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Quantitative Models for Reverse Logistics Decision Making

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2.1 Reverse Logistics and Supply Chain Management

After the general structuring of reverse logistics activities outlined in the previous chapter, we now take a quantitative perspective on this field. The purpose of this chapter is to outline the state of affairs of quantitative research in reverse logistics and to explain our contribution. To this end, Section 2.1 locates reverse logistics within the broader context of supply chain management. Section 2.2 characterizes the state of reverse logistics research in comparison to general supply chain management literature and highlights the contribution of the REVLOG network. Finally, Section 2.3 explains the structure of this book and provides an outline of the individual chapters.

As discussed in the previous chapter, reverse logistics reflects a generalization of traditional supply chain concepts. Rather than being a one-way street from producers towards consumers, today's supply chains encompass several types of 'upstream' product flows during the production, distribution, and consumption phases. While these flows have not been considered in traditional supply chain definitions, they do not surpass the concept of supply chain management as such. On the contrary, the call for a holistic perspective that allows for an optimization of the overall value creation by coordinating the individual processes that contribute to it naturally extends to product returns as well. As noted in the previous chapter, this perspective on reverse logistics as an element of supply chain management is emphasized by the recent term 'closed-loop supply chains'. For a discussion of managerial topics in closed-loop supply chains, see Guide and Van Wassenhove (2003).

Recognizing reverse logistics as a part of supply chain management suggests that it should be analyzed, at least initially, by the means that have proven successful in conventional supply chain management. As discussed in Fisher's famous Harvard Business Review article, supply chain management involves a fundamental trade–off between cost and service (Fisher, 1997). A more responsive supply chain, in general, implies higher costs. A given state of technology defines a frontier of efficient solutions of this cost-service trade-off. Which point on this frontier represents the best solution for a specific supply chain depends on its market environment, in particular on the customers' willingness to pay for a higher level of service.

Once the target point on the cost-service efficient frontier is identified, managers have several levers for steering their supply chain in this direction. Chopra and Meindl (2001) group these options into four categories, namely facilities, transportation, inventories, and information. It is easy to see that reverse logistics decisions may relate to any of these levers. For example, inspection and reprocessing of returned products requires corresponding equipment and facilities; transportation decisions relate to the movement of products between the different actors in the reverse chain; inventory buffers provide a means for decoupling consecutive reverse chain processes; and enhanced information on product returns allows for a more responsive recovery strategy. The question therefore becomes how to use these different levers in reverse logistics in such a way as to support the supply chain's overall strategy in an optimal way.

2.2 Quantitative Analysis and Decision Support

In traditional supply chain management, quantitative models have long been recognized as a powerful tool to support decision making. Quantitative models have the potential to contribute to improved decision making in two ways, directly and indirectly. On the one hand, quantitative models may be embedded in software systems to automate and optimize decisions, such as automatic order generation to replenish inventory. Even more important, however, analytic models contribute to a better understanding of the interactions, dynamics, and underlying trade-offs of the various supply chain processes, and thereby enable managers consciously to take these factors into account in their decisions. The goal of our research within the REVLOG project has been to contribute to a sound basis of quantitative models that support reverse logistics decision making in a similar way.

In order to characterize today's state of affairs in this endeavor, we first take a look at the body of quantitative research in conventional supply chain management as a benchmark. We emphasize that this discussion is not meant to provide a detailed literature review, but rather a high-level mapping of

Table 2.1. Quantitative Models for Supply Chain Management – Major Themes

Strategic	*Tactical/operational*
Distribution:	
Strategic network design	Transportation
Global sourcing	Warehousing operations
Facility layout	
Inventory + Production:	
Capacity planning	Lot sizing
Inventory location	Safety stocks
+ risk pooling	Aggregate production planning
	Production scheduling
Supply Chain Scope:	
Supply chain coordination	Dynamic pricing
+ contracts	+ revenue management
Multi-channel conflicts	Value of information
Auctions	

research areas. For a more detailed discussion of many of these topics we refer to, for example, Tayur et al. (1998) and Simchi-Levi et al. (2002). See also Kopczak and Johnson (2003) for a discussion of major shifts in supply chain thinking from a managerial perspective.

Table 2.1 lists important areas in supply chain management for which a substantial body of quantitative models has been established by the scientific community. We structure these contributions along two dimensions, namely their functional area and their decision horizon. In the first dimension, we distinguish between the areas of distribution management, production planning and inventory control, and research that explicitly focuses on the inter-organizational scope of a supply chain. While it is this last area that has been the focus of recent supply chain management literature in a strict sense, the first two areas have provided important building blocks for these analyses. The second dimension of Table 2.1 refers to the usual distinction between long-term strategic decisions and shorter-term tactical and operational decisions. Let us go briefly through this list of topics.

Logistics network design and facility location are among the classical strategic *distribution* decisions, for which numerous models of different levels of complexity have been developed throughout the decades. In recent years, particular attention has been paid to the global scope of many of today's supply chains. Financial issues such as tax implications and currency risks are becoming increasingly important in this context. Whereas strategic network design relates to external product flows, facility layout addresses similar design decisions on an internal level, considering the flows within a factory or distribution center.

For shorter-term distribution-related models, we refer to transportation issues primarily. A countless variety of models has been developed, aiming to support decisions such as fleet management, route planning, zoning, or real-time vehicle scheduling. Warehousing operations again refer to internal transportation flows.

Production planning and inventory control has been another fruitful area that has seen abundant modeling contributions. On the strategic level, we name capacity planning as the foremost example. This includes decisions on manufacturing and handling equipment and on the workforce size. Other strategic models address the question of where in the supply chain to locate inventory buffers. The trade-off between risk-pooling and response time plays a key role in these approaches.

The literature on production planning and inventory control models for short- and medium-term decisions is even more extensive. On the one hand, we have countless variants of models that address the trade–offs related to different inventory functions, such as cycle stock, safety stock, and seasonal stock. On the other hand, we have an equally broad variety of production planning and scheduling models that consider the timing, sequencing, and batching of manufacturing operations on a given set of equipment.

As noted above, the focus of recent modeling efforts in supply chain management is on capturing the complexities that arise from the *interaction between different organizations* and between different functional areas. In particular, a major stream of research addresses the coordination of multiple decision makers in the supply chain, such as to achieve an overall optimal solution. Interaction between multiple distribution channels, in particular conflicts around disintermediation, also pertains to this theme.

Pricing is another important element of supply chain management that has seen significant modeling contributions during the past few years. Pricing has been recognized as a means for matching supply and demand in an optimal way. Specific topics include the ever-expanding field of revenue management, design of and strategies for auctions, but also the coordination of pricing decisions with operations.

The value of information is another theme within supply chain management that should not go unmentioned here, as it has spurred an important stream of analytic research. As information is becoming ever more easy to collect and to process, the question of which information actually contributes to improving a given set of business processes, and to which extent, is becoming increasingly more relevant.

When we started the REVLOG project in 1997, the equivalent of Table 2.1 for reverse logistics models would have been fairly sparsely populated. We summarized the state of related quantitative literature at that time in a review paper (Fleischmann, 1997). Therein we noted that '...the results published to date are rather isolated. Comprehensive approaches are rare.' While a number of individual contributions had been developed, e.g. facility

Table 2.2. Quantitative Models for Reverse Logistics – State of Affairs and REVLOG Contributions

Strategic	*Tactical/operational*
Distribution:	
Reverse logistics netw. design (4)	**Product return forecasting (3)**
Reusable packaging	**Collection and distr. routing (5)**
	Return handling (6)
Inventory + Production:	
Valuation of recoverable inventories (11)	**Lot sizing in PR* operations (7)**
	Safety stocks in PR systems (8)
Product design for reusability	**Dynamic control of PR ops. (9)**
	Production planning for PR (10)
	Remanufacturing operations
	Production planning for bulk recycling
Supply Chain Scope:	
SC coordination + contracts (12)	**Value of information (3, 16)**
Long-term perf. development (13)	**Product acquisition (3, 9)**
Environmental perf. (14, 15)	
Collaborative recycling networks	

* PR = product recovery
boldface = REVLOG contribution
(#) = chapter number

location and inventory control models with product returns, they were not part of a coherent, broader stream of research.

Since then, however, a rapidly increasing number of researchers has brought about significant advances in reverse logistics literature. Therefore, the number of entries in Table 2.2, which outlines the state of affairs to date, is substantial. We structure the topics analogous with the general supply chain management models above. In addition, we highlight in boldface the fields to which the participants of REVLOG have contributed. These are also the topics that we discuss in detail in this book (chapter numbers are listed in braces). We provide a detailed outline of the individual chapters in the next section. Before doing so, we characterize the state of affairs in quantitative reverse logistics research by comparing it to that in general supply chain management. To this end, we go through the entries of Table 2.1 again and comment on corresponding research in a reverse logistics context. In addition, we point out themes that are reverse logistics specific.

We start again with the area of *distribution* management. Network design issues in a reverse logistics context relate to the infrastructure for collecting and reprocessing returned products. A considerable number of corresponding models has been presented in the literature, most of which lean closely towards traditional facility location approaches. We review this area in Chapter 4. Chapter 5 addresses the corresponding transportation operations.

Modeling approaches to the analogous internal logistics issues, such as the impact of product returns on facility layout and internal transportation, are still scarce to date. While internal handling is consistently identified as an important factor in reverse logistics, most available studies on this topic take a qualitative perspective, as we discuss in Chapter 6.

All of the above issues naturally correspond with issues in traditional supply chains. In addition, reverse logistics brings about more particular novel tasks. These include the forecasting of product returns, which provides information that is vital for any reverse logistics operation. The relation between demand and returns is a key element of the corresponding models. Chapter 3 reviews different approaches to this issue.

Another distribution-related issue concerns the management of reusable packaging (see also the discussion under 'functional returns' in the previous chapter). The literature includes models assessing, for example, the number of reuse cycles and an appropriate pool size. While we touch upon these issues on several occasions in this book, we do not dedicate a specific chapter to them.

Product returns also have a significant impact on *inventory control*. Issues relate to the potential discrepancy between supply and demand and to the coordination of returns with other supply sources. It is this area for which the largest number of reverse logistics models has been presented in the literature to date. In particular, many classical inventory control models have been adapted to a reverse logistics setting, including lot-sizing, safety stock, and seasonal stock models. These are reviewed in detail in Chapters 7 through 9.

The impact of product returns on more strategic inventory issues, such as the coordination of inventory and location decisions, remains to be explored. On the other hand, inventory control in a reverse logistics setting gives rise to fundamental issues concerning inventory cost metrics. In particular, it is not always obvious how to assign holding costs to inventories of returned goods. We discuss this issue in more detail in Chapter 11.

The reprocessing operations (see previous chapter) also give rise to particular production planning issues in a reverse logistics context. In this book, we restrict ourselves to generic concepts, such as MRP approaches and disassembly strategies, which we discuss in Chapter 10. More specific production planning aspects that are linked to particular recovery processes, such as control of remanufacturing operations or bulk recycling processes, are beyond the scope of this book. Similarly, we leave the large field of product-design-related decisions outside our discussion.

The bottom part of Table 2.2 lists a number of issues in reverse logistics that exceed the boundaries of a single functional area. Analogous with conventional *supply chains*, the interaction between different organizations with different incentives adds to the complexity of reverse logistics systems. This concerns, for example, transactions between the collector and the reprocessor in the reverse chain and competition between original equipment manufacturers and independent reprocessors (see Chapter 1). Chapter 12 reviews recent approaches in the literature that explicitly model these interactions between multiple decision makers in the reverse chain.

As in conventional supply chains, assessing the value of different types of information is an important issue in reverse logistics. In addition to demand information, as in traditional chains, reverse chains are dependent on information on product returns, which are perceived as a highly uncertain factor in many cases. Chapters 3 and 16 discuss models that provide a starting point for analyzing value of information issues in the reverse chain.

Taking this route one step further, companies are seeking to influence their reverse product flows. In addition to improved information, these organizations are looking for appropriate incentives which allow them to balance supply (in the form of product returns) and demand in an optimal way. For this area, also denoted as 'product acquisition management', a few initial models have recently been proposed which focus on determining appropriate buy-back prices to maximize the financial contribution of reverse product streams. These are addressed in Chapters 3 and 9.

Particular supply chain issues arise from the link between reverse logistics programs and environmental management. Given that ecological benefits are among the proclaimed drivers of many reverse chains, environmental issues are particularly relevant here (see Chapter 1). In particular, the relation between economic and environmental performance of reverse logistics systems is a matter of importance. Chapters 13 through 15 present different approaches to this issue.

Comparing Tables 2.1 and 2.2 leads us to the following assessment of the current state of quantitative reverse logistics research. In the past few years, a significant number of reverse logistics models has been developed for several basic functional areas, notably in distribution management and inventory control. In these areas, many of the standard traditional models have been extended in such a way as to match reverse logistics contexts. At the same time, specific mathematical difficulties linked to the incorporation of reverse flows have been identified. The limits of what is tractable are becoming clearer. All in all, reverse logistics modeling is quickly catching up with the level of conventional supply chains in these basic areas. There are a few exceptions of functional areas for which well-established reverse logistics models are still scarce. Notably, these include the area of internal logistics.

As the basic building blocks are available, the next step to extend reverse logistics literature should be in the direction of broader, cross-functional and inter-organizational models, analogous with the concepts that have driven supply chain management for conventional 'forward' chains. To date, such approaches to reverse logistics and closed-loop supply chains remain few and far between. For the issues listed in the rightmost column of Table 2.2, the current state of the literature resembles that of the basic functional areas in

1997. While a number of important contributions have been made, the overall picture is yet to be uncovered.

Research within our REVLOG network has contributed significantly to the advances in reverse logistics literature during the past five years. On the one hand, REVLOG has brought about numerous individual models in all of the areas listed above. Even more important, however, by bringing these models together and relating them to each other and to traditional literature, we are aiming to contribute to a better understanding of reverse logistics in general. In this book we present our view on this field.

2.3 Roadmap

The goal of this book is to contribute to a better understanding of reverse logistics decision making. To this end, we highlight major issues that companies face as they engage in reverse logistics activities. The focus then is on quantitative models that capture these issues and support the decision maker. By analyzing these models, we highlight the underlying key trade-offs. Moreover, by comparing the models with approaches in conventional supply chains, we explain what is particular about reverse logistics. Presenting a state-of-the-art review of quantitative models for reverse logistics decision making, this book is meant to serve as a basis for future research in this field.

We structure the material roughly around Table 2.2. In particular, we group the contributions in three parts of four to five chapters that address distribution issues, production planning and inventory control issues, and broader supply chain issues, respectively. Each chapter is dedicated to a specific reverse logistics topic. The structuring of the material is very similar across all chapters. Each one starts by highlighting the main decision issues, in most cases based on an illustrative case example. The core of the chapter then is dedicated to a presentation and analysis of corresponding quantitative models. The focus is on material developed within REVLOG. However, each chapter refers to other material in the literature to provide a complete state-of-the-art picture.

In what follows, we outline the topic of each chapter. Table 2.3 summarizes the corresponding modeling approaches and links them to related traditional models.

Part II — Collection and Distribution Management Issues

The part of the book following these introductory chapters focuses on the physical flows arising in reverse logistics systems. We open this part in Chapter 3 with a discussion of forecasting methods for estimating product returns. The procedures discussed in this chapter provide the basis for attaining the information on product returns that is used explicitly or implicitly throughout the remainder of the book. Chapter 16 at the end of the book complements this analysis by discussing related information systems. Chapters 4 through

Table 2.3. Modeling Approaches by Chapter

Chapter	Topic	Methodology	Related traditional models
3	product return forecasting	time series analysis	demand forecasting models
4	reverse logistics network design	MILP, stochastic programming	facility location models
		continuous approximation	logistics cost models
5	collection and distribution vehicle routing	MILP, continuous approximation	vehicle routing models
6	return handling and warehousing	—	facility layout models, order-picking models
7	lot sizing in product recovery	continuous optimization, MILP	EOQ, dynamic lot-sizing models
8	stochastic inventory control in product recovery	Markov decision processes	stochastic inventory control models
		stochastic optimization	news vendor model
9	dynamic product recovery	optimal control theory	optimal control models
10	production planning for product recovery	MILP, continuous optimization	MRP, aggregate production planning
11	inventory valuation	net present value analysis	EOQ, stochastic inventory control models
12	coordination in closed-loop supply chains	game theory	supply chain contracts
13	long-term analysis of closed-loop supply chains	system dynamics	industrial dynamics models
14	environmental management	life cycle analysis	life-cycle analysis
15	economic and environmental perfomance	MILP, LP	network flow / facility location models
16	information technology	—	—

6 address traditional areas of distribution management, namely network design, vehicle routing, and internal logistics handling. Each of them extends approaches from conventional supply chains to a reverse logistics setting. On each level, the potential integration of forward and reverse flows turns out to be a key issue. Chapters 4 and 5 use very similar methodologies. Both consider traditional mixed integer linear programming (MILP) models, which can be readily extended to include reverse product flows. In addition, both chapters discuss continuous approximation methods which facilitate sensitivity analyses and reveal the impact of key parameters on system performance. Chapter 6 focuses on a structuring of the relevant issues, since corresponding quantitative models are not yet available. Specifically, the chapters of Part II proceed as follows.

Chapter 3 addresses the forecasting of product returns. It analyzes time series models that represent returns as a function of past sales, under different levels of information. Based on these models, it compares different forecasting approaches with respect to their performance in terms of robustness to errors in parameter estimates and of propagation of variability. The chapter argues that using past sales information can significantly improve return forecasts. In addition, it appears that more advanced procedures are more sensitive to inaccurate parameter estimates.

Chapter 4 is dedicated to reverse logistics network design. It discusses three alternative modeling approaches that rely on MILP, stochastic programming, and continuous approximation, respectively. Based on these models, it analyzes the robustness of logistics networks with respect to varying return flows. The chapter concludes that reverse logistics networks are, in many cases, compatible with existing forward networks.

Chapter 5 complements the preceding chapter by zooming in on vehicle routing issues. The focus is on the relation between collection and delivery. Several alternative policies are compared that rely on different levels of integration of both types of shipments. To this end, the chapter discusses both traditional MILP models and novel approaches which rely on a combination of MILP with continuous cost approximations. The analysis highlights how a higher degree of freedom in collection policies as compared to deliveries can be exploited to increase transportation efficiency.

Chapter 6 addresses the internal handling of return streams. The chapter reviews the issues that arise in this context, such as inspection and storage decisions. For most of these issues, no quantitative models are available to date that explicitly take reverse flows into account. However, existing traditional models provide a promising starting point for future modeling contributions.

Part III — Inventory Control and Production Planning
The next part of the book focuses on the coordination of product recovery processes. This leads us to inventory control and production planning issues

in reverse logistics. Particular inventory control tasks in this context concern the potential mismatch between supply and demand and the coordination of product recovery with alternative supply sources, such as conventional production. Chapters 7 through 9 provide a detailed analysis of these issues. They all consider essentially the same inventory system, which includes a single stock of end-items fed by product recovery and regular production, and potentially an additional stock of returned items prior to recovery. The chapters differ in their assumptions on the demand process and hence in the role of the resulting inventories. Chapter 7 assumes deterministic demand and considers inventories as cycle stock. Chapter 8 assumes stochastic demand and therefore also includes safety stock considerations. Chapter 9 focuses on seasonal stock by assuming non-stationary, deterministic demand. Each of these cases leads to an extension of traditional inventory control models with an exogenous reverse product flow. Moreover, it is the coordination of product recovery with the regular production source that turns out to be the main challenge throughout. All of these inventory models assume that holding cost parameters are given for the different stock points at hand. Chapter 11 reveals that it is a non-trivial task to choose these parameters such that they reflect the financial consequences of alternative decisions appropriately. The chapter applies a financial net present value approach to address this issue. Chapter 10 complements the preceding material by considering the recovery processes in more detail. Specifically, it applies traditional production planning concepts such as material requirements planning (MRP) and linear programming to the reprocessing operations in the reverse chain. Summing up, Part III is structured as follows.

Chapter 7 analyzes lot-sizing decisions in the reverse chain. It identifies two main factors that distinguish this issue from the setting of traditional supply chains, namely the choice between alternative supply sources and the choice between alternative return dispositions. The chapter illustrates how these factors can be incorporated in traditional lot-sizing models. It reveals that these extensions significantly increase the mathematical complexity since they affect some of the structure that is key to traditional solution approaches. An analysis of the extended model provides insight into the optimal coordination of production and recovery lot sizes.

Chapter 8 reviews stochastic inventory control models in a reverse logistics context. The discussion distinguishes between push- and pull-driven recovery. In the first case, the recovery process is entirely exogenous to the decision maker, whereas in the second case the timing of individual reprocessing steps is a decision variable. This distinction turns out to be a key determinant of the mathematical complexity of the corresponding models. The chapter presents a decomposition approach, which allows the incorporation of autonomous return flows in traditional inventory control in many cases. In contrast, managed return flows in general complicate the model structures to an extent that is only tractable through heuristics. In particular, lead time differences between alternative supply sources are a key complicating factor in this context.

Chapter 9 focuses on dynamic aspects of reverse supply chain flows. It addresses the question of how to manage product recovery processes given the variability of product returns along seasonal and life-cycle patterns. In particular, a key decision is when to stock product returns for future use and when to dispose of them. The chapter presents deterministic optimal control models to address the trade-offs underlying these decisions. The results reveal the value of product returns at different points in time.

Chapter 10 is dedicated to production planning issues in product recovery management. Specifically, it reviews managerial planning tasks related to disassembly operations, coordination of recovery and manufacturing operations, and rework of manufacturing defectives. The chapter argues that conventional production planning tools such as MRP systems can be effective for managing product recovery operations in many cases, provided that they are appropriately adjusted. The high uncertainty inherent in many product recovery environments complicates the matter.

Chapter 11 considers holding cost metrics for recoverable inventories. To this end, the common average cost criterion is compared with a more detailed net present value approach. The analysis reveals that, unlike in many traditional inventory control systems, both approaches are not equivalent, in general, in a product recovery setting. Therefore, the selection of appropriate holding cost rates requires additional thought. The chapter introduces a holding cost framework that is based on opportunity costs rather than on cost price.

Part IV — Supply Chain Management Issues

The last part of the book addresses reverse logistics issues in a broader supply chain setting. Chapter 12 opens this discussion by considering coordination issues between multiple decision makers in a reverse logistics environment. It applies game theoretic supply chain management concepts to analyze these issues. Chapters 13 through 15 all address long-term, strategic supply chain design issues in reverse logistics. Moreover, they all combine economic and environmental perspectives. The chapters differ in their methodologies and in the focus of their contributions. Chapter 13 takes a systems dynamics approach that allows the analysis of the migration of reverse logistics systems during product life cycles and the dynamic response to external and internal policy changes. Chapter 14 addresses the environmental impact of reverse logistics systems in considerable detail through a life-cycle analysis (LCA). Chapter 15 uses rougher, aggregate measures of environmental performance and integrates them into traditional MILP network design models. In this way, it complements the pure economic analysis of Chapter 4. Each of the three above chapters illustrates the complexity of combining economic and ecological aspects in supply chain design decisions. Chapter 16 rounds off the discussion of reverse logistics systems by reviewing corresponding information technology solutions. Complementary to Chapter 3, it presents tools that help satisfy the information needs of the various examples discussed in this book. Summing up, Part IV encompasses the following contributions.

Chapter 12 addresses coordination issues in closed-loop supply chains. These include, in particular, pricing decisions as a means for managing reverse product flows. Corresponding game theoretic models are presented that relate to the design of the reverse channel and to market segmentation between new and recovered products. Pointing out that research on the coordination of closed-loop supply chains is yet at an early stage, the chapter suggests avenues for further investigations.

Chapter 13 studies the long-term behavior of closed-loop supply chains. Specifically, it considers the dynamic development of product recovery activities over time that results from the complex interaction of numerous external and internal factors. A system dynamics approach is used to model these interrelations. The model provides a tool for evaluating long-term strategies of both companies and environmental regulators.

Chapter 14 addresses reverse logistics from an environmental management perspective. It discusses the application of LCA methods to evaluate the environmental impact of reverse supply chains. An extensive example concerning the recycling of car batteries illustrates this approach.

Chapter 15 considers the relation between economic and environmental performance in closed-loop supply chains. To this end, quantitative models are reviewed that explicitly take both of these factors into account. This allows the highlighting of the synergies and potential trade-offs between different performance criteria. In addition, the models are used in this chapter to analyze the impact of different types of environmental regulation. Examples illustrate that simplistic environmental targets can have counter-productive effects.

Chapter 16 addresses the role of information technology in closed-loop supply chains. The chapter reviews factors of uncertainty, which complicate reverse logistics decision making, and discusses how information technology can help reduce these hurdles. In addition, the chapter provides a detailed review of available information systems that support the different business processes in the reverse supply chain.