Chapter 6

THE DESIGN, PLANNING, AND OPTIMIZATION OF REVERSE LOGISTICS NETWORKS

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Abstract Reverse logistics is concerned with the return flows of products or equipment back from the consumer to the logistics network for reuse, recovery or recycling for environmental, economic or customer service reasons. In this paper, we review applications, case studies, models and techniques proposed for the design, planning and optimization of reverse logistics systems. We consider both cases of separate and integrated handling of original products and return flows throughout the logistics network. According to the hierarchical planning framework for logistics systems, the works are described in relation to their contribution to strategic, tactical or operational planning. Major contributions concern facility location, inventory management, transportation and production planning models. Directions for further research are indicated in all of these areas as well as for the general development of reverse logistics activities in a supply chain network.

1. Introduction

1.1 Basic concepts

In recent years, many companies have begun to pay attention to used products and materials, because of legislative, economic and commercial factors (Fleischmann et al., 2000b). Reduction of waste has become a major concern for industrial countries in view of declining landfill and incineration capacity. In addition to growing disposal costs, governmental legislation requires producers to take charge of their products throughout their life cycle. Environmentally concerned customers now expect "green companies" to reduce the quantity of waste generated and to recycle resources encompassed within used products.

Recovery programs have also demonstrated an economic interest for industry: a reduction in the cost of raw materials due to recycling, a reduction in the cost of manufacturing packages by reutilization, a decrease in disposal costs because of reduced quantities (Lu et al., 2001). For enterprises whose products are particularly costly and sophisticated, the reuse of products or components may represent a reduction of 50% of production costs (Fontanella, 1999).

Several definitions of reverse logistics (RL) have been proposed by various authors, such as the American Reverse Logistics Executive Council (Rogers and Tibben-Lembke, 1998), but also Philipp (1999); Stock (1999); Beaulieu et al. (1999); Browne and Allen (1999). In order to emphasize the links between traditional forward flows and reverse flows in an integrated logistics system, we propose the following definition: "Reverse Logistics can be viewed as an evolution of traditional forward logistics in an environmentally-conscious industry or due to other commercial drives; it encompasses all the logistics activities and management functions necessary for reintroducing valued-objects, which have finished or are not suitable to perform their primary function any more, into certain recovery systems for either recapturing their value or proper disposal" (Lu, 2003).

De Brito and Dekker (2002) have compared existing reverse logistics definitions. They distinguish several types of recovery activity:

product recovery (products may be recycled directly into the original market or into a secondary market, or repaired and sent back to the user under conditions of warranty),

component recovery (products are dismantled and parts can be remanufactured into the same kind of product or different products),

material recovery (materials are recuperated and recycled into raw materials like metal, paper or glass),

energy recovery (incineration).

At this point, it is important to emphasize the global nature of the reverse logistics concepts and their differences from concepts such as:

- waste management, because for these products there is no new use or no recovery value,
- green logistics, which considers environmental aspects of forward logistics,
- transportation of empty materials such as containers or movements of empty vehicles, transport activities being complementary to logistics activities.

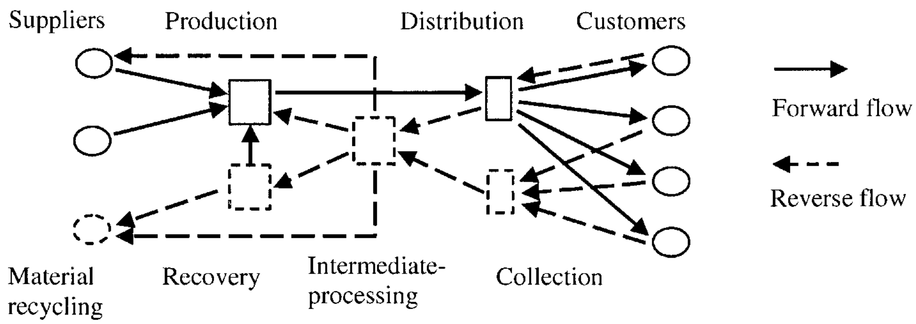

Figure 6.1. Framework of an integrated logistics system with forward and reverse flows

A reverse logistics system consists of a series of activities such as: collection, cleaning, disassembly, testing and sorting, storage, transport and recovery operations. An integrated logistics system with forward and reverse flows can be represented as shown in Figure 6.1.

The nodes of the network represent forward or reverse activities; solid arrows represent forward flows whereas dashed arrows represent reverse flows between nodes.

The design and management of such an integrated network is more complex than that of traditional logistics networks limited to direct flows. Two factors cause these difficulties:

- the simultaneous existence and mutual impact of the two types of flow: the possible coordination /integration and interfering constraints between forward and reverse flows must be considered;
- the existence of numerous uncertainties about the return flows: choice of recovery options, quality of return objects, quantity, reprocessing time (Dekker and van der Laan, 1999; Jayaraman et al., 1999).

Reverse logistics systems can be classified into various categories depending on the characteristics that are emphasized thus several classifications may be found in the literature: Fleischmann et al. (1997); Rogers and Tibben-Lembke (1998); Beaulieu et al. (1999). If two important factors are considered, the types of return items([Fleischmann et al., 1997) and the main options of recovery (Thierry et al., 1995), four kinds of typical reverse logistics networks can be proposed as follows:

directly reusable network: return items (like pallets, bottles or containers) can be directly reused without major operations on them (only cleaning or minor maintenance). This is a closed-loop system because forward flows are closely associated with reverse flows.

remanufacturing network: products at the end of their life or needing maintenance (such as copy machines or aircraft engines) are returned and some parts or components are remanufactured to be used like new parts. This is also a closed-loop system, because remanufacturing is often implemented by the original producer.

repair service network: defective products (like durable products or electronic equipment) are returned and repaired in service centers. In this type of network, there are few links with the forward channel so it can be considered an open-loop system.

recycling network: raw materials (such as metal, glass and paper) are recycled and, as this operation is often carried out by specialized third parties, it can be considered an open-loop system. The collection and elimination of waste is also found in this category.

1.2 Earlier reviews, applications and case studies

In the area of transportation planning, Dejax and Crainic (1987) carried out a review of problems related to the transportation of empty equipments or vehicles , such as containers for reutilization, separately or jointly with the transportation of loaded containers. They classified problems and published work according to the hierarchical planning framework into strategic, tactical and operational problems. The survey focused on purely transportation problems without considering manufacturing activities.

Fleischmann et al. (1997) and Fleischmann (2001) published a review of quantitative models for reverse logistics. They discussed the various dimensions of the reverse logistics context and they analyzed works pertaining to reverse distribution, inventory control in systems with return flows and production planning with reuse of parts and materials.

Several case studies have been reported providing descriptions of reverse logistics organizations in companies as well as management and optimization methods.

De Brito et al. (2003) have published a review of case studies in reverse logistics. They have analyzed over 60 cases, pointing out the variety of real life situations, and have presented comparison tables explaining how reverse logistics activities are undertaken. They have made numerous propositions and pointed out research opportunities. They have identified four different themes for study:

- reverse logistics network structures,
- reverse logistics relationships,
- inventory management techniques,
- planning and control of recovery activities,

- information techniques for reverse logistics.

Gungor and Gupta (1999) provided a literature review on the different aspects of reverse logistics systems, in the context of Environmentally Conscious Manufacturing and Product Recovery (ECMPRO). Environmentally conscious methods suggest taking into account environmental factors when designing products: *design for recycling* (choosing materials better so that the process of material separation and recovery becomes more efficient) and *design for remanufacturing* (designing to disassemble more easily). These concepts have a direct impact on reverse logistics performance. Then they reviewed studies on material and product recovery methods, pointing out:

- the collection of returned products (reverse distribution),
- disassembly with two related problems: disassembly leveling (how far to disassemble) and disassembly process planning,
- inventory control,
- production planning.

In addition to the above reviews, several authors have described specific industrial practices, as well as definitions of processes and strategies of management. The study on copier recovery by Thierry et al. (1995) provides a complete description of the steps to be followed in a product recovery strategy. Clendenin (1997) has reported on a business process reengineering approach to optimize the reverse logistics channel at Xerox. Festinger (1998) and Rohlich (1999) have cited numerous examples of practices of reverse logistics in industry, focusing on the economic interest and pointing out the lack of management science support. Rogers and Tibben-Lembke (1998) presented a monograph introducing reverse logistics and practices in industry. Rogers and Tibben-Lembke (1999) showed the increasing importance of reverse flows and discussed the strategies to reduce the associated costs. Browne and Allen (1999) presented the package recovery activity in Great Britain. Fleischmann (2001) described the organization of the IBM Corporation for product recovery and spare parts management.

1.3 Goal of the chapter

In this chapter, we focus on the methodologies for the design and optimization of networks for logistics systems, including reverse flows, and particularly on the activities regarding the different levels of the hierarchical planning of such systems. We emphasize the specificities imposed upon logistics networks by the consideration of reverse flows and activities. Our approach is based upon the consideration of RL at the different levels of hierarchical planning of the logistics network.

At the strategic level of planning, it is necessary to take into account the recovery option during the design of the product, by including the design for recovery, as well as to consider the costs related to the direct and reverse channels. For the network design, one has to decide where to locate plants and warehouses, but also where to locate the different units for recovery (collection points and remanufacturing plants).

At the tactical level, return flows must be integrated within the overall activities: freight transport (by combining routes for the delivery and collection of returns), handling and warehousing, procurement (recycled parts are an alternative to the procurement of new parts), production planning and inventory management taking into account returns.

At the operational level, production scheduling and control related decisions, such as disassembly and reassembly operations, must be taken in relation to traditional production decisions, as well as the management of all forward and reverse flows for distribution and collection activities.

Section 2 of this chapter is devoted to the hierarchical planning concepts of logistics systems including reverse activities. Section 3 describes strategic planning methodologies for the design of a reverse logistics network. We make a distinction between the qualitative analysis of reverse logistics networks and quantitative methods based on mathematical models. Section 4 of the chapter presents methods for the management of reverse logistics systems at the tactical and operational levels. We discuss inventory management methods and flow optimization models. The final section contains our conclusions and general directions for future work in the area of reverse logistics.

2. Hierarchical planning of reverse logistics systems

The management of logistics networks and their activities is very complex because of their large dimensionality, wide variety of decisions of different scope, focus and time horizon, and disturbance factors (Harhalakis et al., 1992). However, the structure of decisions for such systems presents, in practice, a natural hierarchy of interconnections. According to Anthony's taxonomy (Anthony, 1965), these management decisions can be classified into three categories: strategic planning, tactical planning and operational planning decisions. Generally, these decisions at different categories (levels) are responsive respectively to the managerial functions at different echelons of the organization (Bitran and Tirupati, 1993; Dejax, 2001; Dupont, 1998). In the context of RL, such a hierarchical planning structure can still be employed while the consideration of reverse flows of return products is introduced into the system (Lu, 2003).

Strategic planning decisions are mostly concerned with the design of the network, the establishment of managerial policies and the development of resources to satisfy external requirements in a manner that is consistent with the organizational goals. Such decisions, which are made at fairly high managerial levels, involve large investments and have long-term implications (e.g., more than one year) (Bitran and Tirupati, 1993; Crainic and Laporte, 1997; Dejax, 2001). Typical decisions in the areas of logistics and production systems design consist of the location and sizing of new plants, storage and transfer facilities, acquisition of new equipment, selection of new product lines, and design of the transportation network (Owen and Daskin, 1998). At this level, data and decisions are highly aggregated (Hax and Meal, 1975; Boskma, 1982; Herrmann et al., 1994) on the basis of product types and long-term time horizons (at least three years). The location and sizing of facilities and the design of the network must take into account the impact of the reverse flows and activities and this problem depends on the level of integration of forward and reverse activities. Lu (2003) proposes a hierarchical framework for RL planning in which the strategic planning level covers:

- the design of the logistics network considering both forward and reverse flows: determination of the number and location of all types of logistics facilities, including plants, warehouses, distribution centers, etc., in the forward logistics channel, as well as the corresponding facilities in the reverse channel, e.g., collection and sorting centers, recovery centers, etc.
- the determination of the capacities/resources needed for all the respective facilities.
- the allocation of service areas to each facility for the distribution/collection activities.

The consideration of reverse flows introduces certain important specificities into the structure of logistics systems, and these aspects must be considered in the specific environment of RL applications (Fleischmann et al., 1997; Lu, 2003). Among these questions we can mention:

- What is the objective of a RL system? Who are the actors in the system and their responsibilities (analysis of reverse flow policy and application environment)? Should both forward and reverse activities be jointly or separately considered in the system? Which relationships are to be considered between the two channels and what will be their levels of integration?

- What are the specific functions to be covered all along the network channels?
- What are the relationships and respective importance of the economic and environmental factors and goals of the system in a specific application context?

Tactical planning decisions focus on the resource utilization process within the framework of the strategic plan. The basic problem to solve is the allocation of the resources determined at the strategic level, such as capacity, work force availability, storage and distribution resources to be effectively utilized. Taking the production/distribution capacities as constraints, the tactical planning function tries to establish a plan to meet the demand as effectively and profitably as possible. Typically, a tactical plan will be determined on periods of one month (covering the first part of the strategic planning horizon) over a medium-range planning horizon of up to a year. This timing permits the consideration of yearly seasonality in customer demand. The product structure will still be aggregated but at the level of product types or families only. Data is still aggregated, and decisions are sensitive only to broad variations in data and system parameters without consideration of the shorter term, or day to day information (Bitran and Tirupati, 1993; Crainic and Laporte, 1997; Dejax, 2001). In turn, tactical decisions will be used as a framework for the decision process at the operational level or for day-to-day operations. In the reverse logistics environment, the integration of forward and reverse flows at the production and distribution management levels of the network is important. The problem may be viewed as a combined mathematical model of aggregate production planning and flow optimization with the following features (Lu, 2003):

- the planning horizon depends on the seasonality of demand and should cover at least one cycle, while unit planning periods reflect the dynamic character of the system.
- the optimization of flows is done through a distribution network covering a multi-supply system and a multi-demand system.
- special constraints are designed for the coordination of forward flows and reverse flows.

Operational planning, or operations control, deals with short-term or day-to-day operational and scheduling problems to meet customer requirements within the guidelines established by the more aggregate plans of higher levels. It often requires disaggregation of information generated at higher levels and detailed planning of both forward and reverse flows (Vicens et al., 2001; Jörnsten and Leisten, 1995; Rogers, D.F. et al., 1991). The planning decisions are usually based on specific product items, and the time horizon usually covers a few weeks or days. Operational planning decisions act as a framework and lead to the real time management of operations.

The hierarchical planning process constitutes a framework for top to down decisions. Once the design of the system structure has been defined, the top strategic decisions impose the major constraints (location of facilities, available resources and capacities, network structure) to the tactical planning level (Schneeweifl, 1995); in turn, the tactical level determines a more detailed plan within these constraints, while keeping the consistency of the strategic decisions (Axsater, 1980; Bitran and Tirupati, 1993; Erschler et al., 1986; Mercé, 1987; Gfrerer and Zapfel, 1995). Normally, the basic physical structure of the system is considered stable throughout a rather long time period compared to the time horizon of the tactical plan, and thus the strategic plan could be viewed as static (i.e., covering a single long time period). However, applications of dynamic or multi-period strategic planning have been proposed in certain specific cases (Canel et al., 2001; Chardaire and Sutter, 1996; Melachrinoudis and Min, 2000). Conversely, the strategic planning should be undertaken while considering the impact from the tactical level by anticipation [Schneeweifl, 1995], and the parameters of data aggregation. The effectiveness and efficiency of activities at lower levels could be viewed as possible measures to evaluate the design of the system for the potential future evolution of its structure. Lu (2003) studies the correlation between strategic and tactical planning in the RL context and shows that the coordination of production and recovery processes is necessary to insure the consistency of decisions at the strategic and tactical levels of the hierarchical planning framework.

3. Strategic planning for the design of a reverse logistics system

The basic questions of strategic planning concern the organization and design of the network system, in which we need to address the constitution of flow channels and to identify the relationships between the actors. Such decisions are situated at the top managerial level and depend largely on the policies of the firm. The activities for recovering/reusing used products or materials bring a new complexity to the planning of logistics systems (Dekker and van der Laan, 1999).

As it is a new research field, the results published to date on the design problem of RL systems are rather scarce and isolated. We review here the works reported in the literature in two categories: qualitative analysis based on case studies and quantitative analysis based on optimization models.

3.1 Qualitative analysis of RL networks

In the literature, the analyses of RL networks by most authors are based on case studies in order to provide a clear view of the RL process. Such work can be found for example in Stock (1999), Festinger (1998), Rohlich (1999), Browne and Allen (1999), Rogers and Tibben-Lembke (1998, 1999).

In the design of RL systems, possible actors can be members of the forward channel, e.g., producers, distributors, retailers, logistics service providers, or special third parties, e.g., secondary material dealers, recovery facilities providers, or special reverse logistics operators (Rogers and Tibben-Lembke, 1999; Beaulieu et al., 1999). There are also multiple options of network type. A system in which returns are not sent back to the original producer can be classified as an *open-loop system* as opposed to a *closed-loop system* for the converse situation (Fleischmann et al., 1997). Thus, the enterprises have to clearly determine which kind of system they want to establish and which ones are feasible because, for the same products or activities, an enterprise could decide to build up a closed-loop recovery system (recovery in-house) or consign the relevant activities to a specific reverse logistics operator.

In the choice of recovery options (Thierry et al., 1993), there are usually numerous possibilities even for the same product. The decision may be influenced by different factors such as economic and ecological objectives, recovery technology and experience, possible volumes of return flows, demand for recovered products, legislation, types of reused parts or products and so on. A suitable economic and ecological evaluation method needs to be developed and applied to the design process of a reverse logistics network. After determining the process of recovery operations, an important problem of system design is to choose the locations of the facilities of all the recovery activities, e.g., collection, testing and sorting, and recovery centers.

Reverse logistics also leads to a greater need for cooperation with other partners in the logistics channel (Philipp, 1999). Based on common objectives and interests, it requires a greater exchange of information, joint recovery operations (e.g., some of the necessary technologies can come from the suppliers because they produce and supply the parts or components of the product), joint product design, and cooperation in the common market of recovered products or parts.

Fleischmann et al. (1997) discuss the new issues arising in the context of reverse logistics according to three aspects: distribution planning, inventory control and production planning. They briefly review the mathematical models proposed in the literature on these three topics, and point out that "*in a number of situations, the two flows (reverse and forward) cannot be treated independently but have to be considered simultaneously to achieve adequate planning, and it is the interaction of these two flows that adds complexity to the system involved.*" Meanwhile, handling the uncertainty in the system is also a major task in the planning of reverse activities. The authors conclude that efforts for further research in this area are needed, particularly about the influence of return flows on supply chain management.

Two categories of modeling of network design are identified by the authors, i.e., separate modeling of reverse flows, where only reverse activities (channels) are considered and integration of forward and reverse distribution, which considers two distributions simultaneously. For this second problem, the authors also remark that very few models have been proposed in the current literature.

Then, in Fleischmann et al. (2000a), the authors summarize the general characteristics of logistics networks for product recovery, based on an analysis of diverse examples of applications. They indicate that a RL network is not normally the symmetrical image of a traditional network, which means that new actors and new functions can be involved in such a system. According to their paper, the activities composing a typical network structure can be grouped into collection, inspection/separation, reprocessing, disposal and re-distribution. The main differences between a RL system and a traditional logistics system are the following:

- *The collection phase of the system characterizes a convergent structure, where reverse flows are converging from the disposal market to recovery facilities. Conversely, for the re-distribution phase, flows are diverging from recovery facilities to demand points in the reuse market (Ginter and Starling, 1978).*
- *The geographical distribution and volume of both supply and demand are considered as exogenous variables.*
- *The network structure may be more complex because of a multiple sequence of processing steps.*

They also conclude that a further analysis of the aspects characterizing different network types is worthwhile and that more mathematical models based on the specificities of reverse logistics systems are desirable.

Reverse logistics being a relatively new research field, the topics addressed and results obtained are still far from satisfactory (Jayaraman et al., 1999, Fleischmann et al., 1997). Sometimes, the definitions of concepts and denominations proposed by various authors are different even in this field because of the differences in focus of different researchers. Contrary to the numerous practices in other industrial fields, the theoretical results have not so far provided systematic methods and supports for these systems.

3.2 Quantitative analysis of design problems of RL systems based on mathematical models

Most of the studies found in the published literature suggest extending classical facility location models to support the analysis of design problems for RL systems. All works reviewed below, except for Marín and Pelegrín (1998) and Lu (2003), are devoted to specific application cases. We divide these models into three categories depending on the integration or not of forward and backward flows and the consideration of a weak or strong correlation between the two types of flow.

3.2.1 Independent modes for revers activities. We describe below several analyses of reverse logistics systems, independent of possible corresponding forward flows. Much of this work is based upon the development and experimentation of mixed integer programming models (MIP) and is either generic or devoted to a particular type of application.

Spengler et al. (1997) propose a sophisticated operations research model for recycling industrial by-products in the steel industry. The by-products arising from the production stage of steel have to be totally further treated, and a two-echelon location model (MIP) is formulated to help select the recycling process and to determine the locations and capacities of treatment facilities. Maximum facility capacities are given, and the amounts and sites of by-products are assumed known. The particularity of this model is the integration of the decisions of selection of the process chains (process technologies) into the facility location problem. The model has been applied successfully in the fields of recycling of waste and by-product management.

Barros et al. (1998) consider the problem of establishing an efficient sand-recycling network from construction waste, which is taken charge of by an independent syndicate of construction waste processing companies. The sieved sand from crushing facilities is separated into three categories of clean, half-clean and polluted sand at regional depots. The sand in the first two categories is stored at these depots to be reused in different projects, where half-clean sand has a use restriction. The polluted sand is shipped to treatment facilities and, after treatment, this sand can also be used to satisfy the demand for clean sand. Because the total volume of treated sand is assumed to be greater than the total demand in the system, the storage of processed sand at facilities is necessary. A capacitated three-echelon location model (MIP) with two different types of facility to locate (depot and treatment facilities) is developed to solve this problem. The solution proposed is a heuristic procedure based on linear relaxation, where the lower bound is derived from the linear relaxed problem adding classical valid inequalities and the upper bound is made by heuristics on the basis of iterative rounding rules. The results obtained by the proposed model for the sand problem in the Netherlands are also discussed in this paper.

Jayaraman et al. (1999) present a two-echelon capacitated location model (MIP) for solving the location problem of remanufacturing facilities, where the used electronic products are acquired at collection zones and then transported to remanufacturing facilities. After the value-added process of remanufacturing, the remanufactured products are sent back to serve the demands for these products at customers (same location as the collection zone). The storage of remanufactured products at facilities is assumed if not all of them are demanded. The modeled chain links the supply of used products and the demand for recovered products, both of which are assumed to come from the same customers. The forward production/distribution activities are not considered in this model. The resulting model is solved by the modeling package GAMS, and tested on a set of problems using industrial data.

Louwers et al. (1999) treat a network design problem for the collection, reprocessing, and redistribution of carpet waste in Europe. The carpet waste from different sources is transported to regional preprocessing centers and, after being sorted and separated there, the palletized homogenized materials are transported to different customers for further processing. All reprocessed carpets are assumed to be fully used or disposed of either by customers or at waste disposal units, thus there is no storage at reprocessing centers. The authors propose a continuous location model to determine appropriate locations and capacities of regional centers. An iterative procedure using a standard software package to calculate the capacities, numbers and locations of facilities is given. The modeling of the problem can be categorized as two-echelon with a single type of facility to locate.

Shih (2001) describes the design problem of a reverse logistics system for recycling electrical appliances and computers in Taiwan. The system structure involves collecting points, storage sites, disassembly/recycling plants, and the final disposal/reclaimed material market. The problem has been formulated as a three-echelon model (MIP) with three different types of facility to locate (storage sites, disassembly/recycling plants, and final disposal facilities). The modeled chain connects the disposal market and the reuse market. All the collected returns are recycled or disposed of. Although some numerical results are given, no solution method to the model is explicitly presented.

Lu (2003) presents generic MIP models for both the uncapacitated and capacitated two-echelon location problems with one type of facility to be located for recycling used products as reusable materials, which consists of a pure reverse channel. In such a system, used products are collected from customer zones and recycled as reusable materials at recycling centers, and then sent to a market for reusable materials. According to the parameters of the system, the author proposes the model for two distinct cases, depending on whether the quantity of recycled materials in the system is greater than the demand at the reuse market (case a) or not (case b). A solution algorithm based on Lagrangian heuristics is developed. The model is tested by numerical experiments.

Lu (2003) also studies the facility location problem in a particular case of a repair service network, in which three kinds of flow exist (returned failed products, repaired products and spare parts). Returned products (rotable parts or durable products) need repair or preventive maintenance and are sent back from customers to "service centers," and then returned to customers. The main features of this network and its differences with the traditional network are discussed: the demand for the repair service at customers can be satisfied by any of the available service centers; however, the repaired products at the service centers must be shipped back to the original customer; the requirement for replacing parts at service centers can be met by any of the available suppliers within the constraint of supply capacity. Two uncapacitated and capacitated location models (MIP) are proposed, and algorithms based on Lagrangian heuristics are developed for solving them. For numerical experiments, the author develops a data set consisting of 44 large French cities serving both as customers and as candidate locations for repair service centers, among which 10 cities are selected as suppliers. Through testing, the algorithm proves to have a good performance in terms of quality of solution as well as computing time.

All of the above models are devoted to the design of systems as a location-allocation problem in which only recovery activities are covered. They do not include "forward" activities. The system structure is a priori defined according to the specific application context, which is often represented as a chain to link two demand markets (supply of returns and demand for recovered products). One exception is Spengler et al. (1997). In this work, the reverse flows originate from the "forward" stage of production, but no other interaction with the "forward" channel is further considered in the model. On the other hand, multiple reprocessing stages along reverse channels are often included in these works. Thus, before the returned products enter the recovery facility, a preprocessing activity is required in most cases so as to select/store the recoverable returns from reverse materials. This system structure of multiple stages can be found in the works of Barros et al. (1998), Louwers et al. (1999) and Shih (2001). Even in Jayaraman et al. (1999), although a single recovery stage is included in the model, the authors claim that they made a simplification assumption. It should also be noted that both the supply of returns and the demand for recovered products confine the limits of the reverse chain at its two ends. Moreover, if there is exogenous control (Fleischmann et al., 2000a) on the volume of both supply and demand, then storage is generally necessary in the system, as in Barros et al. (1998), Jayaraman et al. (1999) and the case of recycling network (a) in Lu (2003). However, if the demand for recycled material in the system is assumed sufficient, storage at an intermediate node becomes unnecessary, e.g., in Louwers et al. (1999), Shih (2001), Spengler et al. (1997), and the case of recycling network (b) in Lu (2003).

3.2.2 Integrated models with weak correlation between forward and reverse flows. In comparison with the models in the preceding section, in Spengler et al. (1997), the reverse flows (by-products) generated from the production stage were proportionally related to the volume of production, but the authors considered the reverse activities as an independent system according to their specific application case. We present below some models designed for the simultaneous consideration of forward and return flows in those cases where these two types of flow are only loosely correlated.

Bloemhof-Ruwaard et al. (1996) describe a two-echelon location problem in which two types of facility (production plants and disposal units) need to be simultaneously located. Two types of flow are assumed to exist in the system and to be coordinated at the production stage: forward flows that distribute products to satisfy the demands of customers and waste flows that arise from production and are shipped to disposal units. The authors formulate the problem as a MIP model and try to minimize the total system costs as the sum of fixed costs and variable costs. Lower and upper bound procedures are proposed, in which linear relaxation and Lagrangian relaxations are used to generate the lower bounds. The model and algorithms are tested on generated test problems. The authors claim that the proposed model can be applied in practice to problems like locating feedstock breeding farms and manure processing plants.

Marín and Pelegrín (1998) formulate and analyze, from a purely theoretical point of view, a facility location problem that they name the Return Plant Location Problem. Here, primary products are transported to satisfy the demands of customers, and secondary products available at customer sites are sent back to plants. At the plants, the outbound quantities of flows are proportionally restricted to the inbound amounts. The problem is formulated as a MIP and both a Lagrangian decomposition based heuristic and exact solution method are developed. The results of applying the model and algorithms on test problems are given.

In Fleischmann et al. (2000b), after an analysis of the case studies published in the literature, the authors present a "generic" uncapacitated facility location model (MIP) for logistics network design in the reverse logistics context and discuss its differences with the traditional logistics setting. This model is formulated on the basis of a two-echelon forward chain and two-echelon reverse chain. The coherence of the two kinds of flow at the production facilities is ascertained. Two application examples of the model are illustrated, i.e., copier remanufacturing and paper recycling. The standard solver CPLEX is used to solve the problems.

Lu et al. (2004) present a strategic model for the facility location problem and network design in the general framework of combined forward and reverse flows, in the case of directly reusable products. The producers provide products of a single type shipped to distributors to satisfy their demand. In return, a supply of reusable materials, e.g., containers, bottles, pallets, handling equipment or packages, need to be shipped back from distributors to producers for reutilization, on the basis of economic and environmental considerations. The returns to the production sites will be directly reused in the process of production and forward transportation. The authors propose a capacitated and an uncapacitated location model (MIP) comprising a special linking constraint for the correlation of forward and reverse flows. A specific solution algorithm based on the Lagrangian heuristic technique is developed. Numerical experiments on a sizable example adapted from the OR-Library (http://www.ms.ic.ac.uk/jeb/orlib/) are conducted and their results are presented, including a discussion on the impact of the return flows on the facility locations.

In all of the cases considered above, at the site of plant the return flows (or waste leaving for disposal units in the case of Bloemhof-Ruwaard et al., 1996) are assumed to be coherent with the flows of product shipped to customers. Two types of relationship between these two flows have been considered: *proportionally balanced flows* (the flows at the two ends of the production facility are proportional, as in Bloemhof-Ruwaard et al., 1996; Marín and Pelegrín, 1998); *unbalanced flows* or flows conditioned by an inequality constraint ("greater than") as in Fleischmann et al. (2000b) and Lu et al. (2004). It is important to note that, in these models, the decisions about "forward" and "reverse" flows are made simultaneously. However, the impacts of reverse flows on decisions like the location of production facilities are implicit, rather than explicit, restrictions. In fact, such a correlation relationship between the two types of flow is similar to the quantitative conservation of flow conditions at intermediate network nodes found in the classical multi-stage facility location problem.

3.2.3 Integrated models with strong correlation between forward and reverse flows. Crainic et al. (1989, 1993a) addressed the problem of facility location for the combined distribution of loaded containers and the collection and transfer of empty containers in a container transportation planning system. They proposed multi-level facility location models with inter-depot balancing constraints and a branch-and-bound based solution technique. Their work focused on transportation planning and not on manufacturing activities.

Lu (2003) discusses the problem of the design of an integrated production and remanufacturing system, in which new products are manufactured at production sites and distributed through the "forward channel" while used products (or their components or parts) are sent back through the "backward channel" to be recovered to meet the original quality standard at a relatively low cost. Such a recovery process is designed to be implemented "in-house" and integrated into the forward logistics process in a so-called closed-loop system, combining forward and reverse flows. At customer sites, there is a demand for products and supplies of used products ready to be recovered. Intermediate reprocessing centers are responsible for some necessary preprocessing activities, such as cleaning, disassembly, checking, sorting and so on, before the return products are shipped back to remanufacturing centers. Remanufacturing centers accept the checked returns from intermediate centers and are responsible for the process of remanufacturing. Producers are in charge of the "traditional" production to serve the product demands of customers together with the remanufacturing centers. Such a system is modeled as a MIP location model, comprising two echelons in the forward channel and three echelons in the reverse channel to decide simultaneously on three different types of facility to be located in the network (production facilities, remanufacturing centers and intermediate centers). Solution algorithms based on Lagrangian heuristics are developed, and numerical results are also presented from a large data set.

Like the models presented in the preceding section, this category of models integrates both forward and reverse channels and the decisions related to these two channels are made simultaneously. Normally, in these models the demands for "forward" products and supplies of "reverse" returns originate from the same market (customers) and therefore the flows in the system consist of a closed-loop. It is important to note that, in these models, the flows at the two ends of the production facilities are constrained by a quantitative relationship (e.g., *unbalanced*) and also some other explicit *restrictions* (impacts) from reverse flows are imposed on the decisions about the location, number and capacity of production facilities. For example, in Lu (2003), because part of the reverse flow can become a component of the forward flow after recovery of used products, a "greater than" unbalanced relationship has been imposed to constrain the two flows. Furthermore, the quantity of recovered products at a potential location site directly impacts on the necessity to locate another production facility at this site. In Fleischmann et al. (2000b) (see section above), two different types of facility, for initial production and product recovery respectively, are distinguished but their possible locations are unified to formulate the model under a certain hypothesis. Therefore, the influence of reverse flows on the location decisions of production facilities is not explicit.

3.2.4 Synthesis and future directions. Table 6.1 summarizes all the quantitative models we have reviewed in Section 3.2 with a description of their main characteristics. Except for Louwers et al. (1999), all the models shown are 0-1 mixed integer programming models, and can be viewed as extensions of the traditional facility location model by introducing the specificities of reverse logistics systems. The objective is to propose the location of facilities (forward and reverse) and the quantities of production, trans-shipment, disposal and storage at minimum total cost. In four works (Bloemhof-Ruwaard et al., 1996; Lu, 2003, in the cases of a directly reusable network and a remanufacturing network; Marín and Pelegrín, 1998; Fleischmann et al., 2000b), the authors consider simultaneously the forward and reverse activities in one single system and the ensured coherence of the two types of flow.

As can be seen in this section, a number of strategic models have been developed for facility location and logistics network design to take account of reverse logistics. Some of these models are purely devoted to the management of reverse flows and others integrate traditional production and forward flows for product distribution with forward flows and

Table 6.1. Summary of quantitative location-allocation models for RL systems

Authors	Model type[a]	Stages/ Types of facility ($S^r/F^r-S^f/F^f$)[b]	Correlation[c]	Solution technique	Application
Barros et al. (1998)	D/C MIP	3/2 – 0/0	No	Linear relaxation + heuristics	Recycling sand
Bloemhof-Ruwaard et al. (1996)	D/C MIP	1/1 – 1/1	Yes, weak (balanced)	Linear, Lagrangian relaxation	Breeding farm
Fleischmann et al. (2000b)	D/U MIP	2/1 – 2/2	Yes, weak (unbalanced)	Standard package CPLEX	Copier remanufacturing and paper recycling
Jayaraman et al. (1999)	D/C MIP	2/1 – 0/0	No	Standard package GAMS	Remanufacturing of electronic product
Louwers et al. (1999)	D/C *	2/1 – 0/0	No	Standard package E04UCF	Recycling carpet materials
Crainic et al. (1989, 1993b)	D/U MIP	2/1 – 2/1	Yes	Branch-and-bound	Container transport planning
Lu (2003) in the case of recycling	D/U/C MIP	2/1 – 0/0	No	Lagrangian heuristics	Generic model
Lu (2003) in the case of repair service	D/U/C MIP	2/1 – 0/0	No	Lagrangian heuristics	Generic model
Lu et al. (2004) in the case of direct reuse	D/U/C MIP	1/0 – 1/1	Yes, weak (unbalanced)	Lagrangian heuristics	Generic model
Lu (2003) in the case of remanufacturing	D/U/C MIP	2/1 – 1/1	Yes, strong (unbalanced)	Lagrangian heuristics	Generic model

[a]D/U/C: D represents a deterministic model; U stands for uncapacitated; C stands for capacitated; MIP: Mixed integer programming model; *: continuous location model.
[b]$S^r/F^r-S^f/F^f$: S^r and S^f represent the number of stages (echelons) structured in the system for forward and reverse channels respectively; F^r and F^f stand for the number of types of facility to be located related to forward and reverse channels respectively.
[c]Type of correlation considered between forward and reverse flows.

Table 6.1 (continued).

Authors	Model type	Stages/ Types of facility ($S^r/F^r - S^f/F^f$)	Correlation	Solution technique	Application
Marín and Pelegrín (1998)	D/U MIP	1/1 – 1/0	Yes, weak (balanced)	Lagrangian decomposition based heuristics	Generic model
Shih(2001)	D/C MIP	3/3 – 0/0	No	Not indicated	Recycling electrical appliances
Spengler et al. (1997)	D/C MIP	2/1 – 0/0	No	Standard package GAMS	Recycling of by-products in steel production

product recovery activities. Some of these models are aimed at specific applications and others are generic. The influence of reverse logistics activities on the overall system is discussed.

These works report the growing need for models in the area of logistics systems design for reverse logistics and applications in different sectors. A major difficulty arises from the uncertainty about the rate of product returns and the estimation of supply and the necessity to include uncertainty in these models. There is also a need for the development of more realistic models, capable of handling complex industrial cases, and efficient solution techniques for handling large cases. In this respect, some authors rely on standard MIP software packages and others have developed specific solution techniques for large problems with complex constraints.

4. Tactical and operational planning including reverse flows

The goal of tactical planning is to ensure an efficient use of resources over a medium time horizon (e.g., one year) within the framework of the strategic plan, allocating resources and optimizing the activities, forward and reverse flows and inventory levels throughout the logistics system at short (e.g., monthly) time periods. Tactical planning consists mainly in the determination of the allocation of activities at all levels of the system and time periods in order to ensure the overall goals of the strategic plan. It is necessary to meet the constraints of production, transportation and recovery and achieve a good control of storage levels at each period of the planning horizon to ensure an overall optimization over planning horizon.

Operational planning models aim at short-term optimization of activities such as production scheduling or vehicle routing. Very little work has been published in this area and some models are at the interface between tactical and operational planning. For this reason, we have included published operational planning models with tactical planning models in a single section of this review.

In this section, we distinguish work pertaining to inventory management and work pertaining to flow optimization.

4.1 Inventory management with reverse flows

Appropriate planning and control methods are required to integrate the return flows of used products into the producer material management. The major difficulty is due to the uncertainty of the timing, quantity and quality of return flows. A limited number of case studies have been published on this problem but, since the 1960's, researchers have proposed many quantitative models (Schrady, 1967). Inventory management in reverse logistics has been receiving growing attention in the past decade with the rise in concern for the environment. After a general discussion on inventory management with reverse flows, we discuss deterministic models and stochastic models.

We have selected some representative case studies on inventory management to introduce the subject and their content is subsequently outlined. Toktay et al. (2000) consider the inventory management at Kodak. For a specific product (single-use cameras), printed circuit boards can be bought from suppliers or remanufactured from camera returns. Rudi et al. (2000) study the returns of medical devices for the Norwegian National Insurance Administration, in order to control the purchase of new devices and to decide what to do with returns (refurbished or scrapped). Fleischmann (2001) presents the case of IBM Machines that can be refurbished or dismantled to recover valuable parts. van der Laan (1997) investigates the case of automotive exchange parts, where remanufactured parts are sold more cheaply than new ones.

Compared with a traditional inventory control system, inventory models with reverse flows have two main characteristics:

- an exogenous inbound flow,
- multiple supply options for serviceable stock.

The general structure of inventory control with reverse flows involves two distinct inventories as illustrated in Figure 6.2:

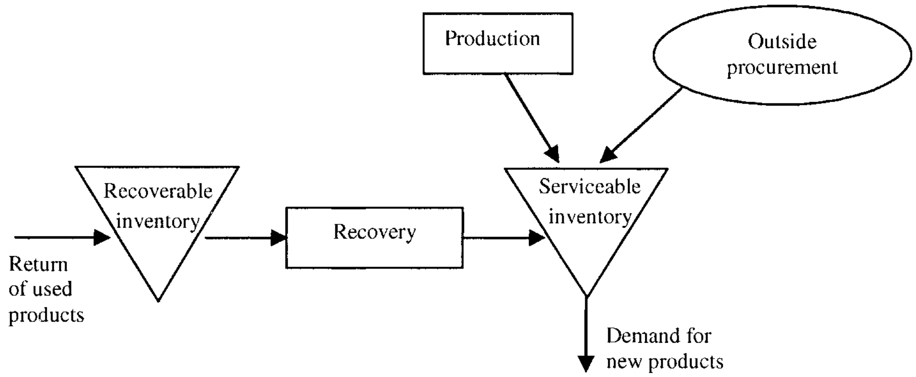

Figure 6.2. Recoverable inventory system (adapted from Fleischmann, 2001)

- the recoverable items returned from the market,
- the serviceable inventory supplies both from outside procurement and a recovery process.

However, specific models depend on the particular characteristics of the return activity. They may consider only one stock (single-echelon model) for the end-item stock, like in the case of directly reusable items, or be two-echelon models distinguishing recoverable inventory and serviceable inventory, as in the case of remanufacturing systems.

In the particular case of a recycling network, returned products are recycled as new raw materials and have no interaction with direct flows (open-loop system) so this can be considered as a classical inventory model.

The repair network is also a particular one. In certain situations, it may involve no closed-loop at all (when defective products are repaired in specialized service centers and then returned to the customer) or there may be no direct relation between demand and returns (for example, returns of used computer equipment for dismantling and demand for spare parts (Fleischmann, 2001)).

The well-known class of repairable item inventory models (where a return necessarily generates a simultaneous demand for a replacement item) has been investigated since the 1960's (see the classical METRIC model (Sherbrooke, 1968)). Many other works have been carried out on this particular subject, such as Pierskalla and Voelker (1976), Nahmias (1981), Cho and Parlar (1991), and Guide, Srivastava and Spencer (1997).

The cases of recycling networks and repair networks having been dealt with above, the rest of this section is devoted to the two other cases in our typology, i.e., directly reusable items and remanufacturing networks.

In a product recovery setting, the correlation between the two types of flow (forward and backward) tends to be much weaker and mainly reflects the dependence of returns on previous demand.

Models with multiple supply options can be a starting point to study inventory models with reverse flows. Moinzadeh and Nahmias (1988) present a two-supplier model, in a continuous review process. These models typically address the trade-off between a fast but expensive supplier and a cheaper, slower one (emergency supplies) and have the particularity that both the regular and emergency supplier are always available. In the recovery process, the cheaper channel (recovery) is often also the fastest one, availability of product returns for recovery is exogenously determined and the recovery supply mode is capacitated. In a recovery context, rather than lead time reduction, it is the restricted availability of the cheaper recovery channel that calls for an alternative supply source.

4.1.1 Deterministic models. Deterministic and static models including reverse flows are derived from classical EOQ models as proposed by Schrady (1967), where demand and returns are constant, lead times are fixed, and disposal is not allowed. Mabini et al. (1992) have extended the previous model by introducing a stockout service level constraint and considering the case of different items sharing the same repair facility. Ritcher (1996) studies the problem of lot-size coordination for production and remanufacturing in an EOQ framework. Teunter (2001) extends this work to the case of different holding costs for produced and recovered products.

Dynamic approaches based on the classical Wagner-Within model have also been proposed in the reverse logistics context. Beltran and Krass (2002) consider dynamic lot-sizing for an inventory point facing both demands and returns and controlled by procurement and disposal. They show that the complexity is increased by the inclusion of returns. Minner and Klerber (2001) also propose a dynamic model for an optimal control formulation in the case of a simple deterministic inventory system with a linear cost structure.

Most models consider linear cost functions. Dobos (2003) proposes a two-echelon system including reverse logistics, where holding costs for the two stores (serviceable and returns) are quadratic, as well as production, remanufacturing and disposal costs. He derives an optimal solution with two state variables (inventory status of the two stocks) and three control variables (production, remanufacturing and disposal rates) to minimize the total cost.

4.1.2 Stochastic models.

These are classified into single period, periodic review and continuous review systems. Two distinct strategies can be studied:

- the push strategy, where returned products are remanufactured as soon as a sufficient quantity of product is available. A manufacturing order is placed only when the serviceable inventory appears to be too low to satisfy future demand.
- the pull strategy, where returned products are remanufactured only when they are needed to satisfy the demand. If the remanufacturing output is too low, a manufacturing order is placed.

4.1.2.1 A single period review system.

This problem concerns products sold through e-commerce or mail sales. Returns may be used to satisfy new demand but only if they are available before the end of the selling period. Otherwise, returns can only be disposed of or sold at a lower price in a secondary market.

Vlachos and Dekker (2003) have extended the classical newsboy problem to set the optimal order quantity by taking into account the returns. They have shown that the classical newsboy solution is inadequate when return rates are significant. They propose different mathematical models for various return handling options depending on cost parameters, collection time and the need for recovery operations.

A related problem is studied by Mantrala and Raman (1999). The fashion goods market has become more unpredictable and competitive so retailers negotiate that suppliers buy back unsold inventory at the end of the selling season. They have studied how the retailer's optimal order quantity decisions are affected by demand uncertainty and how a supplier's returns policy can influence these decisions. Compared to previous works, they have introduced multiple retailer stores with possibly correlated demands.

4.1.2.2 Periodic review systems.

The first stochastic model was developed by Whisler (1967) who proposed an optimal control policy based on two parameters (disposal and new supply) for a single stock inventory with stochastic demand and return. Simpson (1978) extended this to a two-echelon model, where the optimal policy is controlled by three parameters (disposal, remanufacturing and new supply). These models consider no fixed cost and lead time. Inderfurth (1997) shows that the previous results are still valid if repaired and procurement channels have fixed and identical lead times and have zero fixed ordering costs.

Cohen et al. (1980) assume that a fixed fraction of products issued in a given period is returned after a fixed sojourn time in the market and can be reused. They propose an optimal periodic review "order up to" policy, without fixed costs and procurement lead time.

Kelle and Silver (1989) propose an extension of the previous research with a model for container reuse, considering fixed order costs and a stochastic sojourn time in the market. They transform the model into a dynamic lot-sizing problem.

Mahadevan et al. (2003) study a periodic review push policy where returns and demand follow a Poisson process. They develop several heuristics based on traditional inventory models tested by simulation, to determine when to remanufacture returns and how many new products to manufacture. They show that the problem can be reduced to choosing an appropriate order-up-to level. They also investigate the performance of the system as a function of return rates, backorder costs and lead times.

Kiesmüller (2003) analyses a stochastic recovery system with two stocking points, different lead times for production and remanufacturing, and no disposal of returned items. He proposes heuristic policies to make the decisions on production and remanufacturing quantities in a periodic review system, with a pull policy.

Kiesmüller and Scherer (2003) propose a method for the exact computation of parameters for an optimal periodic policy with two stocking points. They consider stochastic and dynamic demands and returns and equal deterministic lead times, taking into account production, remanufacturing, disposal backorder costs and also holding costs for serviceable and remanufacturable inventories. This exact method is very time-consuming and could not be used in practice. However, they propose two approximation methods and study their performance: a dynamic programming model and a deterministic model. They distinguish two cases: without stock of returns (corresponding to a push policy) and with stock of returns.

The study of a more general network has been carried out by Minner (2001). He studies a multi-stage supply chain with regular replenishment in which two types of return are considered: external product returns and internal by-products. This analysis aims to show how these additional external and internal material flows impact on the required amount of safety stock. These safety stocks depend on the service level and are required in relation to uncertain customer demand and returns.

4.1.2.3 Continuous review systems. Fleischmann et al. (2002) propose a model for a single stock point (directly reusable packages), extending a traditional single-item Poisson demand inventory model with a Poisson return flow of items. Procurement orders arrive after a fixed lead time and fixed order costs are considered. They propose an optimal (s, Q) policy for ordering new items and derive optimal values for the control parameters s and Q. They also discuss the impact of the return ratio on costs. Fleischmann and Kuik (2003) also consider a single inventory point system with independent stochastic demand and return items. They transform the model into a traditional (s, S) model without return flows and are able to propose an optimal (s, S) order policy.

van der Laan and Salomon (1997) investigate both continuous push and pull policies, with a disposal option, and analyze the influence of the return rate. van der Laan et al. (1999) evaluate the effects of the lead-time duration and variability on the total expected cost for push and pull control strategies in a system with two stocking points. They propose non-optimal strategies that are easy to implement and use in practice. Earlier, Muckstadt and Isaac (1981) studied a similar model but without considering stochastic manufacturing lead times nor holding costs for returns, and with no disposal possibility. They consider a single stocking point with a (s, Q) strategy to control the procurement.

4.1.3 Synthesis and future directions. Table 6.2 summarizes all the deterministic inventory management models reviewed in Section 4.1.1 with a description of their main characteristics.

Table 6.3 summarizes all the stochastic inventory management models reviewed in Section 4.1.2, except for single period models, with a description of their main characteristics.

As can be seen from these tables, a significant number of models of different types have been developed for inventory management including reverse flows in the deterministic as well as stochastic cases, considering one or two echelons. However, optimal solution techniques have been derived only under limiting assumptions, such as no lead times, equal lead times or no fixed costs. Problems with more realistic hypotheses have led to models that could only be solved approximately.

There is therefore a need for the development of more realistic models for inventory management in multi-echelon logistics channels. Furthermore, all models analyzed here consider single product inventory management. Models for multi-product inventory management should be developed to deal with the recovery of the various components of return products on the basis of their bill of materials. Actually, different components of a returned product may be remanufactured to be used again in different products.

Table 6.2. Synthesis of deterministic inventory models with reverse flows

Authors	Demand[a]	Model type[b]	Stocking points	Number of decision variables	Disposal option	Fixed costs	Lead time	Type of model
Schrady (1967)	C	S	2	3	No	Yes	Yes	EOQ
Mabini et al. (1992)	C	S	2	3	No	Yes	Yes	EOQ
Ritcher (1996)	C	S	2	4	Yes	Yes	Yes	EOQ
Teunter (2001)	C	S	1	4	Yes	Yes	Yes	Simulation
Minner & Klerber (2001)	C	D	2	3	Yes	No	No	Optimal
Beltran & Krass (2002)	D	D	1	2	Yes	Yes	No	Wagner-within
Dobos (2003)	C	S	2	3/5	Yes	Yes	No	Optimal quadratic

[a]D/C: discrete or continuous demand
[b]S/D: static or dynamic model

4.2 Flow optimization models in reverse logistics

After discussing inventory management models involving return products, we will now review tactical models pertaining to flow optimization in logistics networks involving return flows. We distinguish collection and distribution models and models involving disassembly or production activities.

4.2.1 Transportation planning models for product collection and distribution. This area concerns the collection and transportation of used products and packages, integrated or not with forward flows. Models dealing with forward and reverse distribution simultaneously consider the possible location of joint facilities (see strategic models) but there exist few models dealing with the combined routing of new products (forward flows) and return products (reverse flows) with a specific consideration for return flows.

In the area of transportation planning of containerized goods, Crainic et al. (1993b) proposed a multi-periodic and stochastic model for the

Table 6.3. Synthesis of stochastic inventory models with reverse flows

Authors	Demand/ return distribution[a]	Stocking points	Decision variables	Disposal option	Fixed costs	Lead time	Back order	Type of model
Periodic review models								
Whisler (1967)	Gen/gen	1	2	Yes	No	No	No	Optimal
Simpson (1978)	Gen/gen	2	3	Yes	No	No	Yes	Optimal
Cohen et al. (1980)	Gen/gen	1	1	No	No	No	No	Optimal
Kelle & Silver (1989)	Gen/gen	1	1	No	Yes	No	Yes	Dynamic lot-sizing
Inderfurth (1997)	Gen/gen	2	3	Yes	No	Yes	Yes	Optimal
Mahadevan et al. (2003)	Poisson/ Poisson	2	1	No	Yes	Yes	Yes	Heuristics/ simulation
Kiesmüller (2003)	Gen/gen	2	2	No	Yes	Yes	Yes	Heuristics
Kiesmüller & Scherer (2003)	Gen/gen	1/2	3	Yes	Yes	Yes	Yes	Exact method/ heuristics
Continuous review models								
Muckstadt & Isaac (1981)	Poisson/ Poisson	1	2	No	Yes	Yes	Yes	Non-optimal (s, Q) policy
van der Laan & Salomon (1997)	Poisson/ Poisson	2	4/5	Yes	Yes	Yes	Yes	Non-optimal (s, S) policy
van der Laan et al. (1999)	Poisson/ Poisson	2	3/4	No	Yes	Yes	Yes	Non-optimal (s, S) policy
Fleischmann et al. (2002)	Poisson/ Poisson	1	2	No	Yes	Y es	Yes	Optimal (s, Q) policy
Fleischmann & Kuik (2003)	Gen/gen	1	2	No	Yes	Yes	Yes	(s, S) policy

[a]Distribution law for direct demand and returns: general (gen) or Poisson

allocation of empty containers. Their model was aimed at the land transportation of maritime containers for international trade.

Del Castillo and Cochran (1996) studied production and distribution planning for products delivered in reusable containers. In this case, the return of empty containers was a constraint for the production system.

Duhaime et al. (2001) analyze the problem of reusable containers at Canada Post. They show with a minimum cost flow model that stockout can be avoided if containers are returned quickly from customers.

Feillet et al. (2002) studied the problem of the tactical planning of interplant transport of containerized products. They developed vehicle routing models with gains aimed at determining interplant circuits for the combined transport of containers loaded with parts, the return of empty containers and the positioning of empty trucks. They applied their models to a real case in the automotive industry. Lu (2003) proposes an integrated production/distribution linear model including both forward and reverse flows. The model is detailed for the case of directly reusable products and can be easily extended to the case of a remanufacturing network, both cases considering the two channels (forward and reverse) simultaneously. In the case of an open-loop system, such as a repair service network or a recycling network, the reverse channel is independent of the forward one because the actors involved are different. Therefore, the reverse channel can be studied independently, which makes the problem much simpler and allows the application of classical methods for distribution planning in logistics.

Vehicle routing problems considering forward and reverse flows belong to the classes of vehicle routing problems with backhauls (VRPB) (Goetschalckx and Jacobs-Blecha, 1989) or pick up and delivery problems (VRPPD) (Savelsbergh and Sol, 1995). After Nagy and Salhi (2004), we can distinguish three classes of problems involving deliveries from a depot or pick ups to a depot:

- **delivery first, pick up second problems,** where customers can be divided into two categories (linehauls and backhauls) and vehicles can only pick up goods after they have finished delivering all their load,
- **mixed pick ups and deliveries,** where linehauls and backhauls can occur in any sequence on a vehicle route,
- **simultaneous pick ups and deliveries,** where customers may simultaneously receive and send goods.

Reverse logistics problems belong primarily to the last two categories of problems because clients can receive their deliveries and simultaneously return their reusable packages or products to be recycled or remanufactured. In this context, the following works can be quoted.

Min (1989) and Halse (1992) are among the first to study the VRP with simultaneous pick up and delivery. Min et al. (1992) explore the VRPPD in the context of multi depot. Wade and Salhi (2002) propose a practical compromise between the classical VRPB and the mixed VRPB. They allow mixed linehauls and backhauls under particular conditions. Nagy and Salhi (2004) propose heuristic algorithms for single and multidepot VRPPD. Dethloff (2001) studies the vehicle routing problem in the context of reverse logistics and claims that it can be viewed as a VRP with simultaneous pick up and delivery. He proposes a heuristic construction procedure to solve this problem. In his thesis, Vural (2004) proposes a genetic algorithm based metaheuristic for the capacitated VRP with simultaneous pick up and delivery. Rusdiansyah and Tsao (2003) present an integrated approach for solving the period VRP with simultaneous delivery and pick up. They address the problem of a fleet of capacitated vehicles used for delivering products from the warehouse to retailers and collecting the reusable empty containers in the reverse direction. Retailers can be visited once or several times over the period. The problem consists in finding a compromise between inventory costs and travelling costs.

4.2.2 Production planning. The applicability of traditional production planning and scheduling methods to product recovery systems is very limited due to uncertainties (in the quantity, timing and quality of returns) and the specificity of recovery activities (disassembly operations must be planned to fulfil the demand for components for production). New methodologies must be developed for this purpose, such as MRP techniques with a reverse bill of materials and scheduling problems incorporating disassembly activities.

The different cases of recovery activity induce different problems. In the direct reuse activity, no production process additional to the initial production of products is necessary, and the main problem is an inventory management problem with uncertainty.

For material recycling, new production processes are necessary to transform returned products into raw materials. However, it is more a technological problem than a management problem and conventional methods can be used to plan and control recycling operations.

In addition, we can mention Hoshino et al. (1995) who proposed a model for a recycling-oriented manufacturing system, which takes into account the collection of used products to be recycled as raw materials or sold to raw-material suppliers for re-production of raw materials or disposal. The model includes two objectives (maximizing the recycling rate and maximizing the total profit) and is solved by goal programming techniques.

The more complex situation is that of the remanufacturing problem. In this case, there is no predetermined sequence of production steps and the repair operations on components depend on the state of the product and can be known only after testing. Thus, it induces a high level of uncertainty. The coordination of several interdependent activities is necessary: the disassembly operation is a procurement source of various parts simultaneously. Furthermore, a capacity problem may arise if several parts require the same repair equipment.

This analysis has allowed us to identify two distinct subjects of research: disassembly leveling and planning, and production planning including reverse flows.

4.2.2.1 Disassembly leveling and planning. Disassembly activities take place in various recovery operations including remanufacturing, recycling and disposal. The first decision to be made concerns the selection of an appropriate disassembly level (to determine at which level of the bill of materials the product must be disassembled) and processing options, in order to minimize the cost of disassembly (compared to the value of recovered components) with respect to technical constraints. As the number of components increases, the number of alternatives for the disassembly process planning grows quickly. Therefore, this problem is a very important and complex one for disassembly activities. Gungor and Gupta (1999) have provided a detailed review of existing techniques in this field: graph theory and tree representation are frequently used to treat this problem but also branch-and-bound, goal programming, simulation, and neural network techniques.

Johnson and Wang (1995) proposed a model for determining an optimal disassembly sequence for a given product structure, using a network flow algorithm. Penev and de Ron (1996) describe a static cost comparison tool to determine an economic disassembly level and sequence of a single product. Meacham et al. (1999) extend these approaches to multi-product models involving fixed costs and common parts. Krikke et al. (1998) propose a stochastic model taking into account uncertainty. They introduce quality classes for the different components and assign a reuse option to each class. The method is based on two steps:

- optimization at the product level (determination of a multiple product recovery and disposal (PRD) strategy for every product type returned, depending on different objectives or constraints),

- optimization at the group level of different types of product: they assign for each product of a group a PRD strategy to optimize an overall objective.

The authors apply this algorithm to a business case (Krikke et al., 1999) of recycling discarded computer monitors, to determine optimal PRD strategies with given group recovery and disposal policies.

Two other industrial cases related to disassembly and the choice of recycling options are presented by Spengler et al. (1997): dismantling and recycling of end-of-life products and recycling of industrial by-products. The first problem concerns the evaluation of integrated dismantling and recycling strategies for domestic buildings in Germany. They propose a mixed integer linear optimization model for the evaluation of costs and interactions of dismantling and recycling, and for the determination of dismantling procedures, recycling techniques and reuse options. In the second case, they develop a decision support system for by-product management in the iron and steel industry. In these industries, certain dusts and sludges can be recycled into the production chain. Companies have to decide which recycling process to use, and if it is possible to cooperate with other companies by sharing recycling plants to reduce costs.

4.2.2.2 Production planning and scheduling involving return products. The particularity of reverse flows prevents the use of the traditional MRP method for production planning. It needs to be adapted by, for example, a reverse bill of materials.

Authors like Gupta and Taleb (1994) propose an MRP algorithm for scheduling disassembly, taking into account dependencies between different components of the same product. In Taleb and Gupta (1997), they extended it to a multi-product situation. Flapper (1994) considers a situation where components can be obtained by purchase or disassembly of old products, and proposes a simultaneous schedule for disassembly, repair and assembly operations. An interesting approach taking into account uncertainty has been proposed by Thierry (1997) through a simulation study to compare different MRP approaches. Guide, Kraus and Scrivastava (1997) also use simulation to evaluate different scheduling policies in a remanufacturing system and Guide, Srivastava and Spencer (1997) extend the analysis to capacity planning using the techniques of rough cut capacity planning. Veerakamolmal and Gupta (2000) propose an adaptation of the MRP technique to determine the number of components needed, that is to say the number of products to disassemble to fulfil the demand for components for remanufacturing, at minimal disassembly and disposal costs. Kongar and Gupta (2000) describe an integer goal programming model to determine the number and type of products to be disassembled in order to fulfil a demand for used components or subsets for remanufacturing. This tool is relevant to decision-makers because it suggests several plans obtained by varying the objective criterion. Spengler (2002) proposes a decision support system for electronic scrap recycling companies. The recovery of electronic scrap is a multi-stage process. The model proposed is a mixed integer linear program based on activity analysis. It provides a daily plan to determine the recycling schedule of scrapped products, the levels of disassembly, the allocation of reusable parts and modules for the use of producers or suppliers.

4.2.3 Synthesis and future directions. At the tactical and operational levels of planning, flow optimization models are of course complementary to inventory management models. We have categorized flow optimization models into collection and distribution planning models involving only transport activities and planning and scheduling models involving different types of production activity. In both categories, there are models where the treatment of return products is integrated with that of new products, and models where the two types of flow are disconnected. In Table 6.4 we present a synthesis of all the flow optimization models reviewed in the section.

There is a growing need for models integrating all relevant factors, i.e., inventory management, production or disassembly activities as well as transport activities for collection or distribution planning. There is also a need for specialized models adapted to realistic specific cases. As we pointed out regarding strategic models, an important uncertainty factor exists regarding the data of the return flows and models should therefore incorporate stochastic features or be robust regarding the uncertainty of the supply of return products.

5. General conclusions

Although some of the concepts of reverse logistics, such as the recycling of products, have been put into practice for years, it is only fairly recently that the integration of reverse logistics activities has been a real concern for the management and organization of logistics systems. In the past ten years or so, a significant amount of work has been published regarding the management of return flows, independent of or integrated with the management of flows of new products.

This chapter has been an attempt to summarize the work pertaining to the design, planning and optimization of logistics systems according to a classification primarily based upon the three steps of systems planning, i.e., strategic, tactical and operational planning. Strategic plan-

Table 6.4. Synthesis of flow optimization models

Authors	Model type[a]	Type of flow	Mono/multi period	Method	Application
Crainic et al. (1993b)	D	reverse	multi		Allocation of empty containers
Del Castillo & Cochran (1996)	P/D	combined	multi	LP + simulation	Soft drink
Duhaime et al. (2001)	D	combined	mono	Minimum cost flow model	Canada Post
Feillet et al. (2002)	D	combined	multi	VRP with gains	Interplant transport of containerized production
Lu (2003)	P/D	combined	mono	Lagrangian relaxation	Generic model
Hoshino et al. (1995)	P	combined	multi	Goal programming	Numerical example
Johnson & Wang (1995)	P	reverse	mono	Network flow algorithm	
Penev & De Ron (1996)	P	reverse	mono	Graph theory and cost analysis	
Meacham et al. (1999)	P	reverse	mono	Graph theory and cost analysis	
Krikke et al. (1998)	P	reverse	mono	Stochastic model	Computer monitors
Spengler et al. (1997)	P	reverse	mono	MIP – Benders	Demolition waste
Gupta & Taleb (1994)	P	reverse	multi	MRP algorithm	
Taleb & Gupta (1997)	P	combined	multi	heuristics	
Flapper (1994)	P	combined	multi	MRP heuristic	
Thierry (1997)	P	combined	multi	MRP, simulation	Copier reman-ufacturing
Guide et al. (1997)	P	reverse	multi	simulation	
Veerakamolmal & Gupta (2000)	P	reverse	multi	MRP	
Kongar & Gupta (2000)	P	reverse	mono	goal programming heuristic	Numerical example
Spengler (2002)	P	reverse	mono	MILP	Electronic scrap

[a]P/D : Production, Distribution

ning models have focused on facility location models for the design of a logistics network including return flows. Tactical and operational models have been developed regarding the various logistics activities where return flows should be considered, i.e., inventory management models, production planning and scheduling models and transportation planning models for the distribution or collection of products.

As a general conclusion, we must acknowledge the amount of work already published in this area and the effort of researchers in the design and optimization of realistic logistics networks by considering environmental concerns, customer service or simply economic efficiency. However, there is a growing need for new models corresponding to generic or specific cases, focused on the logistics activities of a given firm or on the overall supply chain.

A major difficulty in adequately handling RL activities concerns the uncertainty of the reverse flows themselves. This uncertainty involves numerous factors like the quantity and quality of returns, the selection of the recovery methods, the supply of return products as well as the demand for recovered products. These factors are not appropriately addressed in general in most of the published work. It seems worthwhile to examine the impacts of these uncertainties on the decision factors for the logistics systems at all levels of planning.

At the strategic level of planning, there is room for the extension of the proposed models to more general cases. For example, static simple facility location models might be extended to multi-level, multi-period dynamic models if the evolution of system structure is important in the planning horizon of a specific application. The integration of routing factors may also be interesting for decisions about the location of certain types of facility, like collecting centers in reverse logistics. Other extensions, such as introducing technology or supplier and remanufacturer selection in the supply chain network and economies of scale in recovery activities, are further important directions for future work. This can be compared with the extension, in recent years, of classical "forward" logistics systems to include supply chains.

At the tactical level, research directions should focus on the integration of features that appear only in the different models, such as inventory management, production and transportation planning. An extension of proposed models to include logistics factors ignored so far may be necessary; for example, set-up constraints for production or shipment, shipments of integer vehicle sizes and utilization of empty-ride transportation capacity.

The design of short-term operational planning models for reverse logistics has been quite limited so far. This might be due to the necessary specificity of operational models. However, there is a need to develop a close coordination between forward shipments and reverse returns at this level. Operational planning models including RL activities should therefore be more widely studied for different types of problem, such as remanufacturing and production scheduling and vehicle routing for the collection of returns.

A first step in the development of new models adapted to industrial needs might be to develop the analysis of case studies to get a better knowledge of real problems and practices. One should also pay particular attention to the necessary consistency and complementarity between the various types of model developed, particularly between the different levels of planning.

The analysis presented in this chapter and the directions of research which we have derived confirm the positive contribution of the consideration of reverse logistics for the development of efficient logistics and supply chain systems.

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