds} = \lambda_{sc} = \lambda + \lambda_r$, $\lambda_{cr} = \lambda_{re} = \lambda_r$, $\lambda_{em} = \lambda_{m2} = (1-p)\lambda_r$, and $\lambda_{ed} = p\lambda_r$.

Figure 3: Closed-loop supply chain model



Note: Blank and shaded nodes are modeled as M/M/1 and M/G/∞ queues, respectively

Consistent with empirical data obtained at HP and Bosch, we assume for both new and remanufactured products exponential price decay functions, i.e. $P[t] = P[0]e^{-\alpha t}$ and $P_m[t] = P_m[0]e^{-\alpha_m t}$, and exponential variable cost decay functions, i.e. $v[t] = v[0]e^{-\phi t}$, and $v_m[t] = v_m[0]e^{-\phi_m t}$. The continuous–time decay parameters (α and α_m, ϕ and ϕ_m) may or may not be equal. All decay parameters can be viewed as a measure of industry clockspeed (see, e.g. Williams 1992, Mendelson and Pillai 1999).

There are handling costs for processing returns; $h_i[\mu_i]$ is the handling cost per unit if facility i ($i = r$ for retailer and $i = e$ for evaluating facility) operates at processing rate μ_i. Transportation and handling costs, however, are assumed constant over time; this is because the decay in prices and variable costs is primarily related to material and product value erosion, which does not hold for transportation and handling costs. All cash flows are discounted at a continuous discount factor β, which represents the firm's opportunity cost of capital (i.e., time value of money).

For tractability, we need two assumptions:

Assumption 4-1: New returns are only returned once. That is, a new return only goes through the cycle in Figure 3 once.

Assumption 4-2: The actual flow times in the network of Figure 3 are approximated by their expected values W_{ij}.

Assumption 4-1 is reasonable because new returns constitute a small percentage of all product sales, as we will see later in the numerical examples. Assumption 4-2 is necessary for tractability, because the delays in the network are random variables with complicated gamma-type distributions. We comment on Assumption 4-2 later.

The sequence of events is as follows:

- Time t: the factory produces $\lambda+(1-p)\lambda_r$ units at a per unit cost $v[t]$. These units are shipped to the distributor, where they are joined by $p\lambda_r$ new returns (produced at time $t-W_{loop}$, where W_{loop} is the expected delay through the loop for the network shown in Figure 3), and then transported to the retailer.
- Time $t+W_{fs}$: the retailer sells $\lambda+\lambda_r$ units at a per unit price $P[t+W_{fs}]$. After a sojourn time with the customer, λ_r units are returned to the retailer, where they wait until they are shipped to the evaluating facility for sorting and credit issuance.
- Time $t+W_{fs}+W_{ce}$: after sorting, the manufacturer issues a credit of $P[t+W_{fs}]$ (selling price) for each of the λ_r returns to the retailer. New returns $p\lambda_r$ are shipped to the forward distribution center; non-new returns $(1-p)\lambda_r$ are shipped to the remanufacturing facility.

- Time $t+W_{fs}+W_{cm}$: non-new returns $(1-p)\lambda_r$ are remanufactured at a per unit cost $v_m[t+W_{fs}+W_{cm}]$, and then shipped to the secondary market.
- Time $t+W_{fs}+W_{c2}$: $(1-p)\lambda_r$ remanufactured products are sold at the secondary market at a per unit price $P_m[t+W_{fs}+W_{c2}]$.

The expected delays W_{ij} are computed as follows:

$$W_{fs}=1/\mu_f+\tau_{fd}+1/\mu_d+\tau_{ds}+1/\mu_s\,, \tag{1}$$

$$W_{ce}=\frac{1}{\mu_c}+\frac{1}{\mu_r-\lambda_r}+\tau_{re}+\frac{1}{\mu_e-\lambda_r}\,, \tag{2}$$

$$W_{cm}=W_{ce}+\tau_{em}+\frac{1}{\mu_m-(1-p)\lambda_r}\,, \tag{3}$$

$$W_{c2}=W_{cm}+\tau_{m2}+1/\mu_2\text{ , and} \tag{4}$$

$$W_{loop}=W_{ce}+\tau_{ed}+1/\mu_d+\tau_{ds}+1/\mu_s\,. \tag{5}$$

The expected profit rate at time *t* for the existing network is:

$$\begin{aligned}\pi[t]=&\left(\lambda+\lambda_r\right)P[t+W_{fs}]-\left(\lambda+(1-p)\lambda_r\right)v[t]-\lambda_r P[t+W_{fs}]e^{-\beta W_{ce}}\\&-p\lambda_r\left(v[t-W_{loop}]-v[t]\right)+(1-p)\lambda_r\left(P_m[t+W_{fs}+W_{c2}]-v_m[t+W_{fs}+W_{cm}]\right)\\&-\sum_{(i,j)\text{ in net}}\lambda_{ij}c_{ij}-\lambda_r h_e[\mu_e]-\lambda_r h_r[\mu_r],\end{aligned} \tag{6}$$

The terms in (6) represent sales revenue for $\lambda+\lambda_r$ products sold at a unit price $P[t+W_{fs}]$ at the retailer, variable production cost at the factory at time *t*, credit issued for λ_r returns W_{ce} time units after they were sold at time $t+W_{fs}$, difference in variable costs for new returns (i.e. new returns were produced at W_{loop} time units before other non-returned products and hence at a higher cost), unit margin for remanufactured products (unit price $P_m[t+W_{fs}+W_{c2}]$ minus unit production cost $v_m[t+W_{fs}+W_{cm}]$), sum of transportation costs across all network arcs, handling costs at the evaluating facility and retailer, respectively.

The total expected discounted profit over the steady state period is given by $\Pi = \int_0^T \pi[t] e^{-\beta t} dt$, and can be easily derived, resulting in

$$\begin{aligned}\Pi = {} & \lambda\left(\tilde{P}e^{-\alpha W_{fs}} - \tilde{v}\right) + \lambda_r \tilde{P} e^{-\alpha W_{fs}}\left(1 - e^{-\beta W_{ce}}\right) - p\tilde{v}\lambda_r\left(e^{\phi W_{loop}} - 1\right) \\ & + (1-p)\lambda_r\left(\tilde{P}_m e^{-\alpha_m (W_{fs}+W_{c2})} - \tilde{v}_m e^{-\phi_m (W_{fs}+W_{cm})} - \tilde{v}\right) \\ & - \sum_{(i,j)} \lambda_{ij}\tilde{c}_{ij} - \lambda_r \tilde{h}_r[\mu_r] - \lambda_r \tilde{h}_e[\mu_e]\end{aligned} \tag{7}$$

where, for notational convenience, we define the total discounted (including discounting and time–decay) revenue and cost parameters over *T*, denoted with tildes, as $\tilde{P} = P[0]\left(1 - e^{-(\alpha+\beta)T}\right)/\left(\alpha+\beta\right)$, $\tilde{v} = v[0]\left(1 - e^{-(\phi+\beta)T}\right)/\left(\phi+\beta\right)$, $\tilde{v}_m = v_m[0]\left(1 - e^{-(\phi_m+\beta)T}\right)/\left(\phi_m+\beta\right)$, $\tilde{P}_m = P_m[0]\left(1 - e^{-(\alpha_m+\beta)T}\right)/\left(\alpha_m+\beta\right)$, $\tilde{c}_{ij} = c_{ij}(1 - e^{-\beta T})/\beta$, and $\tilde{h}_i[\cdot] = h_i[\cdot](1 - e^{-\beta T})/\beta$.

The terms in (7) represent the net margin for (net) new products sales (revenues are "discounted" by the delay between production and sale), the "interest" gained by the manufacturer as a result of returns (credit of returns to retailer is issued later than sale), the difference in variable costs for new returns, the margin for remanufactured products, transportation and handling cost.

For the remainder of the analysis, we introduce, for tractability, an approximation:

Assumption 4-3: Approximate $e^{-\alpha W_{ij}} \approx 1 - \alpha W_{ij}$; similarly for $e^{\alpha_m W_{ij}}, e^{\phi_m W_{ij}}, e^{\phi W_{ij}},$ and $e^{\beta W_{ij}}$.

Assumption 4-1 is reasonable because for real-life parameters $\alpha W_{ij} << 1$ (similarly for $\alpha_m, \phi, \phi_m,$ and β)— this approximation implies a maximum error of 0.5% for the numerical examples of §7. We *do not* use an approximation for $\tilde{P}, \tilde{v}, \tilde{P}_m, \tilde{v}_m, \tilde{c}_{ij}$ and $\tilde{h}_i$ above because *T* is considerably larger than any delay W_{ij} in the network; thus $\alpha T >> \alpha W_{ij}$.

We now comment on Assumption 4-2. Consider an M/M/1 queue with arrival rate λ and processing rate μ; revenue per completed unit is $P[t] = P[0]e^{-\alpha t}$. The flow time X follows an exponential distribution with mean $1/(\mu - \lambda)$. The total expected discounted revenue over [0, T] is $\Pi \; = \; \lambda E_X \left\{ \int_0^T P[t+X] e^{-\beta t} dt \right\} \; = \; \lambda P[0] \int_{t=0}^{T} \int_{x=0}^{\infty} e^{-\alpha(t+x)} (\mu - \lambda) e^{-(\mu-\lambda)x} e^{-\beta t} dx dt \; = \; \lambda \tilde{P} \left(1 - \frac{\alpha}{\alpha + \mu - \lambda} \right)$. Under Assumption 4-2 and Assumption 4-3, $\Pi \approx \lambda \tilde{P} \left(1 - \alpha W \right) = \lambda \tilde{P} \left(1 - \frac{\alpha}{\mu - \lambda} \right)$; again, this is a very good approximation for realistic values of α (maximum error of 0.5% for the parameter values considered in the numerical examples here).

After regrouping the terms, (7) becomes.

$$\begin{aligned}
\Pi \approx\ & \lambda \left(\tilde{P} - \tilde{v} \right) + (1-p)\lambda_r \left(\tilde{P}_m - \tilde{v}_m - \tilde{v} \right) - \sum_{(i,j)} \lambda_{ij} \tilde{c}_{ij} - \lambda_r \tilde{h}_r \left[\mu_r \right] - \lambda_r \tilde{h}_e \left[\mu_e \right] \\
& - \left(\tau_{ed} + 1/\mu_d + \tau_{ds} + 1/\mu_s \right) p \lambda_r \tilde{v} \phi - W_{fs} \left\{ \lambda \tilde{P} \alpha + (1-p)\lambda_r \left(\tilde{P}_m \alpha_m - \tilde{v}_m \phi_m \right) \right\} \\
& - W_{ce} \lambda_r \left\{ -\left(\tilde{P} \beta - p \tilde{v} \phi \right) + (1-p) \left(\tilde{P}_m \alpha_m - \tilde{v}_m \phi_m \right) \right\} \\
& - \left(\tau_{em} + \frac{1}{\mu_m - (1-p)\lambda_r} \right) (1-p)\lambda_r \left(\tilde{P}_m \alpha_m - \tilde{v}_m \phi_m \right) - \left(\tau_{m2} + \frac{1}{\mu_2} \right) (1-p) \lambda_r \tilde{P}_m \alpha_m
\end{aligned} \tag{8}$$

An analysis of (8) allows for an easy visualization for the sources of revenues and costs in the network, as well as the monetary effects of network delays. The first row indicates the steady state expected discounted profit without accounting for delays of new and returned products in the network: new product margins, remanufactured product margins, transportation and handling costs. Equation (8) reveals that this base expected profit is decreased by the delays in the network:

(i) The delay of new returns from production until sale (they are delayed by the loop shown in Figure 3). Thus, a one–day increase in τ_{ed} decreases expected profit by $p\lambda_r \tilde{v} \phi$, corresponding to the difference in variable production costs. Delays in other components of the loop also affect new products, as explained in (ii) below.

(ii) The delay of new products to reach the consumer W_{fs}. Considering (1) and (8), a one–day increase in the path between factory and distributor ($1/\mu_f$ or τ_{fd}) decreases expected profit by $\lambda\tilde{P}\alpha + (1-p)\lambda_r\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right)$, corresponding to revenues for new and remanufactured products. A one–day increase in the path from distributor to sales ($1/\mu_d$, τ_{ds} or $1/\mu_s$) decreases expected profit by a higher amount $\lambda\tilde{P}\alpha + (1-p)\lambda_r\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right) + p\lambda_r\tilde{v}\phi$ due to its effect on new returns.

(iii) The delay of returned products to reach the evaluating facility W_{ce}. Thus, a one-day increase in the path from consumer to evaluating facility (2) decreases expected profit by $\lambda_r\left\{-\left(\tilde{P}\beta - p\tilde{v}\phi\right) + (1-p)\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right)\right\}$. The time–lag for credit issuance to retailers has a positive effect on expected profit, however, the difference in production costs for new returns and the decrease in value for the remanufactured product have negative effects on expected profit.

(iv) The transportation and production delay between the evaluating facility and remanufacturing $W_{cm} - W_{ce}$. Thus, a one–day increase in the path from the evaluating facility to remanufacturing (3) decreases expected profit by $(1-p)\lambda_r\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right)$, corresponding to net revenues for remanufactured products sold in the secondary market.

(v) The delay incurred for transportation and sales in the secondary market $W_{c2} - W_{cm}$. Thus, a one–day increase in the path from the remanufacturing facility to the secondary market (4) decreases expected profit by $(1-p)\lambda_r\tilde{P}_m\alpha_m$, corresponding to sales revenues for remanufactured products sold in the secondary market.

We note that the value of one–day reduction in delays for the reverse network (iii)–(v) increases linearly with the returned product volume to be remanufactured $(1-p)\lambda_r$ and the term $\tilde{P}_m\alpha_m$, which is a function of α_m. Because of this, we say that the *drivers* of responsiveness in the reverse network are the fraction of new returns *p*, and the decay parameter α_m. As we see later in §7, these drivers essentially determine the choice between a responsive and an efficient commercial returns network.

5 Improving Network Responsiveness

The preceding analysis provides the monetary benefits of decreasing delays in different parts of the network. The firm can invest, although at a cost, in network responsiveness to decrease these delays; we analyze this trade–off here. By simple inspection of (1)–(4), actions to improve network responsiveness include increasing the processing rate of returns μ_i at each node (retailer, evaluating and remanufacturing facilities), and decreasing the average transportation times τ_{ij} (by co–location of facilities, or faster transportation modes). We analyze these alternatives separately below. First, note that Π is a separable function in each delay variable μ_i (that is, $\partial^2\Pi / \partial\mu_i\partial\mu_j = 0$ for $i \neq j$), and thus a sufficient condition for (8) to be jointly concave in μ_i, for all *i*, is that $\partial^2\Pi / \partial\mu_i^2 < 0$ for all *i*.

5.1 Increasing Processing Rate of Returns at the Retailers or Evaluating Facilities

Product returns are delayed at the retailers because of several reasons, as discussed in §3. Improving responsiveness μ_r at the retailer requires investments by the manufacturer according to the unit handling cost function $h_r[\mu_r]$—e.g., consider the situation at Bosch, where returns wait in cages at the retailer until a visit by a Bosch sales person to make the disposition and shipment decision. Bosch can increase the processing rate at each retailer by increasing the number of visits, which may require more service personnel. Similarly to improving responsiveness at the retailers, the manufacturer can also improve the processing rate of returns at the central evaluating facility μ_e. This would again involve investments in workforce for parallel processing, or investments in sorting, picking, and routing technology. To find the optimal level of responsiveness, we apply the first order condition to (8), recalling that $\mu_i, i \in \{r,e\}$ impacts W_{ce} according to (2):

$$\frac{\partial \Pi}{\partial \mu_i} = 0 \Rightarrow \frac{\left(-\left(\tilde{P}\beta - p\tilde{v}\phi\right) + (1-p)\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right)\right)}{\left(\mu_i^* - \lambda_r\right)^2} = \tilde{h}_i'[\mu_i^*], \quad i \in \{r,e\}\,, \tag{9}$$

which can be solved to find the optimal μ_r^*. Sufficient conditions for (8) to be jointly concave (such that the solution to (9) is sufficient for optimality) are that (i) $\tilde{h}_i[\mu_i]$ be a convex function (including a linear function which is a reasonable assumption as stated below), and (ii) that $(1-p)\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right) > \tilde{P}\beta - p\tilde{v}\phi$, that is, remanufacturing margins are higher than the net (negative) impact of the time lag for returns (i.e., difference between time–value of money for credit issuance and production cost lag for new returns), since

$$\partial^2\Pi / \partial\mu_i^2 = -2\lambda_r \frac{\left(-\left(\tilde{P}\beta - p\tilde{v}\phi\right) + (1-p)\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right)\right)}{(\mu_i - \lambda_r)^3} - \lambda_r\tilde{h}_i''[\mu_i]\,,$$

which is strictly negative if these two conditions are satisfied.

Now, assume a linear function for the unit handling cost as a function of the processing rate for returns, i.e., $h_i[\mu_i] = a_i\mu_i + b_i$. This linear function can be justified because return handling operations are labor intensive (Lund 1983). Then, $\tilde{h}_i[\mu_i] = \tilde{a}_i\mu_i + \tilde{b}_i$, where $\tilde{a}_i = a_i(1 - e^{-\beta T})/\beta$ and a similar expression holds for $\tilde{b}_i$. For this linear cost case, (9) yields:

$$\mu_i^* = \lambda_r + \sqrt{\frac{(1-p)\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right) - \left(\tilde{P}\beta - p\tilde{v}\phi\right)}{\tilde{a}_i}}, \quad i \in \{r,e\}\,. \tag{10}$$

We note that (10) has the solution form of a classic queuing design problem: find the optimal processing rate at an M/M/1 queue that minimizes the expected cost rate (see, e.g., Gross and Harris 1998, p. 304), with waiting cost rate $(1-p)\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right) - \left(\tilde{P}\beta - p\tilde{v}\phi\right)$ and service cost rate $\lambda_r\tilde{a}_i$. The waiting cost term can be interpreted as follows: only a fraction 1 – *p* of all returns λ_r are remanufactured and sold at a revenue of $\tilde{P}_m$ with an "interest rate" α_m; this revenue is decreased by the variable remanufacturing costs $\tilde{v}_m$, which also decrease with time (thus waiting decreases costs) at a rate ϕ_m; in addition the waiting cost rate should be decreased by the time–value of money amount corresponding to delayed credit issuance to retailers $\tilde{P}\beta$, but increased by the difference in variable cost of production for new returns. The *optimal* return processing rate at either retailer or evaluating facility is *not* influenced by transportation costs, but it is directly influenced by the remanufactured product margin—low margins result in a low level of responsiveness. Note that a higher remanufacturing price decay parameter α_m and a higher variable cost decay parameter ϕ (higher clockspeed) increase the waiting cost rate (numerator in the square root of (10)), increasing processing capacity and consequently decreasing waiting time (responsive supply chain); in agreement with Fisher's framework.

A similar analysis can be conducted for the optimal level of responsiveness in the forward distribution network, i.e., μ_i, $i \in \left\{f, s, d\right\}$, however, that requires modeling specific costs associated with a level of responsiveness at the factory (e.g., increased transportation frequency to the distributor), distributor (e.g., more frequent deliveries to retailers), and retailer (e.g., advertising, promotion, and pricing), and the focus of this paper is not on forward supply chains.

We also note that we are using a macro model approach. The facility is modeled as a single server queue, but the facility is comprised of a complex set of operations involving a large number of people. Therefore, improving the processing rate implies improving the internal operations at the facility.

5.2 Increasing Transportation Responsiveness

Transportation responsiveness in the network can be influenced by either reducing distances (e.g., co–locating facilities) or choosing different modes of transportation (e.g., air vs. ground). For example, if the firm co–locates the remanufacturing and the evaluating facilities, then τ_{em} = 0, and profits increase by $\tau_{em}(1-p)\lambda_r\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right)$, according to (8).

Regarding different transportation modes, consider that each of the unit cost parameters $\tilde{c}_{ij}$ (or c_{ij}) is a function of transportation time τ_{ij}, that is, $\tilde{c}_{ij}[\tau_{ij}]$. Finding the best transportation mode for a particular network arc is straightforward; consider, for illustration, that there are only two transportation modes, air and ground. One first computes the monetary value of a one–day delay reduction on that arc of the network (§4) and then multiplies this number by the number of days saved by going from ground to air in that link; these savings are compared against the additional transportation costs of going from ground to air considering product volume in that link.

So far, we have analyzed design issues related to the level of *responsiveness* in the network. Another design dimension to consider is *centralization*, which we analyze next.

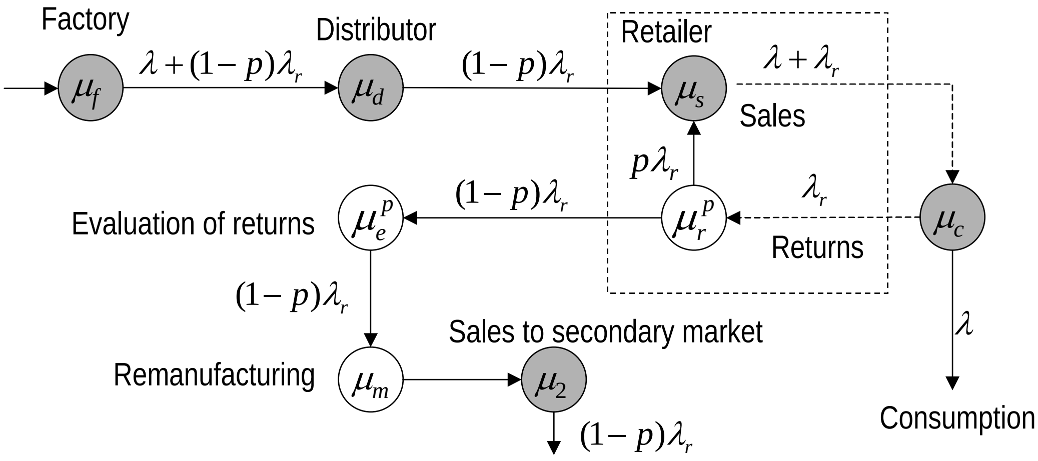
6 Preponement: Decentralized Returns Network

Figure 3 shows the processes for returns evaluation and credit issuance as *centralized*, where all commercial returns are shipped to a central facility. The benefits in economies of scale for evaluation and credit issuance are clear. An alternative design is to have *new returns* sorted and re–stocked at the retailer, which reduces transportation costs, utilization at the central evaluation facility, and consequently the delay of *other* returned products, which increases their value in the secondary market. We call this *decentralized* design concept *preponement* (or early product differentiation) in the returns stream to distinguish it from postponement (or late product differentiation); a well-known concept in forward supply chains (see Feitzinger and Lee 1997). Both HP and Bosch are considering the use of preponement.

It is reasonable that under the proposed configuration, retailers will need additional workers to handle and re–package the returns, and these additional costs will be charged to the manufacturer, otherwise the retailers have no incentives to modify their current policies. The retailer may hire and train workers to perform this task, and maintain extra packaging material at the stores, provided the proper incentive by the manufacturer. Alternately, the manufacturer could periodically send workers at the retailer's site to handle the returns, similar to Vendor Management Inventory (VMI). This alternative may prove easier to implement and control.

We evaluate the *potential* benefits of preponement using the latter alternative. The new (proposed) system is shown in Figure 4. We use a superscript p to denote, when different, parameters for this proposed (preponement) network.

Figure 4: Closed-loop supply chain with preponement: retailers handling new returns



Note: Blank and shaded nodes are modeled as M/M/1 and M/G/∞ queues, respectively

The flow rates between each pair of nodes are defined as in Figure 4, that is, $\lambda_{rs}^p = p\lambda_r$, $\lambda_{re}^p = (1-p)\lambda_r$, $\lambda_{ds}^p = \lambda + (1-p)\lambda_r$, and $\lambda_{ed}^p = 0$; other flows are defined as before.

An analysis similar to that performed in §4 provides the total expected discounted profit over the steady state period of the lifecycle:

$$
\begin{aligned}
\Pi^{p} \approx\ & \lambda\left(\tilde{P}-\tilde{v}\right)+(1-p)\lambda_{r}\left(\tilde{P}_{m}-\tilde{v}_{m}-\tilde{v}\right)-\sum_{(i,j)}\lambda_{ij}^{p}\tilde{c}_{ij}-\lambda_{r}\tilde{h}_{r}^{p}\left[\mu_{r}^{p}\right]-(1-p)\lambda_{r}\tilde{h}_{e}^{p}\left[\mu_{e}^{p}\right] \\
& -\frac{1}{\mu_{s}}p\lambda_{r}\tilde{v}\phi-W_{fs}\left\{\lambda\tilde{P}\alpha+(1-p)\lambda_{r}\left(\tilde{P}_{m}\alpha_{m}-\tilde{v}_{m}\phi_{m}\right)\right\} \\
& -W_{ce}^{p}(1-p)\lambda_{r}\left\{-\tilde{P}\beta+\left(\tilde{P}_{m}\alpha_{m}-\tilde{v}_{m}\phi_{m}\right)\right\}+\left(\frac{1}{\mu_{c}}+\frac{1}{\mu_{r}^{p}-\lambda_{r}}\right)p\lambda_{r}\left(\tilde{P}\beta-\tilde{v}\phi\right) \\
& -\left(\tau_{em}+\frac{1}{\mu_{m}-(1-p)\lambda_{r}}\right)(1-p)\lambda_{r}\left(\tilde{P}_{m}\alpha_{m}-\tilde{v}_{m}\phi_{m}\right)-\left(\tau_{m2}+\frac{1}{\mu_{2}}\right)(1-p)\lambda_{r}\tilde{P}_{m}\alpha_{m}
\end{aligned}
\tag{11}
$$

The differences between (11) and (8) regard:

(a) The lower transportation costs as a result of $p\lambda_r$ less product. This corresponds to new returns, which flow from the retailer to the evaluating facility; from the evaluating facility to the distributor, and from the distributor to the retailer.

(b) Different handling costs at the retailer and evaluating facility. As a consequence of the extra tasks, we expect higher handling costs at the retailer for the same processing capacity, or a lower processing capacity for the same handling cost. The reverse is true at the evaluating facility because less work is performed there.

(c) The lower delays for new returns $p\lambda_r$. This has two opposite effects relative to the network of Figure 3: (i) a decrease in profits because of the lower time lag for crediting new returns to the retailers, and (ii) an increase in profits because of the lower time lag between production and sale.

We do not include in (11) the incentive, if any, paid by the manufacturer to the retailer, or the extra VMI cost. Our analysis focuses on the total benefits of the proposed network. This benefit can be weighed against these extra monetary incentives or costs. Relative to the existing network of Figure 3, the only delay that is different in the proposed network of Figure 4 is the delay for the returned product between the consumer and the evaluating facility W_{ce}^{p}. This is a result of reduced flow at the evaluating facility:

$$W_{ce}^{p} = 1/\mu_c + \frac{1}{\mu_r^p - \lambda_r} + \tau_{re} + \frac{1}{\mu_e^p - (1-p)\lambda_r}. \tag{12}$$

Taking the difference (11) – (8), and defining Δ_i as the difference in waiting times at node *i* between the existing and proposed network (e.g., $\Delta_r = \left(\mu_r - \lambda_r\right)^{-1} - \left(\mu_r^p - \lambda_r\right)^{-1}$), we state, after some algebra, the monetary benefits of the proposed network:

$$\begin{aligned}
\Pi^p - \Pi = \lambda_r \Big\{ & (1-p)\left(\tilde{P}_m \alpha_m - \tilde{v}_m \phi_m\right)\left(\Delta_r + \Delta_e\right) \\
& - \tilde{P}\beta \left\{ \Delta_r + \Delta_e + p\left(\tau_{re} + \frac{1}{\mu_e^p - (1-p)\lambda_r} \right) \right\} \\
& + p\tilde{v}\phi \left(\tau_{ed} + \frac{1}{\mu_d} + \tau_{ds} + \Delta_r + \Delta_e + \tau_{re} + \frac{1}{\mu_e^p - (1-p)\lambda_r} \right) \\
& + p\left(\tilde{c}_{dr} + \tilde{c}_{re} + \tilde{c}_{ed}\right) + \\
& + \left(\tilde{h}_e[\mu_e] - (1-p)\tilde{h}_e^p[\mu_e^p]\right) + \left(\tilde{h}_r[\mu_r] - \tilde{h}_r^p[\mu_r^p]\right) \Big\}.
\end{aligned} \tag{13}$$

The terms in (13) indicate, respectively:

(i) The value savings for remanufactured products because of lower delays for reaching the secondary market in the preponement network (see below),

(ii) the decrease in profit since there is no time lag for credit issuance for new returns in the preponement network,

(iii) the savings in variable cost for new returns since they do not undergo the network loop before being sold,

(iv) the decrease in transportation cost for new returns in the preponement network, and

(v) the difference in handling cost at the retailer and evaluating facility.

The returns volume λ_r multiplies the entire right–hand side of (13), that is, λ_r is a *scaling* parameter for the benefits of preponement. Note that (13) has negative terms, so preponement is not necessarily always attractive. We develop two general propositions concerning the attractiveness of preponement.

Proposition 1: The benefits of preponement $\Pi^p - \Pi$ are increasing in ϕ if

$$\left(\tau_{ed}+\frac{1}{\mu_d}+\tau_{ds}+\Delta_r+\Delta_e+\tau_{re}+\frac{1}{\mu_e^p-(1-p)\lambda_r}\right)\geq 0\,. \tag{14}$$

The proof of Proposition 1 is immediate and omitted. Proposition 1 implies that there is a ϕ^* such that a decentralized (preponement) network design is preferred if $\phi \geq \phi^*$; else a centralized network is appropriate. Condition (14) is very weak—it only requires that the time necessary to restock a new return is lower in the preponement network—and should hold under all real–life networks. A similar result can be derived regarding the other design driver *p*:

Proposition 2: The benefits of preponement $\Pi^p-\Pi$ are increasing in *p* under (14), $\tilde{v}\phi \geq \tilde{P}\beta$, and if the remanufactured product margin savings (as a result of lower delays to reach the secondary market) are outweighed by all other preponement benefits.

Proof: Simple algebra shows that

$$\begin{aligned}\left(\Pi^p-\Pi\right)p^{-1}\lambda_r^{-1} &= \left(\tilde{v}\phi-\tilde{P}\beta\right)\left(\tau_{ed}+\tfrac{1}{\mu_d}+\tau_{ds}+\Delta_r+\Delta_e+\tau_{re}+\tfrac{1}{\mu_e^p-(1-p)\lambda_r}\right)+\tilde{P}\beta\left(\tau_{ed}+\tfrac{1}{\mu_d}+\tau_{ds}\right)\\ &\quad+\left(\tilde{c}_{dr}+\tilde{c}_{re}+\tilde{c}_{ed}+\tilde{h}_e^p[\mu_e^p]\right)-(\Delta_r+\Delta_e)(\tilde{P}_m\alpha_m-\tilde{v}_m\phi_m).\end{aligned}$$

The last term represents the remanufactured product margin savings and represents the only negative term in the partial derivative of $\Pi^p-\Pi$ with respect to *p*. This negative term is relatively small because in practice, $\Delta_r+\Delta_e$ is a small number, particularly when compared with the transportation and handling cost savings.□

Proposition 2 implies that there exists a p^* such that a decentralized network is preferred if $p \geq p^*$. The (weak) condition $\tilde{v}\phi \geq \tilde{P}\beta$ implies that the manufacturer's time–value benefits of delaying credit issuance for new returns, which are absent in the preponement scenario, are outweighed by savings in new returns variable costs; alternatively the manufacturing value decay parameter is significantly higher than the discount factor.

If we further assume the linear unit handling cost function as before $h_i^p[\mu_i^p]=a_i^p\mu_i^p+b_i^p$, then we can find the optimal processing capacities at the retailer and evaluating facility; the analysis is similar to before and the details are omitted. Then,

$$\mu_r^{p*} = \lambda_r + \sqrt{\frac{(1-p)\left(\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m\right) - \left(\tilde{P}\beta - p\tilde{v}\phi\right)}{\tilde{a}_r^p}} \text{ , and} \tag{15}$$

$$\mu_e^{p*} = (1-p)\lambda_r + \sqrt{\frac{\tilde{P}_m\alpha_m - \tilde{v}_m\phi_m - \tilde{P}\beta}{\tilde{a}_e^p}} \text{ .} \tag{16}$$

As suggested above, in (b) , we expect that $\tilde{a}_r^p \geq \tilde{a}_r$ and $\tilde{a}_e^p \leq \tilde{a}_e$. Thus, $\mu_r^{p*} \leq \mu_r^*$, since (15) only differs from (10) in the denominator inside the square-root. Comparing μ_e^{p*} and μ_e^* is not as straightforward since the lower value of $\tilde{a}_e^p$ tends to increase μ_e^{p*} relative to μ_e^*, however, the lower flow of returns $(1-p)\lambda_r$ through node *e* tends to decrease μ_e^{p*} relative to μ_e^*. For large values of *p*, it is clear that the lower flow effect dominates (16)——consider, in the limit, *p* = 1, which implies $\mu_e^{p*} = 0$—and thus, we expect for larger values of *p* that $\mu_e^{p*} \leq \mu_e^*$.

We have discussed supply chain design alternatives for reducing delays in the reverse network, such as increasing processing capacity at the retailer and evaluating facility, increasing transportation speed, and introducing preponement. All of these alternatives assume that the rate of returns is *fixed*. The firm may also take actions aimed at reducing the rate of returns. As an example, the firm may decrease the proportion of new returns through better education of sales personnel at the retailers, e.g., informing customers about common installation issues, which avoids new returns because the customer wasn't able to install the product. Another possibility is to improve product design to decrease the percentage of defective products, which is not likely to impact convenience or new returns, but will decrease λ_r, since defective products do constitute a small percentage of returns—20% in the case of HP.

In the next section, we apply our theoretical results to HP and Bosch, and perform a sensitivity analysis on the key drivers of responsiveness and preponement design alternatives.

7 Application of Model Results

In this section, we apply the theoretical results from §4 and §5 to actual data from HP and Bosch; we also provide a sensitivity analysis on the main drivers of closed–loop supply chain design using parameter values that are representative of other firms. The time unit is one day. Some of the parameter values are approximately equal to both firms, and for reasons of confidentiality, we use common representative numbers assumed fixed throughout the numerical analysis: a 25% gross margin for new products ($v[0]/P[0]$ = 0.75), a 15% price discount for the remanufactured product relative to the new product ($P_m[0]/P[0] = 0.85$), a 7.5% remanufacturing cost relative to the retail price of a new product (0.075), and a 5% yearly discount rate (β = 1.4x10^{-4}). We have also performed a sensitivity analysis on these parameters but chose to omit the results since the insights and magnitude of the values does not change appreciably.

Another commonality on the data for the two firms is that the price decay parameters for remanufactured and new products are approximately the same ($\alpha = \alpha_m$). As for the variable cost decay parameters, although different components decay at different rates, we estimate that the overall manufacturing cost of a product decays at a rate roughly equal to the final product's price decay, that is, $\alpha = \alpha_m = \phi = \phi_m$; denote by φ this common value decay parameter. Again, this assumption brings parsimony to the analysis without compromising insights or the order of magnitude for the delay values.

Thus, the main differences in parameter values for the two firms are product value, life cycle length, common value decay parameter, demand and return volumes.

7.1 Hewlett-Packard Inkjet Printers

The unit of analysis is a delivery truck full of inkjet printers, which contains an average of 250 printers. The median price of an HP inkjet printer is \$200, and thus P[0] = 250·\$200 =

\$50,000. For inkjets, T = 395 days (13 months), returns are 5% of net sales so $\lambda_r / \lambda = 0.05$, total daily returns volume averages λ_r = 6.67 trucks, p = 1/3, and the common value decay parameter is $\varphi = 1.43\text{x}10^{-3}$ (1% per week).

The value of a one–day delay reduction is different for different arcs in the network: between the evaluating facility and distributor is \$35,069; between the customer and evaluating facility is \$93,797; between the evaluating facility and remanufacturing is \$72,475; between remanufacturing and the secondary market is \$79,489. Because of the volumes involved, however, the value of a *one–day* delay reduction in the forward network, between the factory and sales, is \$2.9 million. HP is aware of this amazing number: managers indicate that lead–time reduction in the forward network is currently being pursued at the level of *hours*, not days. Opportunities for significantly reducing lead–times, however, abound in HP's reverse supply chain: sojourn time at retailers, delay between retailers and process completion at the evaluating facility, and delay between the evaluating facility and remanufacturing completion average 10, 8 and 40 days respectively. We analyze each alternative separately below.

First, consider the retailer returns processing capacity. For a more realistic analysis, it is necessary to consider multiple retailers instead of an "aggregate" single retailer. For example, consider 1,000 identical retailers; an average sojourn time of 10 days at each retailer implies $1/(\mu_r - \lambda_r / 1000)$ = 10, or a current return processing capacity of μ_r = 0.1067. Decreasing the average sojourn time by two days (and thus, saving approximately \$180,000) at the same rate of returns implies μ_r = 0.1317, or a 23% increase in returns processing capacity. Finding the *optimal* returns processing capacity (10) requires an accurate estimate of return handling costs at the retailers.[1]

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[1] We note that the conditions (i) and (ii) for optimality of (10), which are described in the paragraph after (9), are both satisfied. Condition (i) is naturally satisfied because (10) assumes linear handling costs. Condition (ii) is satisfied because $(1-p)\left(\tilde{P}_m \alpha_m - \tilde{v}_m \phi_m\right)$ = 10,866, which is always greater than $\tilde{P}\beta - p\tilde{v}\phi$; this is because $\tilde{P}\beta - p\tilde{v}\phi \le \tilde{P}\beta$ = 2,061.

Second, consider transportation to, and sojourn time at, the evaluating facility. Managers at HP believe that this delay can be cut from its current 8 days to 2 days, resulting in lifecycle savings of approximately half a million dollars. Finally, the largest opportunity lies in the long delays for shipment from the evaluating facility until completion of the remanufacturing operation; currently at 40 days. Managers at HP believe that a reasonable goal for this delay is 20 days; achieving this goal implies in lifecycle savings of $1.45 million. We note that our estimates are conservative, since we do not explicitly account for savings in working capital and the corresponding reduction in inventory holding costs. Thus, it is worthwhile for HP to design a responsive network for product returns. We do not attempt to model the benefits of preponement in this example since there was no data available from HP regarding handling costs at the evaluating facility.

Using the base numbers for HP's product value, life cycle length, and demand volume, we perform a sensitivity analysis on the time values, using parameter values for the key drivers of responsiveness and preponement: the scaling parameter λ_r, and the design drivers φ and p. We choose the range for these parameters based on representative values for products in various industries. That is, $\lambda_r \in [0, 15]$, corresponding to a returns volume between 0% and 12% of net sales; $\varphi \in [0.0001, 0.004]$, corresponding to monthly value decay rates between 0.3% and 12%; and $p \in [0, 0.75]$. The analyses assume that every unit decrease in product returns result in one more unit of net sales, that is, $\lambda + \lambda_r$ is kept constant at 140 truckloads per day.

Figure 5 shows the value of one–day delay reduction between customer and evaluating facility, and between remanufacturing and sales at the secondary market, as a function of the scaling parameter λ_r and the time–value parameter φ. Figure 5 shows that without a significant volume of commercial returns, there are no significant monetary advantages gained by designing a responsive network because the *absolute* value of time is low. Figure 6 shows the same values for one–day delay reduction, but now as a function of the design parameters φ and *p*. Note that the value of one–day delay reduction between customer and evaluating facility is relatively insensitive to *p*, but it is linearly decreasing with *p* between remanufacturing and secondary market; this result also hints (indirectly) to the value of preponement for high values of *p*, as argued in Proposition 2.

Figure 5: Sensitivity Analysis (HP): Value (\$) of One–Day Delay Reduction Between Customer and Evaluating Facility (left) and Between Remanufacturing and Sales at Secondary Market (right) as a Function of Value Decay Parameter φ and Returns Rate λ_r

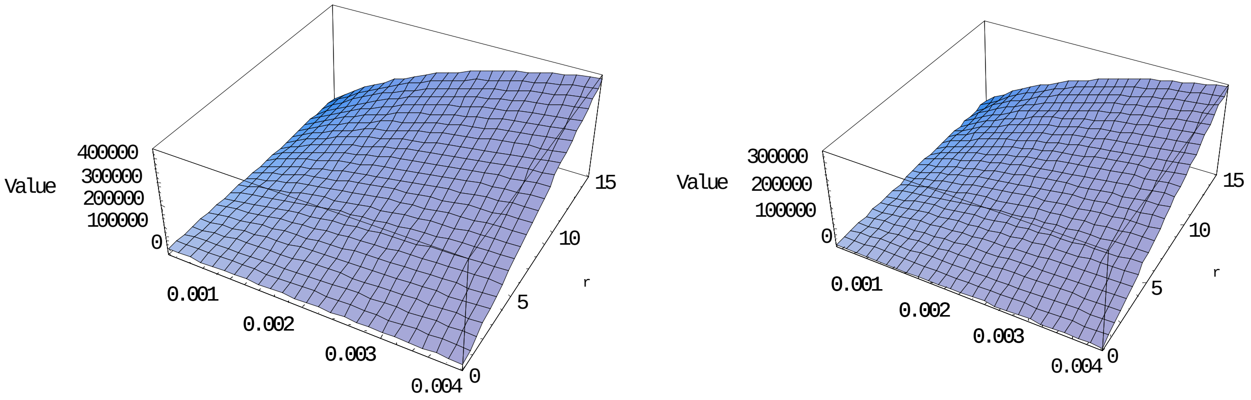
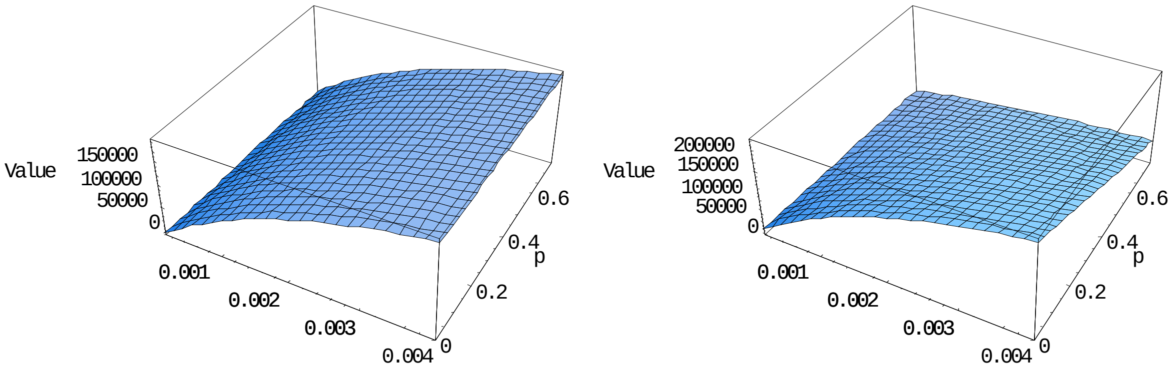


Figure 6: Sensitivity Analysis (HP): Value ($) of One–Day Delay Reduction Between Customer and Evaluating Facility (left) and Between Remanufacturing and Sales at Secondary Market (right) as a Function of Value Decay Parameter φ and p



7.2 Bosch Power Tools

The unit of analysis is a delivery truck full of consumer power tools, which contains an average of 500 tools. The average price of a Bosch power tool is $50, and thus $P[0]$ = $25,000. For power tools, T = 1,675 days (55 months), returns are 2.6% of net sales so $\lambda_r / \lambda = 0.026$, λ_r = 1.5, p = 0, and the common value decay parameter is $\varphi = 3.5\text{x}10^{-4}$ (1% per month).

The value of reducing one day between the customer and evaluating facility (which is located at the factory for new products itself) W_{ce} is $5,624. This number is small compared to HP because prices and costs are relatively stable throughout the product life cycle. The value of one-day reduction between the evaluating facility and remanufacturing $W_{cm} - W_{ce}$, and between remanufacturing and the secondary market are only $11,623 and $12,748, respectively. Considering the large volumes throughout the 1,675–day steady–state period, it is clear that Bosch needs an *efficient* reverse supply chain network to handle returns; the objective is clearly to minimize transportation costs. The sensitivity analysis for Bosch, similarly to HP's, yields the same conclusions and is omitted.

8 Conclusion

In this paper, we study commercial product returns. Many reverse supply chain networks are designed to minimize logistics costs through central product returns depots. In accordance with Fisher’s (1997) framework for forward supply chains, we show through a simple queuing network model and data from HP and Bosch, that cost–efficient reverse supply chain networks are not always appropriate. This is particularly true for *innovative* products such as inkjet printers, where there is a significant decay of product value over time. For these products, it is imperative that one considers the marginal value of time. Cost efficient reverse networks are suited for products with long life cycles and small time decay in prices.

We explicitly model the decay in value for components and finished products for both primary and secondary markets. Focusing on the reverse supply chain network, we find the optimal level of return handling capacity at the retailer and evaluating facility, as well as the impact of choosing different transportation modes with different levels of responsiveness. We also analyze the benefits of *preponement*—having returns sorted at the retailer and routed to the appropriate disposition option, a practice that decreases extra transportation and handling costs, primarily for new returns.

Using data from HP inkjet printers, we show that reducing one day in the average delay encountered by the returned product in the reverse supply chain network increases life-cycle profits by approximately $80,000. This is significant considering the opportunities for reducing delays. Data from Bosch power tools tells a different story. Consumer power tools have lower and relatively stable prices, therefore the benefit of reducing time in the reverse supply chain network is smaller. This shows the need to focus on efficiency and not responsiveness.

We regularly use our model to assist companies in redesigning appropriate supply chains for their increasing rate of commercial returns. The explicit recognition of the marginal value of time in the product returns stream leads to new managerial insights.

Process knowledge on commercial returns in industry is still immature, as reflected by a lack of frameworks, models and insights. Decision makers are confronted with the problem of incomplete data on these processes. Therefore, it would be useful to conduct empirical studies on return profiles, decay functions and other parameters.

This paper provides an innovative and flexible modeling framework to capture the key drivers in commercial returns networks. Several extensions are possible and perhaps necessary when considering other industries.

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