REVERSE LOGISTICS NETWORK STRUCTURES AND DESIGN

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ERIM REPORT SERIES *RESEARCH IN MANAGEMENT*	
ERIM Report Series reference number	ERS-2001-52-LIS
Publication	September 2001
Number of pages	21
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REPORT SERIES
RESEARCH IN MANAGEMENT

BIBLIOGRAPHIC DATA AND CLASSIFICATIONS

Abstract	Logistics network design is commonly recognized as a strategic supply chain issue of prime importance. The location of production facilities, storage concepts, and transportation strategies are major determinants of supply chain performance. This chapter considers logistics network design for the particular case of closed-loop supply chains. We highlight key issues that companies are facing when deciding upon the logistics implementation of a product recovery initiative. In particular, we point out differences and analogies with logistics network design for traditional 'forward' supply chains. Moreover, we discuss the strategic fit between specific supply chain contexts and logistics network structures. Conclusions are supported by a quantitative analysis.	
Library of Congress Classification (LCC)	5001-6182	Business
	5201-5982	Business Science
	HF 5761+	Delivery of goods
Journal of Economic Literature (JEL)	M	Business Administration and Business Economics
	M 11	Production Management
	R 4	Transportation Systems
	R 49	Transportation Systems: Other
European Business Schools Library Group (EBSLG)	85 A	Business General
	260 K	Logistics
	240 B	Information Systems Management
	260 K	Logistics
Gemeenschappelijke Onderwerpsontsluiting (GOO)		
Classification GOO	85.00	Bedrijfskunde, Organisatiekunde: algemeen
	85.34	Logistiek management
	85.20	Bestuurlijke informatie, informatieverzorging
	85.34	Logistiek management
Keywords GOO	Bedrijfskunde / Bedrijfseconomie	
	Bedrijfsprocessen, logistiek, management informatiesystemen	
	Distributiekanalen, Logistiek, Recycling	
Free keywords	Reverse Logistics, Distribution Management, Network Design, Facility Location, Supply Chain Management	

Reverse Logistics Network Structures and Design

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Chapter submitted to 'Business Perspectives on Closed-Loop Supply Chains', Guide, V.D.R., Jr. et. al. (eds.)

Draft : September 2001

Keywords: Reverse Logistics, Distribution Management, Network Design, Facility Location, Supply Chain Management

1. Introduction

In the preceding chapters manifold examples of closed-loop supply chains have been presented, encompassing a variety of products, actors, drivers, and business processes. One of the common elements across all of these cases concerns the need for an appropriate logistics infrastructure. Just as in traditional supply chains, the various business processes need to be embedded in a corresponding logistics network. In conventional supply chains, logistics network design is commonly recognized as a strategic issue of prime importance. The location of production facilities, storage concepts, and transportation strategies are major determinants of supply chain performance. Analogously, setting up an appropriate logistics network has a fundamental impact on the economic viability of a closed-loop supply chain. In order to successfully exploit the opportunities of recovering value from used products, companies need to design a logistics structure that facilitates the arising goods flows in an optimal way. To this end, decisions need to be taken on where to locate the various processes of the reverse supply chain and how to design the corresponding transportation links. Specifically, companies need to consider how to collect recoverable products from the former user; where to grade collected products in order to separate recoverable resources from scrap; where to reprocess collected products to make them fit for reuse; and how to distribute recovered products to future customers.

In this chapter, we take a detailed look at logistics network design for closed-loop supply chains. We highlight key issues that companies face as they decide upon the logistics implementation of a product recovery initiative. In particular, we point out differences and analogies with logistics network design for traditional 'forward' supply chains. Moreover, we discuss the strategic fit between the specific context of a closed-loop chain and the logistics network structure.

To illustrate the scope and variety of these issues we complement the business cases presented in the previous chapters by some additional examples.

- IBM's business activities involve several closed-loop chains, concerning end-of-lease product returns, buy-back offers, environmental take-back, and production scrap. The total annual volume of these flows amounts to several ten thousand metric tons worldwide. In order to recover a maximum of value from the various sorts of 'reverse' goods flows IBM considers a hierarchy of reuse options on a product, part, and material level. In this way, product recovery accounts for an annual financial benefit of several hundred US$ and at the same time reduces landfilling and incineration to less than 4% of the volume processed (see IBM, 2000).

- In The Netherlands manufacturers and importers of electric and electronic equipment are legally obliged since 1999 to take-back and recover their products after use. In response, manufacturers have set up a joint collection and recycling network managed by the branch organization NVMP. The system includes a network of regional storage centers where products that are collected via municipalities and retailers are sorted and consolidated and then shipped to some recycling subcontractors. The system is financed by a fixed recycling charge added to the sales price of the products (NVMP, 2001).
- Dupont operates several facilities for recycling nylon from used carpeting material. A large-scale plant in Tennessee (USA) processes carpet waste collected from carpet dealerships in major US metropolitan areas. Reusable content is separated from waste and is recycled for several applications, including new carpet fibers and automotive parts. In 2001 a pilot project for additional recycling operations was implemented in Ontario, Canada (Dupont, 2001).

In what follows we consider management issues arising in these and other examples as companies design and implement reverse logistics networks. The material is organized as follows. The next section links logistics network design to the framework laid out in Chapter 1. We discuss the impact of the various reverse channel functions from a network design perspective and highlight the main business decisions involved. Section 3 takes a more detailed look at different types of closed-loop supply chains and discusses specific requirements for each of them. Section 4 then presents a quantitative modeling framework for addressing the key issues identified. In particular, the impact of several context parameters on reverse logistics network design and related costs is illustrated. Finally, Section 5 summarizes our conclusions and indicates further research needs.

2. Issues in Reverse Logistics Network Design

In Chapter 1 the channel functions closing the supply chain loop have been structured in a generic set of activities, namely acquisition and collection, testing and grading, reprocessing, and redistribution. While the specific implementation of these tasks differs per example the overall scheme is reflected in all of the various cases presented in the preceding chapters. At the same time, this set of activities naturally delineates the scope of the logistics network we are considering here. Specifically, an appropriate logistics structure is sought for bridging the gap between two market interfaces, namely acquisition of used products on the one hand, and sales of reusable products and materials on the other hand. Figure 1 illustrates the typical structure of such a network (compare Fleischmann et al., 2000).

The figure suggests a subdivision of the network in two main parts. First, a convergent part accumulates used products from individual sources and conveys them to some recovery facility. Second, a divergent network part links recovery facilities to individual customers purchasing reusable products. Between these two parts the network hosts the actual transformation process of turning used products into reusable ones, in other words the test and grade and the reprocessing stages.

It is worth indicating that only the first, convergent network part is actually ‘reversed’, in the sense that it concerns goods flows from the user back to a producer, thereby reversing some previous steps of the original value chain. In contrast, the outbound network part very much resembles a traditional distribution network. Furthermore, it should be noted that a company may not necessarily be responsible for the entire network as sketched in Figure 1. Depending on the role of various channel members, the selected scope may extend across the boundaries of several parties. However, in line with supply chain management philosophy, it seems wise to consider the presented network in its entirety, in order to correctly understand the relevant issues in reverse logistics network design. As the different network stages have a significant impact on each other, considering a single one in isolation reflects a distorted picture and may entail sub-optimal decisions. In fact, one may argue that even more supply chain stages should be taken into account, namely the distribution of the original 'virgin' product, as sketched in Figure 1. We return to this point in our analysis below. In the next step, let us consider specific issues for each of the aforementioned channel functions.

Acquisition / Collection

Collection of used products potentially accounts for a significant part of the total costs of any closed-loop supply chain. Analogous with the 'last mile' issue in distribution, transportation of a large number of low volume flows tends to render collection an expensive operation. While this issue is particularly apparent for the case of acquisition from a consumer market, transportation cost for the 'first mile' may be a significant burden even for business products. In addition, it should be noted that transportation is a key factor in the overall environmental performance of any closed-loop chain. Hence, avoiding conflicts with 'green' arguments that play an important role – at least for marketing - in many product recovery initiatives, may be another reason for avoiding excessive transportation.

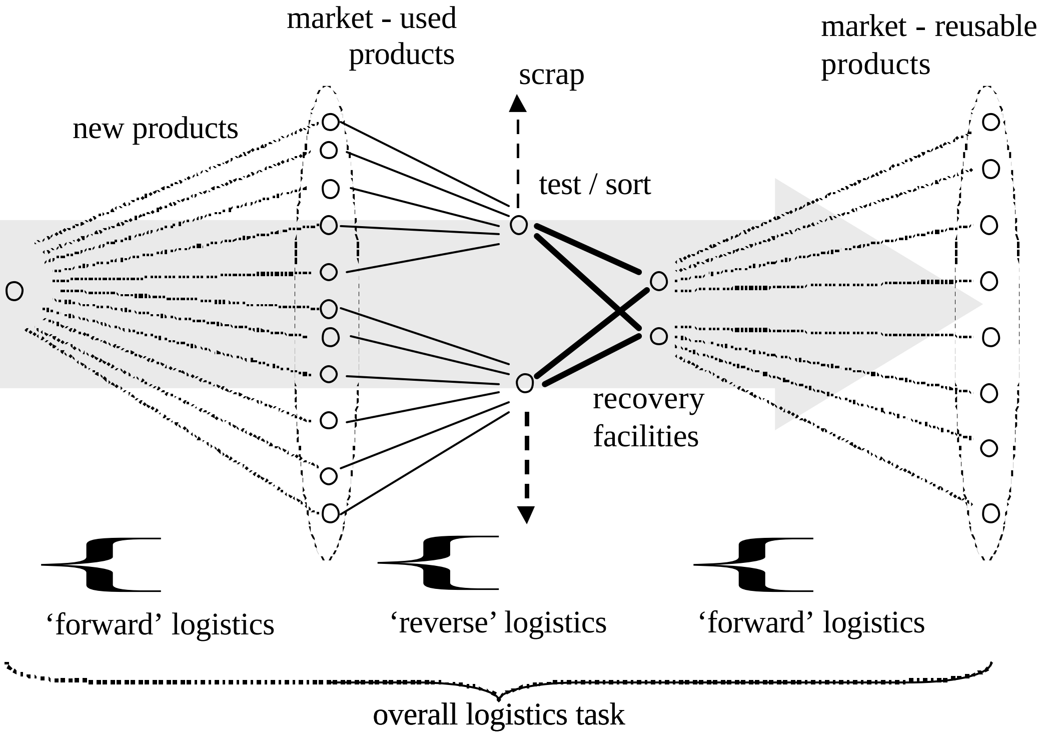

Figure 1: Reverse Logistics Network Structure

Companies have explored several options for reducing transportation costs of the 'first mile'. First of all, analogous with distribution, some of the most expensive tasks may, partly, be shifted onto the customers. Rather than actively collecting goods, a company may install some drop-points where customers can hand in used products. In this way, a first consolidation step is achieved. For example think of public glass or paper collection boxes and of consumer electronics handed in at retail outlets. While this strategy reduces transportation, additional storage space is required. Moreover, this approach may be limited to relatively small, low-value consumer products.

Another route to consolidation is in combining collection with other transportation flows. In particular, there may be synergies in combining distribution and collection. Typical examples include refillable softdrink bottles and various 'old for new' programs. This integration of 'forward' and 'reverse' goods flows is facilitated by the fact that the reverse channel may involve less time pressure. Hence, flows may be planned forward driven, with collection being added afterwards. On the other hand, efficiently integrating distribution and collection requires both flows to follow the same route, which may not always be optimal. The transportation of empty toner cartridges and reusable cameras by express mail, as discussed in previous chapters, illustrates examples where bypassing some network stages 'on the way back' appears to be a better choice. The same holds for cases where speed does matter in the return channel, such as in electronics remanufacturing, which faces quick depreciation.

Testing / Grading

The location of the test and grade operations in the network has an important impact on the arising goods flows. It is only after this stage that individual products can be assigned to an appropriate recovery option and hence to a geographical destination. Basically, we observe a tradeoff between transportation and investment costs at this stage. Testing collected products early in the channel may minimize total transportation distance since graded products can directly be sent to the corresponding recovery operation. In particular, unnecessary transportation can be avoided by separating reusable items from unrecoverable scrap. On the other hand, expensive test equipment and the need for skilled labor may be drivers for centralizing the test and grade operations.

It is worth mentioning that this centralization may be restricted by legal constraints. Transportation of waste across borders is strictly regulated in many cases, such as between different states in the USA and between countries in Europe. Often, cross-border transportation is allowed only for recoverable resources but not for waste that is to be disposed. Centralizing the test and grade operation of a large scale network results in a concentration of disposable waste in one country or state, which may be infeasible. On the other hand, recent developments in information and communication technologies may help reduce the cost of 'local' testing. By means of sensoring and online data exchange test and grade operations may increasingly be carried out in a 'remote' fashion, thereby substituting information flows for physical flows. We illustrate this trend in more detail in Section 3.

Finally, one should observe a tradeoff between the effort for testing and the aforementioned collection strategies. While shifting part of the collection function onto the customer may help minimize transportation cost, it may be difficult in this case to keep different products separated, which tends to increase testing and sorting costs. Alternatively, individual collection may offer opportunities for separating recoverable items from scrap right at the source, thereby reducing the need for sorting later in the channel.

Reprocessing

Often, the reprocessing stage requires the highest investments within the reverse logistics network. The costs for specialized remanufacturing or recycling equipment largely influences the economic viability of the entire chain. In many cases, high investment costs at the reprocessing stage call for high processing volumes to be profitable. It is worth emphasizing that the chain's throughput is dependent on both of the aforementioned market interfaces. Not only is a sufficient sales volume required for recovered products but also a sufficient supply of recoverable resources. The latter entails the need for a collection strategy that not only minimizes transportation cost but also, or even primarily, assures a sufficient acquisition volume. Recall in this context the different incentive schemes for managing product returns, as discussed in Chapters 2 and 8.

If the closed-loop chain is managed by the original equipment manufacturer (OEM) designing the reprocessing stage may involve a tradeoff between integration and dedication. In this case, partly integrating product recovery operations with the original manufacturing process may offer economies of scale. Integration may concern shared locations, workforce, or even manufacturing lines. On the other hand, variable processing costs may benefit from two separate, dedicated systems. Similarly, transportation economics may differ for 'virgin' versus 'recovered' products. Furthermore, it should not be overlooked that integration in many cases adds significantly to organizational complexity.

Redistribution

As discussed at the beginning of this section the design of the redistribution stage very much resembles a traditional distribution network. In particular, we find the conventional tradeoff between consolidation and responsiveness in transportation. What may add to managerial complexity in redistribution is again the issue of integration. For example, one may consider combining collection and redistribution in order to increase vehicle loading, as discussed above. In addition, OEMs may find opportunities for integrating redistribution with the distribution of the original product.

We condense the above discussion in three main managerial issues that distinguish the design of reverse logistics networks from traditional distribution networks, namely

- *centralization of testing and grading;*

  We have seen that the location of the test and grade operations has major consequences for the product flows in a closed-loop supply chain. What is special about this situation is the fact that product destinations can only be assigned after the test stage. In a traditional distribution environment product routings are, in principal, known beforehand. While there may be exceptions, e.g., for by-products or rework, this is not a major focus of conventional production-distribution networks.

- *uncertainty and lack of supply control;*

  It has often been claimed that reverse logistics environments are characterized by a high level of uncertainty (see e.g. Thierry et al., 1995). While in traditional supply chains demand is typically perceived as the main unknown factor, it is the supply side that significantly contributes to additional uncertainty here. Used products are a much less homogenous input resource than conventional 'virgin' raw materials in that timing, quantity, and quality may be uncertain and difficult to influence. Effectively matching demand and supply therefore is a major challenge in closed-loop supply chains. Consequently, robustness of the logistics network design with respect to variations in flow volumes and composition appears to be particularly important in this context.

- *integration of forward and reverse flows;*

  As discussed above, logistics implementation of closed-loop supply chains may offer several opportunities for exploiting synergies between different product flows. While traditional distribution networks are typically perceived as ‘one-way’ objects, closed-loop chains naturally involve multiple inbound and outbound flows of different ‘orientation’. Hence, there may be room for integration both in transportation and facilities. At the same time, these opportunities raise a compatibility issue. In many cases, reverse logistics networks are not designed ‘from scratch’ but are added on top of existing logistics structures. One may wonder whether this sequential approach allows for efficient solutions or whether an integral redesign of the entire closed-loop network offers tangible benefits.

Before addressing these issues in a quantitative analysis we discuss their relative importance in different supply chain contexts in some more detail. To this end, the next section takes a closer look at different types of reverse logistics networks.

3. Fitting Reverse Logistics Networks to the Supply Chain Context

The framework presented in Chapter 1 and the various cases discussed throughout this book demonstrate that closed-loop supply chains are far from homogenous. Different business environments result in different factors being dominant and hence in different forms of closed-loop chains. Clearly, the disparate supply chain contexts also have a major impact on the design and operation of corresponding reverse logistics networks. Therefore, we complement the general discussion developed in the previous section by a more differentiated picture.

Fleischmann et al. (2000) have distinguished three classes of reverse logistics networks based on the form of reprocessing, namely remanufacturing, recycling, and reuse-networks. We extend this classification by including two additional context variables, namely the driver for product recovery (economics versus legislation) and the owner of the recovery process (OEM versus third party). In what follows we consider reverse logistics networks for different combinations of these variables and put the issues discussed in the previous section into perspective. It should be noted that the three proposed dimensions are not independent. In particular, we do not have evidence for all possible combinations. Table 1 summarizes the cases considered in the sequel.

Table 1 : Supply chain context of reverse logistics networks

	Economically-driven			*Legislation-driven*		
	Reuse	*Remanufacturing*	*Recycling*	*Reuse*	*Remanufacturing*	*Recycling*
OEM	3.5	3.2	3.4	-	-	(3.1)
3rd Party	(3.5)	3.3	(3.4)	-	-	3.1

3.1. Networks for Mandated Product Take-Back

A first important group of reverse logistics networks concerns supply chains established in response to environmental product take-back legislation. For a typical example recall the national electronics recycling network in the Netherlands from Section 1. Similar systems have been implemented or are underway in Scandinavia and in several countries in Asia, and are discussed on a European scale. Furthermore, consider the well-known German 'green dot' system for packaging recycling (Duales System, 2001). Scrap cars form another important product group targeted by legislation. In all of these cases OEMs are held responsible for keeping their (mostly consumer-) products out of the waste stream at the end of the lifecycle. As the opportunities for recapturing value from end-of-life products are small in most of these cases, we see companies opting for a fairly conservative approach, focusing on cost minimization. Material recycling is the typical form of recovery. Costs are charged to the customers either directly or via the price of new products.

While OEMs are legally and financially responsible for product take-back and recovery, the execution is typically outsourced to logistics service providers and specialized recycling companies. Moreover, in many cases we see systems established in industry-wide co-operation. The corresponding reverse logistics network design very much focuses on low-cost collection. Typically, we find solutions involving drop-locations, possibly in co-operation with municipal waste collection, where customers can hand in their products, which are then stored and shipped for further processing once a certain volume has accumulated. In contrast, the test and grade operation does not appear to play a prominent role in these systems. Products may be roughly sorted by product category at the collection side, partly for administrative reasons. Further separation of material fractions occurs during the recycling process.

3.2. OEM Networks for Value Added Recovery

Another important class of reverse logistics networks concerns closed-loop supply chains managed by OEMs with the goal of recapturing value added from used products. The case of IBM sketched in the introduction to this chapter is one of the typical examples. Other cases have been discussed in the previous chapters, e.g. copier and automotive parts remanufacturing.

Typically, OEM-managed closed-loop chains encompass multiple sorts of used product flows, from different sources and with different motivations, such as end-of-lease returns, 'old-for-new' buy-backs, and take-back as an element of customer service. However, the focus in all of these cases tends to be on the business market, due to higher product values and closer customer relations, which facilitate product monitoring during the entire lifecycle. At the same time, OEM-managed systems often include a scale of alternative, quality-dependent recovery options on a product, component, and material level.

In view of these heterogeneous product flows the test and grade operations play an important role, in order to maximize the value recovered. Currently, we see a tendency towards a centralized test operation in many cases. Analogous with the development of supra-national distribution structures in the past decade, economies of scale appear to largely outweigh transportation costs. Rather than cost considerations, it may be legal constraints to cross-boarder transportation that form a barrier to further geographical concentration of return flow management (see Section 2). As discussed in the previous section, advances in IT may be a factor that reverses the balance in this cost tradeoff. For example, electronic sensors already allow copiers to be closely monitored during the entire lifecycle. Extensive data collected in this way may support the assignment of returned machines to appropriate recovery options without detailed physical inspection. In addition, remote monitoring may even provide a basis for a proactive take-back policy instead of purely reactive recovery decisions. Similar technological developments can easily be imagined for other product categories.

Finally, it should be noted that coordination issues are particularly important in these OEM-managed networks. As indicated in the previous section, not only inbound and outbound flows of used products need to be coordinated but also recovery and original manufacturing, which may partly substitute each other. Hence, reverse logistics networks typically need to be embedded in a larger overall solution. While this close interrelation may allow for exploiting synergies it also adds to the complexity of logistics decision making.

3.3. Dedicated Remanufacturing Networks

In addition to OEM-managed product recovery programs, specialized remanufacturing companies have been around for a long while. Recall, for example, the case of ReCellular discussed in detail in Chapter 1. Automotive remanufacturers, industrial equipment remanufacturers, and tire retreaders are some of the numerous other examples (Guide 2000). Comparing these types of closed-loop chains with the OEM-systems sketched above we observe a much more prominent trading and brokerage function. The business is strongly opportunity driven, seeking an optimal match of supply and demand.

The brokerage character of dedicated remanufacturing chains is also reflected in the corresponding logistics networks. Rather than adding some collection infrastructure to an existing logistics network, remanufacturing companies need to design an integral network spanning all the way from supply to demand. In particular, the location of the actual remanufacturing site naturally relies on both the supply sources and customer locations. Furthermore, it is worth emphasizing that profit maximization rather than cost minimization is the dominant decision criterion.

At the same time, the fact that specialized remanufacturers cannot rely on established relations in the original ‘virgin’ product business makes acquisition a key activity in these cases. Careful management of the supply side is vital to ensure availability of the right recoverable products (see also Chapter 8). In order to optimally support this task, the corresponding inbound network requires a high degree of flexibility and responsiveness. In the same vein, the test and grade operation plays an important role. As remanufacturers, in general, have little means to monitor products during the initial part of the lifecycle the state of an incoming product is only known after inspection. Consequently, location of this operation is an important element of the logistics network design.

3.4. Recycling Networks for Material Recovery

Systems driven by the recovery of material value through recycling form another class of closed-loop supply chains with distinctive characteristics. For a typical example we refer to the case of carpeting recycling by DuPont outlined in the introduction. Above all, material recycling chains are characterized by fairly low profit margins: in view of low raw material prices opportunities for cost advantages through recycling are rather limited. Therefore, it is not surprising that the number of successful recycling chains based on purely economic drivers – as opposed to the legislation-driven chains addressed in Section 3.1 – is rather small.

Another important characteristic of commercial recycling chains concerns the need for high investments for specialized recycling installations and equipment. The combination of high investment costs and low margins obviously calls for high processing volumes. Aggressively exploiting economies of scale is indispensable for achieving economic viability in this context. This reasoning is directly reflected in the structure of the corresponding logistics networks. Typically, one observes a highly centralized network relying on one, large-scale recycling facility.

As indicated in Section 3.1, testing and grading in a strict sense appear not to be very relevant for material recycling. Instead, we often find some pre-processing operation to enhance transportation efficiency. Shredding and combustion may substantially reduce transportation costs for the bulk of collected used products. Benefits are the more significant in view of the large distances implied by the centralized network structure.

3.5. Networks for Refillable Containers

We conclude this section by looking at the class of closed-loop supply chains that has been presented in Chapter 1 under the header of ‘refillable containers’. Many examples of this class concern reusable packaging, such as refillable beer or softdrink bottles, crates, pallets, and reusable boxes. However, recall from Chapter 1 that ‘containers’ may also take more sophisticated forms, such as reusable cameras (serving as ‘packaging’ of the film) or toner cartridges.

All of these examples have in common that the various ‘containers’ may be reused almost instantaneously. The reprocessing stage of the corresponding supply chains is typically limited to cleaning and possibly some minor repair or replacement operations. Similarly, the main function of the test and grade stage is to filter out damaged or obsolete containers. In view of this ease of reusability a company’s pool of containers may be characterized as an asset rather than a set of consumables. Determining an appropriate pool-size is one of the main issues in this context.

In this light, assuring availability becomes the main task of the corresponding logistics networks. In the first place, this concerns the collection strategy, which ought to minimize leakage from the system due to limited customer responsiveness, damage, or acquisition by competitors. Several instruments have been used to keep the supply chain closed, including deposit schemes, rebates, or direct old-for-new exchange. In addition, availability is also influenced by the routing of the empty containers. In view of the close correspondence between inbound and outbound flows in this case, companies often use the same network structure in both directions. In addition to limiting transportation cost this strategy facilitates organization and planning. Typically, management may concentrate on ‘forward’ flows, while taking returns into account via some simple cost surcharge. Yet in some cases considering returns more explicitly may be beneficial, as illustrated in the aforementioned example of reusable cameras. By bypassing some stages of the ‘forward’ distribution network the throughput-time of the reverse flows, and hence the pipeline inventory, may be reduced, which eventually allows for a smaller pool size.

4. Quantitative Models for Reverse Logistics Network Design

Having highlighted the distinctive characteristics of Reverse Logistics networks we now address some of the main issues in a quantitative analysis. We start by taking a look at related literature in Section 4.1. It turns out that most of the currently available models rely on mixed-integer linear programming (MILP). While this approach allows for large-scale mathematical optimization, deriving general insights as to the impact of various parameters is difficult.

Table 2 : Reverse Logistics Network Design Models in Literature

		Spengler et al. (1997)	Fleischmann et al. (2001)	Jayaraman et al. (1999)	Barros et al. (1998)	Kroon and Vrijens (1995)
application	case	steel by-products recycling	electronics remanufacturing / paper recycling	cellphone remanufacturing	sand recycling	reusable packaging
	supply chain context (Section 3)	3.1	3.2 / 3.4	3.3	3.4	3.5
model	*# network levels (of which free)*	N+2 (N)	5(3)	3 (1)	4 (2)	3 (1)
	# dispositions	N	2	1	3	1
	dispositioning	upper bounds	upper bounds	-	fixed fraction	-
	# inbound commodities	N	1	N	1	1
	# periods	1	1	1	1	1

Therefore, we pursue another road and follow the so-called ‘continuous approximation’ methodology (Daganzo, 1999). In Section 4.2 we use this approach to develop a cost model for reverse logistics network design. Analyzing this model we highlight the impact of several context variables in Section 4.3 and derive tentative answers to the issues formulated in Section 2.

4.1. Reverse Logistics Network Design Models in Literature

Logistics network design is one of the areas within the field of reverse logistics for which evidence is available from a relatively wide collection of case studies. In the past few years a considerable number of detailed business cases on this issue has been presented in literature (see Fleischmann et al., 2000). In several of these studies dedicated optimization models have been developed that rely on extensions and modifications of traditional facility location models. Table 2 summarizes examples for the different supply chain contexts distinguished in Section 3. In addition to the specific applications some major modeling elements are listed. We briefly consider each of these cases below before commenting on general lessons learned. For a more comprehensive literature review and discussion of mathematical details we refer to Fleischmann (2001).

Spengler et al. (1997) have examined recycling networks for industrial by-products in the German steel industry. Steel production gives rise to a substantial volume of residuals that have to be recycled in order to comply with environmental regulation and to reduce disposal costs. For this purpose, different processing technologies are available. The authors analyze which recycling processes or process chains to install at which locations at which capacity level in order to minimize overall costs. To this end, they propose a modified MILP warehouse location model. The model formulation allows for an arbitrary number of network levels, corresponding to individual processing steps, and an arbitrary number of end products, linked to alternative processing options. Analyzing multiple scenarios the authors emphasize the need for industry-wide co-operation to achieve sufficient capacity utilizations. Moreover, they conclude that recycling targets and disposal bans may entail severe investment burdens for the industry and should therefore be handled with care.

Fleischmann et al. (2001) focus on the consequences for OEMs of adding product recovery operations to an existing production-distribution network. A fairly general MILP facility location model is presented that corresponds with the network structure in Figure 1 and encompasses both 'forward' and 'reverse' product flows. Based on a numerical study the authors conclude that the overall network structure is fairly robust with respect to variations in the recovery volume and that reverse logistics networks can efficiently be integrated in existing logistics structures in many cases. This situation is illustrated for the example of OEM copier remanufacturing. A second numerical example, referring to the pulp and paper industry shows that one must be careful, though, if 'virgin' and recovered products rely on fundamentally different cost drivers. In that example an increasing recycling volume literally pulls the network away from distant raw material sources closer to the users. We reconsider these findings in Section 4.2 below.

Jayaraman et al. (1999) have analyzed the logistics network of an electronic equipment remanufacturing company in the USA. The activities considered include core collection, remanufacturing, and distribution of remanufactured products, where delivery and demand customers do not necessarily coincide. In this setting, the optimal number and locations of remanufacturing facilities and the number of cores collected are sought, considering investment, transportation, processing, and storage costs. The authors show that this network design problem can be modeled as a standard multi-product capacitated warehouse location MILP. In this formulation, limited core supply acts as a capacity restriction to the overall level of operation. The authors highlight that managing this 'capacity', which is crucial for the system's performance, requires different approaches than in a traditional production-distribution network. Rather than considering technical capacity extension options, appropriate marketing instruments are needed to assure a sufficient core supply.

Barros et al. (1998) provide an example of a material recycling network, namely sand recycling from construction waste. In view of a substantial annual volume of sand landfilled on the one hand and the need for sand in large infrastructure projects, such as road construction on the other hand a consortium of waste processing companies in The Netherlands is investigating opportunities for a nation-wide sand recycling network. Pollution is a major issue in this context. This means that sand needs to be analyzed and possibly cleaned before being reused. Cleaning of polluted sand requires the installation of fairly expensive treatment facilities. In addition, regional depots need to be set up for inspection and storage. The authors develop a tailored multi--level capacitated facility location model for this network design problem. In their analysis they emphasize the need for a robust network structure since both supply and demand involve significant uncertainties. Therefore, multiple scenarios are evaluated, of which the solution with the best worst-case behavior is selected. Listes and Dekker (2001) revisit this case and explicitly take the uncertainty issue into account in their modeling approach. They propose a multi-stage stochastic programming model where location decisions need to be taken on the basis of imperfect information on supply and demand while subsequent processing and transportation decisions are based on the actual volumes. The model maximizes the expected performance for a set of scenarios with given probabilities. The authors emphasize that the solution needs not to be optimal for any individual scenario and hence that this approach is more powerful than simple scenario analyses. We return to this point below.

To round up this set of examples from literature we mention a study on reusable packaging (Kroon and Vrijens, 1995). More specifically, this case concerns the design of a closed-loop deposit based system for collapsible plastic containers that can be rented as secondary packaging material. The system involves multiple actors, including a central agency who owns a pool of reusable containers and a logistics service provider who is responsible for storing, delivering, and collecting the empty containers. For the latter operations a set of depots needs to be located. The authors document how this issue may be addressed by means of a standard warehouse location model. In addition, they emphasize that the overall network design problem is characterized by the interaction between the various parties involved and their respective roles. Depot location, pool size, and payment structures all have an important impact on the system's performance as a whole and its competitiveness with respect to traditional 'one-way' packaging.

Considering the overall state of the literature on reverse logistics network design, as illustrated by the above examples, one observes close analogies with conventional production-distribution networks. From a mathematical perspective the models that have been proposed in a reverse logistics context differ fairly little from traditional MILP facility location models. Some special features reflect the particular role of testing and grading and alternative market conditions on the demand and supply side. One aspect that is worth considering concerns the issue of supply uncertainty. In line with the discussion in Section 2 many authors name this issue as one of the distinguishing characteristics of a reverse logistics environment. At first glance it may therefore be surprising that few models explicitly incorporate uncertainty other than by means of scenario analyses. Besides the aforementioned stochastic programming model (Listes and Dekker, 2001) one of the few exceptions concerns a robust network design model for carpet recycling (Newton et al., 1999). However, while these approaches may, indeed, result in different network structures than a simple scenario analysis the corresponding cost advantages turn out to be fairly limited in many cases. Therefore, it may be debatable whether the significant additional computational effort of stochastic or robust programming pays off in this context.

What may be more important is an analysis of long-term market developments. Almost all of the reverse logistics network design models to date take a stationary, single-period perspective. However, closed-loop supply chains are yet in an emerging state where we see companies gradually extending their operations from moderate pilots to full scale business processes. To support this strategic transition multi-period network design models may be helpful. Realff et al. (1999) provide a first step in this direction.

As a general observation we note that the above type of location models have some drawbacks when it comes to establishing general insights. Sensitivity analyses in MILP models have rather severe limitations and the interrelation between various parameters is not made explicit. Consequently, conclusions often rely on extensive numerical experiments rather than on analytic arguments. In the sequel we therefore explore a different road and complement preceding studies by a continuous cost model for reverse logistics network design.

4.2. A Continuous Network Design Model

In order to investigate logistics costs and to optimize the design of corresponding logistics systems Daganzo (1999) introduced what has become known as the 'continuous approximation methodology'. A key element of this approach is the modeling of demand as a continuous geographic density function, as opposed to the discrete demand locations assumed by traditional MILP approaches (see Section 4.1). Assuming the demand density and other system parameters to be slowly varying across the given service region, logistics costs can be approximated by geographical averages, which result in fairly simple expressions in a limited number of parameters. In this way, the cost impact of critical system parameters can be revealed and guidelines for setting up appropriate logistics structures can be derived.

We apply this approach to the analysis of reverse logistics systems. To this end, let us return to the general setup presented in Figure 1. Specifically, we start by considering the reverse logistics network in a strict sense, i.e. the logistics structure conveying used products from a collection point to some given recovery facilities. In line with the discussion in Section 2 assume that used products are collected via some collection tours and that collected products need to be tested and sorted, after which a certain unreusable portion is scrapped while the remainder is shipped to a recovery facility to be redistributed eventually.

Following the ‘continuous approximation’ approach assume that the collection volume per time is given by a location-dependent continuous density function, denoted by $r(x)$, which is slowly varying in x within some overall service area A. Our goal is to approximate the total logistics costs for serving A, and eventually to minimize these costs by choosing an appropriate reverse logistics network design. To this end, it is useful to consider the costs per unit collected. The idea of the ‘continuous approximation’ approach is to express these costs in ‘local’ problem parameters only and then to approximate the overall costs by integrating over the service area. In this light, let $C_R(r,r)$ denote the reverse logistics costs per unit for an (imaginary) subarea with constant collection density r at a distance r from the corresponding recovery facility. To assess $C_R(.)$ it is useful to distinguish two cases, depending on whether the testing and sorting is carried out at the recovery facility or at some distinct location. In what follows we refer to them as ‘central’ and ‘local’ testing, respectively and denote the corresponding unit cost functions by $CR_1(.)$ and $CR_2(.)$. For both cases one may consider a number of cost components, namely inbound transportation costs to the test and sort process, outbound transportation costs after sorting, variable sorting and handling costs, and fixed installation costs for the test facility. Let us look at each of these components in some more detail.

The inbound transportation costs to the test and sort process concern the collection tours within the corresponding service area. These can be approximated based on a probabilistic analysis of the standard vehicle routing problem by the sum of a line-haul distance from and to the test and sort installation and the distance between two consecutive collection stops (see e.g. Daganzo 1999). Specifically, in the case of central testing we get

$$\text{unit inbound transportation cost} \approx 2\frac{c_d}{v}r + 0.57 \cdot c_d \; r^{-1/2}, \tag{1}$$

where c_d denotes the transportation cost per distance and v the capacity of the collection vehicles. In the case of local testing and sorting the line-haul distance depends on the surface I_R of the area covered by the test facility:

$$\text{unit inbound transportation cost} \approx \frac{4}{3\sqrt{p}}\frac{c_d}{v}\sqrt{I_R} + 0.57 \cdot c_d \; r^{-1/2}. \tag{1'}$$

In the case of central testing the only relevant outbound costs concern scrapping of rejected products, which are of the form $c_s\gamma$, where γ denotes the disposal fraction and c_s the unit scrap costs. For local testing one also needs to consider the flow of accepted products to a recovery facility. Assuming those shipments to be carried out as line-hauls rather than in tours we can express the corresponding costs in the form

$$\text{unit outbound transportation cost} \approx 2\frac{\tilde{c}_d}{\tilde{v}} \; r(1-g) + c_s g \;, \tag{2}$$

where $\tilde{c}_d$ and $\tilde{v}$ are the appropriate transportation cost and vehicle capacity analogous with (1'). Finally, an (annualized) fixed cost c_f for a local test and sort installation can be expressed on a per product basis as

$$\text{fixed installation cost per product} \approx \frac{c_f}{I_R\, r} \tag{3}$$

and any variable handling and processing costs can be aggregated into a term c_h. Summing up, one obtains the following expression for the unit reverse logistics costs in the case of central testing and sorting

$$C_{R1}(r,r) \;=\; 2\frac{c_d}{v}r \;+\; 0.57\cdot c_d\; r^{-1/2} + c_s g + c_h\,. \tag{4}$$

For the 'local testing' case, one can estimate the optimal size of the service area I_R from (2) and (3). First order conditions yield

$$I_R^* \;=\; \left(\frac{3\sqrt{p}\cdot c_f\; v}{2\cdot c_d\, r}\right)^{2/3} \;\approx\; 1.92\left(\frac{c_f\; v}{c_d\; r}\right)^{2/3}. \tag{5}$$

Inserting this expression for I_R and summing up the different cost components then leads to the following cost function

$$C_{R2}(r,r) = 2\frac{\tilde{c}_d r}{\tilde{v}}(1\text{-}g) + c_s g + 0.57\cdot c_d\, r^{-1/2} + c_h + 1.56\left(\frac{c_d^2\, c_f}{v^2 r}\right)^{1/3}. \tag{6}$$

By comparing $C_{R1}(r,\rho)$ and $C_{R2}(r,\rho)$ one can now derive an appropriate service area for the central test and sort operation. Specifically, (4) and (6) define a critical distance r_R^* from the recovery facility up to which central testing is preferable over local testing. Equating the cost functions yields

$$r_R^* \;=0.78\left(\frac{c_f v}{c_d\, r}\right)^{1/3}\left(1-\frac{\tilde{c}_d}{\tilde{v}}\frac{v}{c_d}(1-g)\right)^{-1}. \tag{7}$$

From the above analysis one finally obtains the overall reverse logistics unit cost function $C_R(.)$ which can be written as $C_R(r,\rho) = \min\{C_{R1}(r,\rho), C_{R2}(r,\rho)\}$ and the total reverse logistics cost which, as discussed above, is approximated by $\int_A r\; C_R(r,r)dx$.

Analogously, one can derive cost expressions for the 'forward' parts of logistics networks (see Figure 1). Assuming that items are shipped via some distribution center one obtains the same formulas as above, where ρ is replaced by an appropriate demand density δ and γ equals zero. In fact, in this way one obtains the original formulas discussed by Daganzo (1999). Let us denote the 'forward' logistics costs by $C_F(.)$ in what follows.

In the next section we exploit the above cost expressions for analyzing in more detail the reverse logistics issues highlighted in Section 2. Before doing so, however, some remarks may be in order. First of all, it should be clear that the above discussion provides a very basic cost model which can be extended in manifold ways. In particular, we have not included any inventory considerations and we have assumed all vehicles to operate at full capacity. While it is easy to relax these assumptions and to include additional aspects such as lotsizing and dispatching frequencies these refinements do not change the core of our argumentation and are therefore omitted for sake of simplicity. The reader is referred to Daganzo (1999) for more

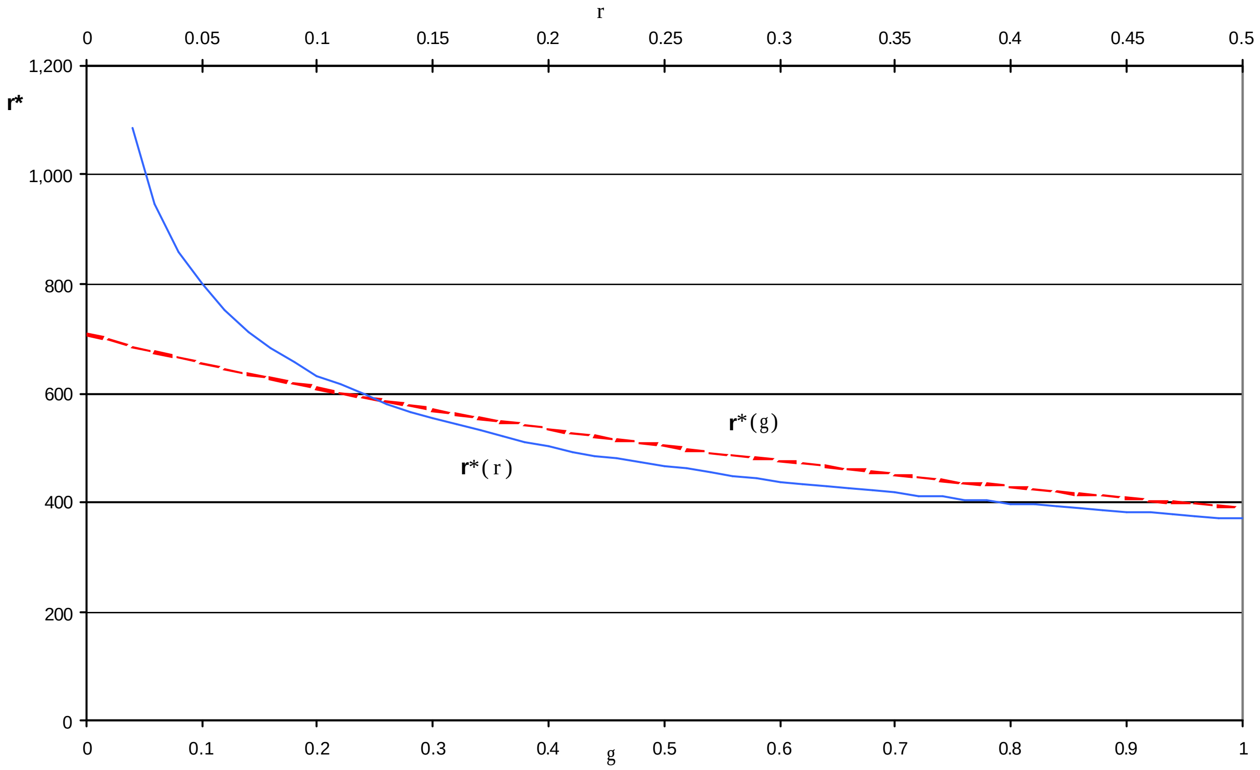

Figure 2 : Dependence of Optimal Service Area on Collection Density and Scrap Rate

detailed modeling using the 'continuous approximation' technique. Second, we have assumed collection and disposal volumes to be given and therefore have not included any revenues in the analysis. However, it should be noted that the above cost expressions can also be used to assess profitability of a recovery operation. In particular, the tradeoff between reverse logistics costs and production cost savings or additional revenues can be made explicit. Finally, it is worth mentioning that the above cost model is very much a continuous analogue to the MILP model presented in Fleischmann et al. (2001). More specifically, the expression $\int_A [r\, C_R^*(r, r) + d\, C_F^*(r, d)]dx$ provides a continuous approximation of the cost function of the latter. In this light, we revisit the conclusions of that paper in the next section.

4.3. Analysis of Reverse Logistics Network Design Issues

In Section 2 three major issues in reverse logistics network design have been highlighted, namely the degree of centralization of the test and grade operation, supply uncertainty, and integration of 'forward' and reverse logistics. Let us look at how the cost expressions formulated in the previous section can help in analyzing these issues.

The centralization issue is reflected in the above model in the size of the service areas of the different test locations, which again is captured in the parameters r^* and I_R^*. Expressions (7) and (5) show the impact of the various context parameters on these two design variables. Not surprisingly, the range of central testing r^* depends on the tradeoffs between fixed installation costs and variable collection costs and between short and long distance transportation costs. In fact, these are the usual tradeoffs concerning the use of transshipment points in distribution.

Table 3: Parameter Settings

parameter	value
$\tilde{c}_d$	0.9
c_d	0.4
$\tilde{v}$	100.0
v	20.0
r	500.0
c_f	500000.0
c_h	3.0
δ	0.4
ρ	0.2
γ	0.5

What may be more interesting is the impact of the parameters ρ and γ that characterize the supply of used products. Their influence on the optimal distance for switching from central to local testing is depicted in Figure 2. Table 3 lists the parameter settings for this example, which are used throughout this section unless stated otherwise.

As expected, the critical distance *r** from the recovery facility is decreasing in the supply density ρ. The more products need to be shipped the sooner an investment in local test installations separating scrap from valuable resources and consolidating transportation volumes pays off. Moreover, it should be noted that the impact of ρ is quickly decreasing. Unless supply volumes are very low the boundary between central and local testing shifts fairly little. This is an important observation for understanding the impact of supply uncertainty, which is addressed in more detail below. In addition, it should be noted that this relation again is analogous with what we know from conventional 'forward' distribution. Furthermore, Figure 2 illustrates *r** to be decreasing in γ, in other words a higher scrap rate calls for a more decentralized network design, which is in line with intuition. Equation (7) shows that the importance of this shift towards decentralization depends on the relation between long and short distance transportation costs. If both cost rates differ a lot the need for consolidation requires a decentralized network structure, independent of γ. Only if both shipment rates (per product) are fairly close the scrap rate becomes a more crucial factor, which acts, in fact, as a reduction of the long distance transportation costs.

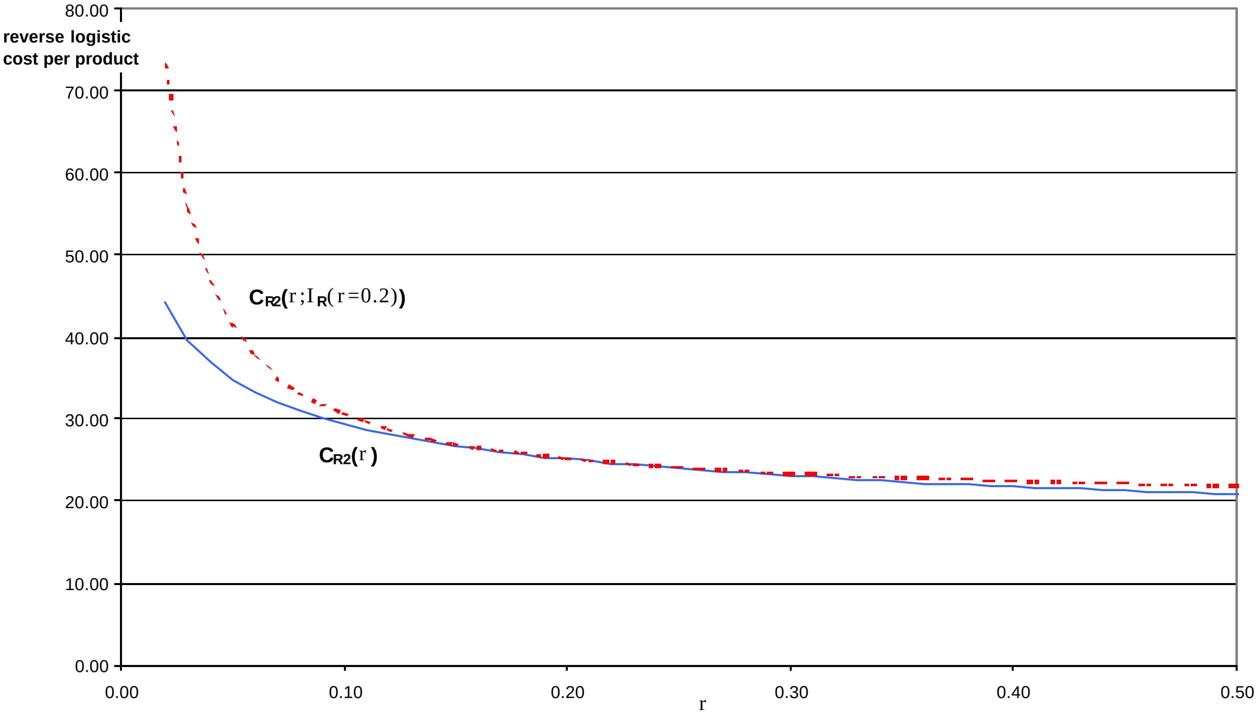

Figure 3 : Dependence of Reverse Logistic Costs on Collection Density

The surface of the area covered by a local test installation I_R* is another facet of the centralization issue. Equation (5) documents that the optimal size of this service area depends on ρ in much the same way as the area for central testing. (Note that I_R* denotes a surface area whereas r* is expressed as a distance, which explains the difference by a power of two.) In contrast, I_R* does not depend on γ at all, which may be surprising at first sight. This can be explained, however, from the fact that the average line-haul distance to the recovery facility is fairly independent of the size of the individual collection areas.

Having analyzed these relations we can now take a closer look at the consequences of supply uncertainty which is another important characteristic of reverse logistics networks, as discussed in Section 2. In the above model the supply characteristics are expressed in terms of the parameters ρ reflecting the supply volume, and γ capturing supply quality. In this setting, supply uncertainty thus concerns variations in both of these parameters. Their impact on the network design has been highlighted above. Let us now look at the corresponding cost effects. To this end, Figure 3 illustrates the reverse logistics costs per unit as a function of the supply density. Specifically, the solid graph depicts $C_{R2}(\rho)$, i.e. the unit cost function in case of local testing (see Equation (6)). As expected, one observes economies of scale since more concentrated supply allows for more efficient transportation and processing. In order to illustrate the impact of uncertainty in the supply volume the dashed graph in Figure 3 displays the corresponding costs for a fixed network structure with $I_R = I_R^*(\rho=0.2)$. The figure clearly shows that the cost penalty for deviating from the optimal network design is very small in this example. We only find a significant difference between both cost functions in case of very low supply volumes.

This observation can be generalized as follows. From (1') and (3) we see that unit costs as a function of I_R have the form $c + \alpha\sqrt{I_R} + \beta / I_R$. Very much as in the well known case of the EOQ-formula this function turns out to be extremely 'flat' around its minimum. Specifically, one can show that a deviation by a factor $1+\varepsilon$ from the optimum entails a relative cost penalty of less than $\varepsilon^2 / 3(1+\varepsilon)$. In addition, Equation (5) shows that a relative error ε in ρ leads to a relative error of at most ε 2/3 in I_R. Putting both of these relations together one finds, e.g. that an error of 50% in ρ entails an eventual cost penalty of less than 3%. Clearly, this is good news since it documents that the reverse logistics network design is fairly robust and may be based on rough supply estimates without too much concern. In other words, supply uncertainty has little effect in this context. It should be noted, though, that the *level* of the reverse logistics costs does depend on the supply volume (see Figure 3) and hence that uncertainty surely does play a role in the decision of whether or not to set up a recovery process at all.

While the above analysis concerns only one of the parameters and one of the cost functions the other cases exhibit a fairly similar behavior. As noted before, I_R* is independent of γ and hence there is no cost penalty in $C_{R2}(.)$ for a misjudgment of this parameter. With respect to the area assigned to central testing and grading, Equation (7) shows that error propagation both with respect to ρ and γ is limited. In addition, one should note that choosing a critical distance r' different from r* only affects the reverse logistics costs for supply locations at a distance between r* and r' from the recovery facility. Therefore, the average cost penalty across the entire service region is again small for moderate deviations from the optimal network design. This confirms earlier results based on MILP models (see Fleischmann et al., 2001).

This robustness of reverse logistics networks also has important implications for the potential integration of 'forward' and 'reverse' logistics operations. In particular, it can be expected to leave a fair amount of flexibility for using joint locations, such as co-locating test and grade operations with distribution centers, which may allow for exploiting economies of scale (see also Section 2).

Another aspect of the 'integration' issue concerns the compatibility of reverse logistics networks with logistics structures already in place. In order to analyze this matter one may extend the above cost model to include both 'forward' and 'reverse' network parts (see also Figure 1). Analogous with the above analysis one can then determine the optimal size of the service area covered by a single recovery facility. If demand and collection densities are roughly proportional the resulting area is characterized by an expression analogous with (5) where ρ is replaced by $\delta + \rho\ (1-\gamma)$. However, this means that the impact of variations in the collection density is even smaller in this case. Therefore, one may expect little difficulties with respect to the compliance of reverse logistics with previously designed distribution structures. This is again in line with earlier findings (Fleischmann et al., 2001).

Things may be different if the densities ρ and δ are far from proportional. It goes without saying that reverse logistics programs may call for substantial changes in the overall network design if supply and demand are located in largely different areas, such as e.g. collection of used products in industrialized countries for 'second hand' sales in developing countries. Another example reported in literature where reverse logistics has a significant impact on the overall network structure concerns the substitution of virgin raw materials that strongly influence the 'forward' network, such as in the pulp and paper industry (Fleischmann et al., 2001; see also Section 4.1). While again one may modify the above model for capturing these situations we omit a detailed development here since results appear to be rather intuitive.

5. Conclusions and Outlook

In this chapter we have addressed the structure and design of reverse logistics networks. We have delineated this topic as concerning the logistics structures that link the different physical processes of a closed-loop supply chain. Numerous examples from various industries highlight the prime importance of reverse logistics networks as a key issue that largely impacts the profitability of any closed-loop chain. In order to structure the discussion we have considered specific network design issues for each of the closed-loop channel functions, namely acquisition and collection, testing and grading, reprocessing, and re-distribution. Contrasting our observations with logistics network design in a more traditional context, three main issues have been highlighted that appear to be specific of reverse logistics networks.

First, the need for testing and grading entails a particular centralization-decentralization tradeoff when it comes to the network structure. What distinguishes this situation is the fact that goods flows can only be assigned to a definite destination after testing. Therefore, testing and grading close to the source may reduce transportation costs, in particular by separating scrap from valuable resources. On the other hand, investment costs for test equipment may call for a more centralized operation. In Section 4 we have captured this tradeoff in a quantitative model, illustrating the impact of several parameters, such as transportation costs, collection volume, and scrap rate. Finally, it appears interesting to see whether new advances in IT that facilitate remote testing may change the balance in this tradeoff.

Second, uncertainty on the supply side is another key feature that reverse logistics network design is confronted with. Used products form a supply source that is much more variable and difficult to control than conventional 'virgin' resources with respect to volume, timing, and quality. Consequently, reverse logistics networks need to be particularly robust with respect to variations in flow volumes and composition. It comes as good news that a quantitative analysis indeed confirms this robustness property. The relevant logistics costs turn out to be fairly stable with respect to the network design. Therefore, a moderate deviation from the 'optimal' network structure results in low cost penalties. One may conclude that rough supply estimates, as opposed to more advanced stochastic models, may be sufficient for a company's reverse logistic network design. It should be noted, though, that this does not mean that supply uncertainty is irrelevant in this context. As discussed, supply variations may have a significant impact on the overall cost level and hence on the profitability of the closed-loop chain as a whole.

Third, integration and coordination of different inbound and outbound flows is key to reverse logistics. The discussion unfold in this chapter should have made clear that reverse logistics networks should not be perceived as isolated objects but rather as a part of some larger overall logistics structure. Both at the front and the back-end the actual 'reverse' network is linked with other logistics structures that one would typically consider as 'forward' networks. Interaction, coordination, and integration of these different structures are among the key logistics issues in managing closed-loop supply chains. More specifically, there may be synergies in terms of transportation or shared facilities, e.g. between collection and distribution or between distribution of new and recovered products. At the same time, these opportunities raise a compatibility issue since reverse logistics networks often are not designed 'from scratch' but are added on top of existing logistics structures. A quantitative analysis puts this issue into perspective and suggests that there is enough flexibility in the design to successfully exploit potential synergies. While, of course, this does not mean that 'forward' and 'reverse' logistics operations should always be integrated (see also Section 2) it indicates that transportation economics do not prevent potential synergies from being realized.

Given the short history of reverse logistics it goes without saying that many issues are yet to be explored. The same is true for underlying network design aspects more specifically. To conclude this chapter we list some issues that may stimulate further developments in this field.

Maybe the most important aspect, which surely deserves more detailed analyses concerns the multi-agent character of reverse logistics network design. While different roles in reverse logistics, such as collectors, intermediaries, and processors have been identified since a long while (see, e.g. Pohlen and Farris, 1992) their impact on the logistics network structure seems to have been largely neglected. Establishing general conclusions concerning this relation would surely be valuable. Moreover, all of the network design models referred to in Section 4 follow the perspective of one central decision maker. However, as emphasized in recent supply chain management philosophy the interaction between different players with different goals and different market power is one of the important drivers of logistics systems. Addressing reverse logistics network design from this perspective may therefore be worthwhile. Potential issues include, e.g. revealing underlying incentives for different parties and analyzing the propagation of the aforementioned supply uncertainty through the reverse network (see also Chapter 2).

Another important aspect that appears not to have been addressed in much depth yet concerns the role of inventories in reverse logistics networks. All of the above models largely focus on transportation considerations. However, inventory is well known to be an important factor determining the design of distribution networks. For example, risk-pooling and postponement play a major role in this context. Consequently, the impact of inventories on the structure of the reverse network undoubtedly deserves a closer analysis. This step may call for a better understanding of the role of inventories in closed-loop supply chains in general. While in traditional 'forward' chains the function of inventories as a buffer between two value-adding activities is, in general, well understood the situation in the ‘reverse’ chain still asks for more thorough explanations (see also Chapter 5).

Finally, reverse logistics issues related to a global supply chain scope appear to be another fruitful field that has been barely touched. Throughout the past decade we have witnessed the development of supply chains consisting of a large number of specialized parties located all over the globe. Intuitively, one may doubt whether such a globalization is equally attractive for the reverse channel. Some potential obstacles, such as tax and cross-border waste transportation have already been briefly touched above. However, there may be more fundamental arguments concerning the role of the individual players within the channel. A thorough analysis of these issues seems indispensable for a better understanding of the inherent differences between forward and reverse channels and related business implications.

We conclude by noting that all of the above aspects underline once more the nature of reverse logistics as a novel element within an evolving integral logistics concept, rather than an isolated topic on its own.

Acknowledgements

The author would like to thank the participants of the working group on Reverse Logistics Networks (Markus Biehl, Rommert Dekker, Monique French, Harry Groenevelt, Terry Harrison, Rajesh Piplani) during the seminar on Business Perspectives on Closed-Loop Supply Chains (Carnegie Bosch Institute, Pittsburgh, May 30 - June 2, 2001) for their valuable input, which greatly helped to compose the material presented in this chapter.

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