Invited Review

Quantitative models for reverse logistics: A review

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Abstract

This article surveys the recently emerged field of reverse logistics. The management of return flows induced by the various forms of reuse of products and materials in industrial production processes has received growing attention throughout this decade. Many authors have proposed quantitative models taking those changes in the logistics environment into account. However, no general framework has been suggested yet. Therefore the time seems right for a systematic overview of the issues arising in the context of reverse logistics. In this paper we subdivide the field into three main areas, namely distribution planning, inventory control, and production planning. For each of these we discuss the implications of the emerging reuse efforts, review the mathematical models proposed in the literature, and point out the areas in need of further research. Special attention is paid to differences and/or similarities with classical 'forward' logistics methods. © 1997 Elsevier Science B.V.

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1. Introduction

Reuse of products and materials is not a new phenomenon. Metal scrap brokers, waste paper recycling, and deposit systems for softdrink bottles are all examples that have been around for a long time. In these cases recovery of the used products is economically more attractive than disposal. In the recent past the growth of environmental con-

cerns has given 'reuse' increasing attention. Waste reduction efforts have promoted the idea of material cycles instead of a 'one way' economy. In 1994, paper recycling in Europe amounted to 27.7 million tonnes with an annual growth rate of about 7%, signifying a recovery rate (in percentage of total paper consumption) of about 43%. European glass recycling grew by almost 10% (in tonnes collected) in 1994 to more than 7 million tonnes, being a recycling rate (in percentage of total glass consumption) of roughly 60% (Eurostat, 1997). In Germany, recovery goals for sales packaging

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materials are mandatory between 60% and 75%. In The Netherlands, 46% of all industrial waste was reused in 1994, rising from 36% in 1992 (CBS, 1997).

In all cases the reuse opportunities give rise to a new material flow from the user back to the sphere of producers. The management of this material flow opposite to the conventional supply chain flow is the concern of the recently emerged field of 'reverse logistics' (Stock, 1992; Kopicki et al., 1993). Our review is dedicated to the planning and control tasks arising in this context which we address from an Operational Research point of view. For a more qualitative discussion see also Flapper (1996).

Reverse logistics encompasses the logistics activities all the way from used products no longer required by the user to products again usable in a market. First of all – and probably most intuitively related with the notion 'reverse' – this involves the physical transportation of used products from the end user back to a producer, thus *distribution planning* aspects. The next step is the transformation by the producer of the returned products into usable products again. From a logistics point of view we focus on *inventory management*. In addition, although not a logistics activity in the strict sense, we also include *production planning* aspects in our discussion. These three domains roughly demarcate the scope of this review.

We proceed as follows. Section 2 structures the considered field. Sections 3–5 are dedicated to distribution planning, inventory control, and production planning aspects, respectively. We take the situation in practice as a starting point and then discuss the contributions that Operational Research offers to solving the various decision problems. To this end, each of these sections has been given a rather detailed introduction. Based on practical examples for reuse activities we discuss the logistics planning problems arising in the various contexts and indicate in how far these are unique when compared to traditional situations. These parts of the paper are directed in particular to readers not yet familiar with the field. Reading all the introductions should provide an overview of the major 'issues' in reverse logistics.

Subsequently, we give in each section a review of the relevant Operational Research literature. Our selection criteria were twofold: (i) relation with return flow management and (ii) presentation of a quantitative model. We give a rather short discussion of each reference, the aim being to provide the interested reader with a broad overview of the topics investigated so far. Although we do not claim completeness of our selection we hope to have mentioned the most relevant references. Finally, Section 6 states some general conclusions.

2. Dimensions of the reverse logistics context

The situations in which reuse occurs are diverse and can be classified according to a number of criteria, including reuse motivation, type of recovered items, form of reuse, and involved actors. Each of these aspects has important implications for the kind of planning problems arising and for the formulation of adequate models. We discuss each of these aspects in more detail below.

The difference between economical and ecological *motivation* of the reuse efforts has already been sketched in Section 1. Waste reduction has received growing attention in the industrial countries in view of depletion of landfill and incineration capacities. Several countries have enforced environmental legislation, charging producers with responsibility for the whole product life cycle. Take-back obligations after use are typical of the measures taken. In Germany, for example, the packaging ordinance of 1991 requires industry to take back all sales packaging materials and imposes a minimum percentage recycling. The electronic scrap ordinance of 1996 sets similar recycling goals for electronic goods. In The Netherlands the automobile industry is responsible for recycling all used cars (Cairncross, 1992). But even if legislation is less stringent customer expectations impose strong pressure on companies to take environmental aspects into account (Vandermerwe and Oliff, 1990). A 'green' image has become an important marketing element. This development has stimulated a number of companies to explore options for take-back and recovery of their products (Thierry, 1997). These environmentally

motivated reuse efforts appear to be typical for the current situation in Europe.

On the other hand there are also economically motivated reuse activities as stated above. Another typical example is remanufacturing of machine parts. In general the aim of these approaches is to regain the value still incorporated in a used product. Overhauled products may be used as spares or sold on secondary markets while requiring only a small fraction of the original production costs for repair. Essential to this approach is the selection of products for which the savings in production costs are large compared to the drop in value between new and recovered products. These economically motivated approaches appear to dominate the current situation in the USA (Fargher, 1996).

The different motivations have important implications for the situation of the 'reuser'. Whereas take-back obligations may confront producers with excess quantities of returned products for which reuse options have to be found, remanufacturers are reported to have difficulties to obtain sufficient used products of satisfactory quality to be overhauled (Flapper and de Ron, 1996). We conclude by noting that ecological and economical issues are often intertwined. For example, increasing disposal costs make waste reduction more economical, and environmentally conscious customers represent new market opportunities. Ideally, one would like to combine both ecological and economical advantages, as suggested by the concept of a 'sustainable' economy.

With respect to the *type of items* that are recovered, the main categories to be distinguished are packages (e.g. pallets, bottles), rotable spare parts (e.g. machine parts, TV-tubes), and consumer goods (e.g. copiers, refrigerators). These categories differ with respect to when and why items are returned. Packages will be returned rather quickly since they are no longer required once their content has been delivered. Rotable spares are returned upon failure or preventive maintenance, thus typically after a longer time and possibly with some defect. Consumer goods are mostly only returned at the end of their life cycle. This can be rather long and might imply outdating of the product. Another possibility are returns after expiry

of lease contracts. In this case the timing of return is known in advance and can thus be planned for. All these aspects influence the possible forms of reuse of the item considered.

For the different *forms of reuse* many authors have adapted the categorization given by Thierry et al. (1995) which contains direct reuse, repair, recycling and remanufacturing as main options. Examples of items that may be *reused directly* without prior repair operations (though possibly after cleaning and minor maintenance) are reusable packages such as bottles, pallets or containers. The goal of *repair* is to restore failed products to 'working order', though possibly with a loss of quality. Examples are numerous and include a.o. durable products, such as domestic appliances, industrial machines, and electronic equipment. *Recycling* denotes material recovery without conserving any product structures. Examples are metal recycling from scrap, glass and paper recycling, but also plastic recycling. By contrast *remanufacturing* conserves the product identity and seeks to bring the product back into an 'as new' condition by carrying out the necessary disassembly, overhaul, and replacement operations. Traditional examples for remanufacturing are mechanical assemblies such as aircraft engines and machine tools. A more recent example are remanufactured copy machines (Thierry et al., 1995). Remanufacturing has received growing attention especially in the USA (APICS, 1994, 1995). In this review we use 'reuse' as a general term encompassing the above options. In addition, we use 'recovery' when specifying what is actually regained. A major distinction is between *material recovery* (recycling) and *added value recovery* (repair, remanufacturing).

The forms of reuse differ with respect to the production activities to be planned and may involve different levels of coordination. Furthermore, required skills and expertise may differ, imposing constraints on the potential actors involved in reuse activities.

The *actors* involved and their respective functions, including collection, testing, reprocessing, are another important aspect of reuse activities. A major distinction can be made between reuse by the original producer and reuse by a third

party. This sets important constraints on the possibility of integrating forward and reverse logistics activities. From an original producer's perspective the selection of the reuse system functions to carry out in-house involves major strategic trade-offs. Currently producers tend to perform remanufacturing in-house because of the specific product knowledge involved. By contrast, recycling is often carried out by specialized companies (Thierry, 1997). In addition to the actual reprocessing, specialized actors have also emerged for the specific logistics activities and traditional logistics service providers have extended their services. New activities focus in particular on collection and backhaul transportation and on providing reusable transportation packages (Kroon and Vrijens, 1995).

The remaining sections are (loosely) organized around the dimensions discussed above, i.e. motivation for reuse, type of items recovered, form of reuse, and actors involved.

3. Reverse distribution

Reverse distribution is the collection and transportation of used products and packages. Reverse distribution can take place through the original forward channel, through a separate reverse channel, or through combinations of the forward and the reverse channel. Guiltinan and Nwokoye (1975) provided one of the first analyses of reverse distribution networks, identifying four major types of reverse channels according to the actors involved. Pohlen and Farris (1992) claim that the reverse channel may take several different forms depending on individual channel members' functions and ability to perform recycling or remanufacturing tasks. A major issue in reverse distribution systems is the question if and how forward and reverse channels should be integrated. In order to set up an efficient reverse distribution channel, decisions have to be made with respect to:

- *Who are the actors in the reverse distribution channel?*
  Actors may be members of the forward channel (e.g. traditional manufacturers, retailers, and lo-

gistics service providers) or specialized parties (e.g. secondary material dealers and material recovery facilities). This distinction sets important constraints on the potential integration of forward and reverse distribution.

- *Which functions have to be carried out in the reverse distribution channel and where?*
  Possible functions in the reverse distribution channel are: collection, testing, sorting, transportation, and processing (Pohlen and Farris, 1992). A distribution network is to be designed, determining suitable locations for these functions. One important issue is the location of sorting and testing within the network. Early *testing* might save transportation of useless products. On the other hand, sophisticated testing might involve expensive equipment which can only be afforded at a few locations. Decentralized testing is therefore typically restricted to a rather rough, preliminary check. *Sorting* of a return stream into different reusable fractions (e.g. in household waste collection) might be less expensive at an early stage close to collection. However, subsequent handling costs may increase and transportation capacity utilization may decrease for early splitting into distinct streams. Customer ability (and willingness) to partly carry out the sorting function is another aspect to be considered (Jahre, 1995).

- *What is the relation between the forward and the reverse distribution channel?*
  Recycling can often be described as an open-loop system, i.e. the products do not return to the original producer but will be used in other industries. Possibilities for integration of forward and reverse distribution are scant as the actors differ in both channels. Remanufacturing and reuse often lead to closed-loop systems: the product or packaging returns to the original producer. Reverse distribution may either take place through the original network directly, using traditional middlemen or through specialized logistical providers. Even if the same actors are involved, integration of forward and reverse distribution may be difficult at the routing level since collection and delivery may require different handling.
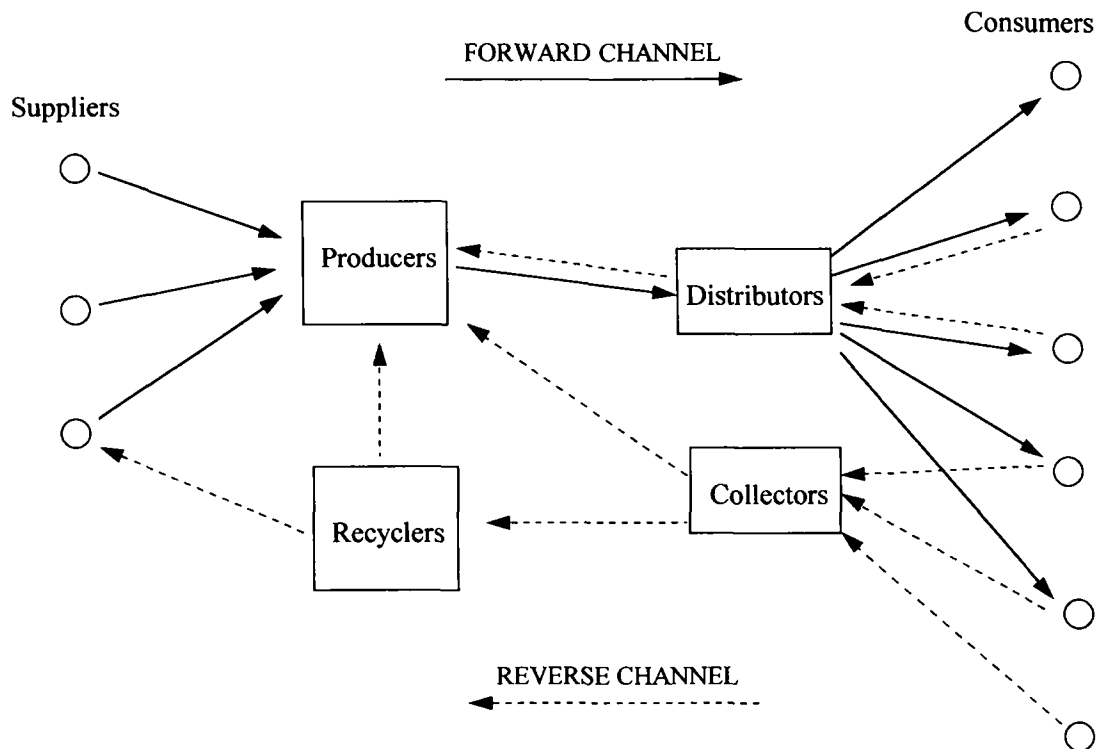
Fig. 1. Framework reverse distribution.

Fig. 1 shows a framework for reverse distribution combining the forward flow from producer to user, and the reverse flow from user to producer. Within this framework, Operational Research methods have been applied to study reverse flow networks. The focus has mainly been on network design issues. We describe models for the separate reverse flow problem in Section 3.1. Models partly using the original forward network for the reverse distribution are described in Section 3.2.

3.1. Separate modelling of reverse flow

Several authors have proposed modifications of traditional facility location models (Mirchandani and Francis, 1989) for the design of reverse distribution networks. One special characteristic to be taken into account is the convergent structure of the network from many sources to few demand points (Ginter and Starling, 1978). Such 'many-to-few' problems have also been studied in the ha-

zardous waste disposal literature (e.g. Batta and Chiu, 1988; Erkut, 1996). By contrast, traditional location models typically consider a divergent network structure from few sources to many demand points.

Another particularity of reverse distribution networks is their high degree of uncertainty in supply both in terms of quantity and quality of used products returned by the consumers. Both are important determinants for a suitable network structure since, e.g., high quality products may justify higher transportation costs (and thus a more centralized network structure), whereas extensive transportation of low value products is uneconomical. Moreover, end-markets for recovered products may not be well known, exposing network planning in this context to even more uncertainty.

Caruso et al. (1993) describe a solid waste management system, including collection, transportation, incineration, composting, recycling and

disposal. A multi-objective location allocation model and some heuristics are used to plan the waste management system. The procedure results in the number and location of waste disposal plants, specification of the technology adopted, and the amount of waste processed.

Kroon and Vrijens (1995) present a return logistics system for returnable containers which was developed in a case study for a logistics service organization in The Netherlands. The system is concerned with the transportation, maintenance, and storage of empty containers. A classical plant location model is formulated to analyse the number of containers, the number of depots and their locations.

Barros et al. (1996) present a network for the recycling of sand from construction waste. Two types of intermediate facilities have to be located. Regional depots receive sand from companies sorting stone materials, test its pollution level, and store clean sand. Specialized treatment facilities receive the polluted sand for cleaning and subsequent storage. Both types of facilities then provide sand to large scale road construction projects. The model is a multi-level capacitated warehouse location model. Scenario analysis is used to cater for uncertainty in location of the demand points and in the return flows.

Spengler et al. (1997) develop a mixed-integer linear programming model for recycling of industrial byproducts which is applied to the German steel industry. Steel companies need to decide which recycling process or process chains are favourable from an economic point of view. Moreover, they should verify cooperation possibilities, decide on the capacities of recycling plants and on their location–allocation. The model is based on the multi-level capacitated warehouse location problem modified for the special problem structure.

3.2. Integration of forward and reverse distribution

At present, there are very few models treating forward and reverse distribution simultaneously. As discussed below, these models consider location of joint facilities for both networks. To the authors' knowledge there are no models dealing with combined routing. We note that in industrial practice rather simple approaches are taken to integrate forward and reverse distribution (e.g. of reusable softdrink bottles). In the network design part, an additional cost component representing collection and return handling is added to the transportation costs. Routings are planned completely forward flow driven, empty bottles are collected along with the delivery tours. Closer investigations whether these simple approaches are adequate have not been reported untill now.

Salomon et al. (1996) develop a Decision Support System REVLOG supporting the design of distribution and collection networks. Given the facility locations, REVLOG determines the optimal good flows in the return network and the resulting costs. In this way different network designs can be compared. In particular, the effects of using existing facilities of the forward network for return tasks can be analysed. REVLOG has been used for educational purposes in a case study of a TV manufacturer, supporting the choice between developing a collection network in-house or outsourcing the reverse flow to third parties.

Del Castillo and Cochran (1996) study production and distribution planning for products delivered in reusable containers. Their model includes transportation of empty containers back to the plants. Availability of empty containers is modelled as a resource constraint for the production of the original product. The model is applied to a case study of a soft-drink company using returnable bottles.

3.3. Summary

In this section we have discussed the distribution aspects of recycling and other industrial reuse activities. Special attention has been paid to the design of the reverse distribution network. We have pointed out that reverse distribution is not necessarily a symmetric picture of forward distribution. Therefore, modifications and extensions of traditional network design models are required. Special characteristics of reverse distribution include a 'many-to-few' network structure and considerable system uncertainty. Both supply of used products by the customers and end markets for

recovered products typically involve many more unknown factors than their counterparts in traditional (forward) distribution networks.

A point of prime importance is the interaction between forward and reverse distribution. While in practice rather simplistic approaches are taken to integrate both transportation flows, scientific literature on these issues is very limited. So far the integration of both channels has only been considered at the network design stage. To the best of our knowledge, no research is available on joint routings, i.e. making use of empty rides for collection and return transfer. However, the amount of additional transportation induced by return flows is a decisive factor in the overall ecological assessment of industrial reuse activities. A closer investigation of these aspects is therefore clearly desirable. A possible starting point may be recent investigations in container transportation systems, including relocation of empty containers (see Crainic et al., 1993). An aspect that might favour further integration of the two channels in practice is closer cooperation of several actors (e.g. logistics service providers) based on modern telecommunication systems, such as electronic data interchange (EDI).

As a general final comment we note that despite the relevance of the topic research publications on reverse distribution are few and far between.

4. Inventory control in systems with return flows

A second key area in reverse logistics is inventory management. Appropriate control mechanisms are required to integrate the return flow of used products into the producers' materials planning. How far traditional inventory management methods are adequate for this task depends on the actors involved in the reuse activities and their respective functions. Specialized recycling companies purchasing used products and/or materials from third parties may possibly rely on traditional inventory control methods. In their case used products simply represent input resources for a specific production process. The situation is different if the used products are returned to the original producer and provide an alternative input resource in

the fabrication of new products. As pointed out in Section 2 this applies, e.g., to the automobile industry where spare parts can often be made out of used parts and the electronics industry where returned modules can be reused in new products (Thierry, 1997; Ferrer, 1997).

A general framework for this situation is depicted in Fig. 2: The producer meets demand for new products and receives used products returned from the market. He has two alternatives for fulfilling the demand. Either he orders the required raw materials externally and fabricates new products or he overhauls old products and brings them back to 'as new' conditions. The objective of inventory management is to control external component orders and the internal component recovery process to guarantee a required service level and to minimize fixed and variable costs.

The producer typically has little control on the return flow in terms of quantity, quality and timing. This is a consequence of the take-back obligations imposed by current environmental legislation, reflecting enhanced producer responsibility. The effects of the return flow in this situation are twofold. On the one hand it may be cheaper to overhaul an old product than to produce a new one. On the other hand reliable planning becomes more difficult due to increased uncertainty which may lead to higher safety stock levels. To avoid excess inventory of used products disposal may be an additional option (possibly adding to the costs).

It should be noted that the system as given in Fig. 2 encompasses a production planning component of the recovery process. However, detailed scheduling of this process is not a prime concern of the approaches discussed in this section. The recovery process is treated in a rather aggregated way, characterized by time and cost parameters. In Section 5 we discuss models focussing on the production operations. Consequently, the technical form of the recovery process has a low impact on the above framework. Recycling, repair, and remanufacturing all fit into this setting. In the case of direct reuse the recovery process may vanish completely with returned products directly entering the serviceable inventory.

Other input parameters that need to be determined externally to the system considered here
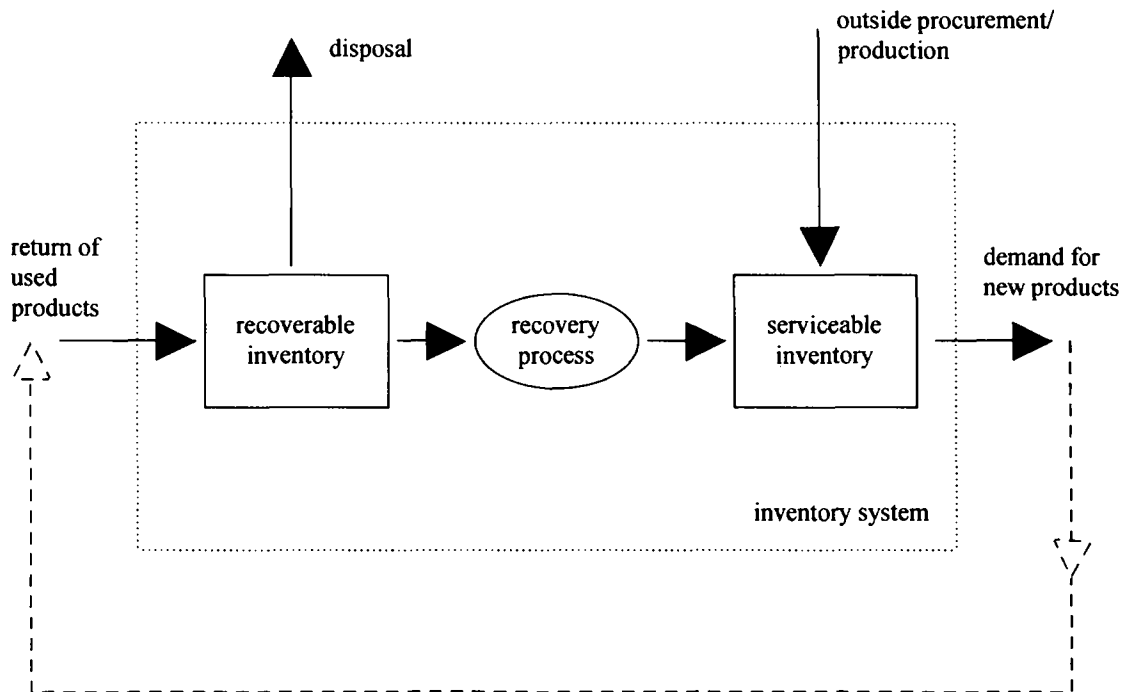
Fig. 2. Framework inventory management with returns.

include a suitable financial valuation of the returned items and forecasting of future returns. While these topics are far from trivial, a detailed discussion goes beyond the scope of this review.

The framework outlined above differs from traditional inventory control situations essentially in three aspects. First, as a consequence of the return flow the inventory level between new component replenishments is no longer necessarily decreasing but may increase also. This loss of monotonicity significantly complicates the underlying mathematical models. A possible starting point for a closer analysis of this aspect are cash-balancing models comprising in and outbound flows (Constantinides, 1976). In practice, this situation is frequently reduced to a traditional setting by simply 'netting' the demand against the returns. Second, the two alternatives for fulfilling the demand impose an additional set of decisions to be taken. External orders and recovery have to be coordinated. This can be compared with a two supply mode inventory system with the special property that supply of one mode cannot fully be controlled. Third,

by distinguishing between products yet to be overhauled and serviceables the situation described above naturally leads to a two-echelon inventory system. Thus, investigations on adequate echelon stock control strategies, such as PUSH versus PULL policies are relevant in this context.

In the sequel we discuss the models proposed in literature within this framework. The models mainly differ with respect to assumptions on demand and return processes and on the recovery process. A first major classification can be made into deterministic versus stochastic models.

4.1. Deterministic models

In deterministic inventory models information on all the components of the framework presented in Fig. 2 is assumed to be known with certainty. In particular, demands and returns are known in advance for every point in time. The objective is to strike an optimal trade-off between fixed setup costs and variable inventory holding costs. This corresponds to the mindset of the basic EOQ

formula in classical inventory theory. Several authors have proposed modifications to this formula taking return flows into account.

A first model of this type was proposed by Schrady as early as 1967. He assumes constant demand and return rates and fixed leadtimes for external orders and recovery. The costs considered are fixed setup costs for orders and recovery and linear holding costs for serviceables and recoverables. For this model Schrady proposes a control policy with fixed lotsizes serving demand as far as possible from recovered products. Expressions for the optimal lotsizes for order and recovery are derived similar to the classical EOQ formula. In particular the optimal order–lotsize equals the EOQ formula applied to the 'net' demand rate (i.e. demand minus returns) in the case of identical holding costs for serviceables and recoverables.

More recently some extensions to the model of Schrady have been proposed by Mabini et al. (1992). They consider stockout service level constraints and a multi-item system where items share the same repair facility. This is one of the very few models considering multi-item inventories in the context of reversed logistics. For these extended models numerical solution methods are proposed.

A model equivalent to the one by Schrady but with a different control policy has been proposed by Richter (1996a, b). For this policy he gives expressions for the optimal control parameter values and discusses their dependence on the return rate.

All these models share the drawback of optimizing the parameters of a predetermined control policy, without studying optimality of the policy itself. To our knowledge there are no results regarding the structure of optimal policies.

4.2. Stochastic models

In this section, we discuss inventory models that treat demands and returns as stochastic processes. First, we characterize the well-known repair models within this framework.

4.2.1. Repair systems

Repair systems consider the replacement of failed items by spares. Failed items are repaired as far as possible and subsequently enter the spares

inventory. In terms of the framework of Fig. 2 repair systems can be characterized by two properties. First, returned items are – as far as possible – immediately replaced by issuing new ones. That is, every return is accompanied by a demand for the same amount. Consequently, returns do not lead to an increase of the total inventory on hand. (In most models the reverse also holds. That is, every demand entails a simultaneous return. In this case demand and return flow are perfectly correlated.) Second, the system is essentially closed in that the total number of items remains constant. These characteristics distinguish repair models from the more general product recovery models discussed in Section 4.2.2. The main question addressed by repair models is how many spares are needed to guarantee a certain degree of availability of the system.

Literature on repair systems is abundant. Many authors have contributed to well establishing this field through the last four decades. Since excellent literature reviews are available we refer the reader to, among others, Pierskalla and Voelker (1976), Nahmias (1981), Cho and Parlar (1991), and Mabini and Gelders (1991).

4.2.2. Product recovery systems

In this section we discuss stochastic inventory models for general product recovery situations. In contrast with the repair models discussed in Section 4.2.1 there are no a priori assumptions on the relation between the demand and return process. Typically they are seen as rather loosely coupled. This reflects the situation where due to time lag and a large population of customers a returned item can rarely be assigned to a specific demand occurrence. Many models therefore assume demands and returns to be independent stochastic processes. However, in principle, any joint probability distribution for demands and returns is admissible. We follow the traditional classification of stochastic inventory models into periodic versus continuous review models.

Periodic review models. Attention has been focused mainly on deriving optimal control policies under various assumptions, minimizing expected costs over a finite planning horizon.

A system where recoverable and serviceable inventory coincide because returned products can be reused directly has been modelled by Cohen et al. (1980). They assume that a fixed share of the products issued in a given period is returned after a fixed leadtime. This model is an extension of a simple stochastic inventory model with proportional costs only, to a situation with reusable items. The objective is to optimize the trade-off between holding costs and shortage costs. Cohen et al. show that under certain assumptions a one-parameter 'order upto' policy is optimal. However, as disposal is not considered the optimal inventory target level will not be attainable if it is exceeded by the returns. This documents the complicating effect of the loss of monotonicity of the inventory level as discussed in the introduction of this section.

A similar model taking also fixed costs into account has been proposed by Kelle and Silver (1989b). They formulate a chance-constrained integer program based on the 'net' demand per period and discuss an approximation procedure for transforming this problem into a classical dynamic lotsizing problem (see Wagner and Whitin, 1958).

A first product recovery model explicitly considering distinct inventories for serviceables and recoverables was proposed by Simpson (1978). He considers the trade-off between material savings due to reuse of old products versus additional inventory carrying costs and proves optimality of a three parameter policy to control order, recovery, and disposal when neither fixed costs nor leadtimes are involved.

Recently, the work of Simpson has been pursued by Inderfurth (1996, 1997) by considering the effects of non-zero leadtimes for orders and recovery. He shows that a decisive factor for the complexity of the system is the difference between the two leadtimes. For identical leadtimes his model is the same as Simpson's. For different leadtimes the growing dimensionality of the underlying Markov model prohibits simple optimal control rules.

Inderfurth also considers the case of a PUSH strategy for recovery, avoiding storage of recoverables. For identical leadtimes a model similar to Cohen et al.'s, extended by a disposal option, is obtained and a two parameter 'order upto, dispose down to' policy is shown to be optimal. Different leadtimes again result in fairly intractable situations.

Continuous review models. In these models the time axis is modelled continuously and the objective is to find optimal static control policies minimizing the long-run average costs per unit of time.

Heyman (1977) analyses disposal policies to optimize the trade-off between additional inventory holding costs and production cost savings. He discusses a model with independent demand and return occurrences with generally distributed quantities and inter-occurrence times. Remanufacturing and outside procurement are instantaneous, resulting in perfect service and only one inventory to be considered. Furthermore, no fixed costs are taken into account. The system is controlled by a single parameter disposal level strategy: incoming remanufacturables exceeding this level are disposed of. Heyman shows the equivalence of this model to a single server queuing model. For the case of Poisson distributed demands and returns he derives an explicit expression for the optimal disposal level. Furthermore, he proves optimality of the one parameter policy in this case. For generally distributed demands and returns an approximation is given.

Muckstadt and Isaac (1981) consider a similar model with explicit modelling of a remanufacturing facility with non-zero leadtimes. In contrast with the above approach disposal decisions are not taken into account and demand and return occurrences are assumed to be of unit quantity following a Poisson distribution. The costs considered comprise serviceable holding costs, backorder costs and fixed procurement costs. A control policy is proposed that controls outside procurement according to a traditional (s, Q) rule whereas returned products are remanufactured as soon as possible. An approximation procedure based on the distribution of the net inventory is presented to determine the optimal values of s and Q. In a second step these results are carried over to a two echelon model.

For the above single echelon model an alternative approximation procedure based on the distribution of the net demand during the procurement leadtime has been proposed by Van der Laan et al.

(1996a). A numerical comparison by Van der Laan (1993) shows this approach to be more accurate in many cases. The model is also extended to include disposals by keeping the number of remanufacturables in inventory limited to a maximum level N.

Finally, Van der Laan et al. (1996b) present a numerical comparison of several disposal strategies. They show that it is advantageous to base disposal decisions on both the inventory level of remanufacturables and an adequately defined total inventory position.

4.3. Summary

In this section we have discussed inventory systems with material return flows. We have pointed out in how far these systems, arising in the context of industrial reuse activities, require extensions to traditional inventory control methods. A major characteristic is the growing uncertainty within the system which partly counterbalances the material savings. Mathematically, the return flow entails a loss of monotonicity of the inventory level, which complicates the analysis of the resulting models.

The results in the literature are rather isolated and widely dispersed. No unifying approach, analysing systematically the impact of reuse activities on inventory management, has been presented yet. In particular, no results are available on numerical comparisons of traditional versus specifically adapted inventory control methods in a return flow environment. Such results clearly would be desirable to assess the rather simplistic methods of current industrial practice and the relevance of extended approaches suggested by researchers. Moreover, nearly all the models proposed so far are one-product, one-component models. Obviously, practical situations usually involve multi-component product structures. Extensions of the current models to multi-echelon systems are therefore desirable.

Finally, we note that recent advances in information technology may contribute to a better control of the systems discussed in this section. Large scale collection, transmission, and analysis of electronic data may considerably decrease system uncertainty. Examples are continuous monitoring

of machine parts and codings for unique identification of returned products (e.g. pallets, bottles). This way information on the actual condition of individual items and statistical data for reliable forecasting may be obtained. It is, however, an open problem how to incorporate such information adequately in the control strategies.

Summing up the discussion we conclude that inventory systems with material return flows are a relevant research topic with many open questions.

5. Production planning with reuse of parts and materials

A third field to be reviewed in the context of reuse activities is production planning. The kind of planning problems arising and the adequacy of traditional production planning methods depend to a large extent on the specific form of reuse considered. A framework for the activities involved is given in Fig. 3.

In the case of direct reuse where returned products can be reused 'as is' (possibly after cleaning or minor repair) no additional production process has to be taken into account. As noted earlier this applies to reusable transportation packages such as pallets, boxes or bottles. In these instances focus is on inventory and distribution–collection aspects rather than on production planning (see Sections 3 and 4).

Material recycling surely does involve new production processes. Returned parts and products have to be transformed into raw material by means of melting, grinding etc. However, the difficulty lies in the technical conversion to usable raw materials rather than in managerial planning and control of these activities. From a production management point of view these activities are no different from other production processes. Consequently, conventional production planning methods should suffice to plan and control recycling operations. The situation may become more complex if disassembly is required prior to the actual recycling process.

By far the most complex situation is found in remanufacturing. Individual repair requirements

repair

new parts

disassembly

new products

old products

(re) assembly

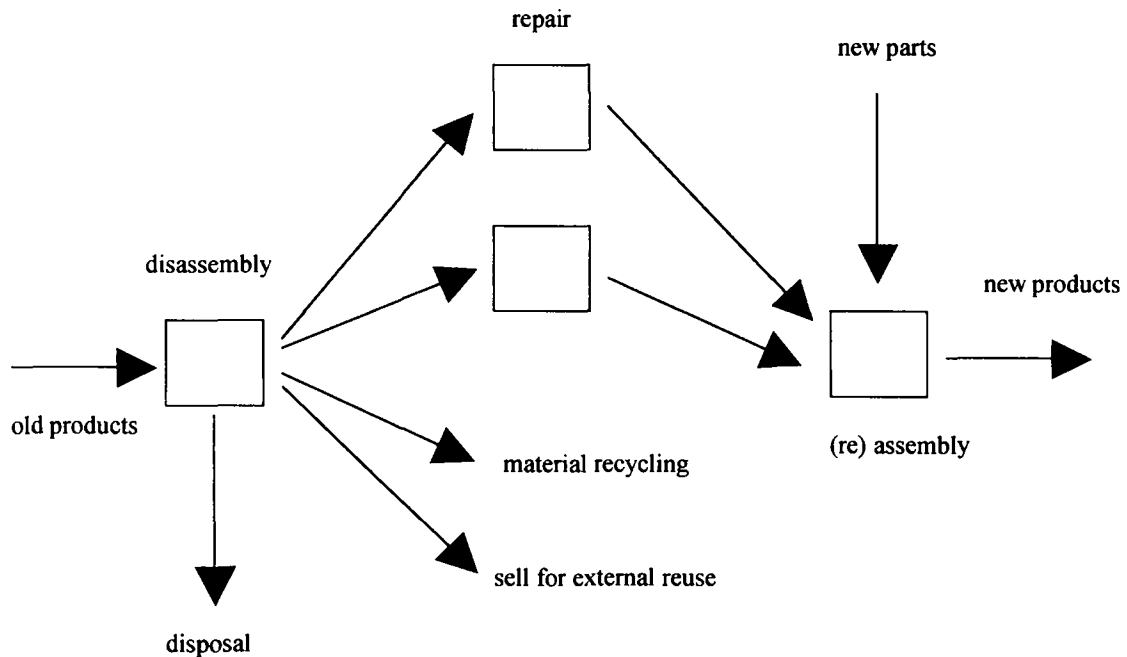material recycling

sell for external reuse

disposal

Fig. 3. Framework production planning with reuse.

for every product returned, and coordination of several interdependent activities makes production planning a highly sophisticated task in this environment (Lund, 1984). The repair operations needed to convert a returned product (in this context also referred to as 'core') back to an 'as new' state depend on the actual condition of the product. This may vary from instance to instance and can in general only be decided after a number of testing and disassembly operations. Therefore, in contrast with traditional manufacturing no well-determined sequence of production steps exists in remanufacturing. This exposes planning in a remanufacturing environment to a much higher uncertainty (Guide et al., 1996). A high level of coordination is required in remanufacturing due to the interdependence between different parts and subassemblies. Disassembly of a returned product is not a procurement source for one individual part but releases various parts simultaneously. Furthermore capacity problems may arise if several parts require the same repair facility. Analogous problems may be encountered for equipment common to new production and repair.

In view of the largely differing forms of reuse the selection of a specific recovery option for a given product is an important task. Technical feasibility sets the constraints for this selection. Within these constraints feasible options are to be compared with respect to their economical attractiveness. This topic is discussed in more detail in Section 5.1. Section 5.2 is concerned with scheduling of the related production and repair operations.

5.1. Selection of recovery options

Prior to actually processing returned products the specific forms of reuse have to be decided upon. For complex product structures this involves the selection of an appropriate disassembly level and of processing options for the components released, taking into account technical as well as economical considerations. Economically the major trade-off is between costs for disassembly and repair and the material value of the recovered components. Several authors have proposed mathematical optimization problems to formalize this

decision. These approaches are related with graph theory and rely mainly on a tree representation of the product structure. A main difficulty is the high amount of input data required. In particular, estimations are required of the costs and processing times of all possible disassembly and repair operations. These may be hard to obtain in practice. In addition to determining the most attractive way to recover a given product a major purpose of these approaches is to assist in product design. 'Design for recycling' and 'design for disassembly' have received much attention in the engineering sciences (Kriwet et al., 1995). The algorithms discussed in this subsection provide tools for comparing the 'reusability' of different product designs from an economical point of view.

Johnson and Wang (1995) propose a model for determining an optimal disassembly sequence for a given product structure. The main idea is to disassemble parts in the order of decreasing value and to continue disassembly as long as the marginal benefits outweigh the marginal disassembly costs. Furthermore, attempts are made to cluster similar parts for simultaneous treatment. A network flow algorithm is given that follow these ideas subject to technical constraints.

Penev and de Ron (1996) present an algorithm for optimal 'cannibalization' of returned products. Optimal disassembly sequences are sought to release a number of preselected components from the product. To this end a shortest path algorithm is proposed. Subsequently, additional disassembly steps can be performed as long as they are economically attractive. All parts released are assigned to one of several reuse options.

Krikke et al. (1996) propose a model that takes the actual condition of the used product into account. They point out that feasibility of certain reuse options may depend on this condition. Therefore they introduce 'quality classes' for every component and consider transition probabilities for the quality of a subassembly given the quality of the parent assembly. A stochastic dynamic programming algorithm is presented to determine an optimal decision rule maximizing total expected profit. To each subassembly a reuse option (including a.o. recycling, incineration, and further disassembly) is assigned for each quality class.

5.2. Scheduling in a product recovery environment

As indicated in the introduction of this section coupled supply of different (used) parts and varying repair requirements are features that distinguish reuse environments from traditional production systems. These aspects have to be taken into account in handling the corresponding production activities. In Section 5.2.1 we review Material Requirement Planning (MRP)-based approaches, while Section 5.2.2 is dedicated to specific operational control aspects of remanufacturing.

5.2.1. MRP for product recovery

A standard concept for scheduling production requirements in order to match demand is MRP. Several authors report on current industry practice, in particular in the remanufacturing industry, in using traditional MRP systems to plan recovery operations (see Thierry, 1997 for an overview). A number of conceptual difficulties arise in the use of traditional MRP in this context. In particular, the dependency between components simultaneously obtainable by disassembly and the choice between multiple supply sources (e.g. different returned products) cannot be handled adequately by a simple level-by-level top down approach as in traditional MRP. Therefore modifications to MRP have recently been proposed to meet the special requirements involved in product recovery planning. Most of these approaches make use of a 'reverse' bill of materials (BOM), documenting for every returned product the content of components and the processing times required to release them. This 'reverse' BOM is not necessarily a symmetric picture of the original BOM as not all components might be (fully) reusable.

Gupta and Taleb (1994) consider a situation with demand on component level rather than on product level. The objective is to schedule the required disassembly operations. The algorithm proposed takes into account the dependency between components in the same product. The component with the largest requirements determines the number of products to be disassembled.

Taleb and Gupta (1996) extend this approach to situations with parts commonality across different products. As there may now exist different

options to obtain a certain component the objective is to choose the cheapest one with respect to total disassembly and procurement costs. Again, the coupling of components within the same product has to be taken into account. The authors propose a two-phase algorithm to solve this problem. First, the total number of products to be disassembled is determined. Then, the corresponding disassembly operations for these products are scheduled over the planning periods.

Flapper (1994a, b) considers a situation with demand on product level. Components required for these products may be obtained from disassembly of old products as well as from purchasing new ones. The objective is to schedule simultaneously the required disassembly, repair, and assembly operations (see Fig. 3). To this end repaired and unrepaired instances of a given component are treated as different items in the proposed MRP scheme, linked by a special BOM. A disadvantage of this model is the use of predetermined priority lists in case of multiple procurement options for a required component. This neglects the dependencies between components simultaneously obtainable since the optimal procurement source for a given component may depend on the requirements for other components.

This difficulty has been overcome in the approach by Clegg et al. (1995). They present a linear programming model to determine for each product the cost-optimal quantities to be overhauled, disassembled into components and disposed in each period. Analogously, for each component, quantities for reuse and for disposal are determined given demand and return for products over a planning horizon. They consider purchasing, inventory, disposal, and processing costs and sales revenues. The model is proposed as a tool for investigating the interaction of the various input parameters, in particular the different cost components.

All of the above approaches are purely deterministic. However, as discussed earlier uncertainty is a major characteristic in product recovery systems. The importance of integrating measures to handle uncertainty into MRP has also been discussed for traditional production systems (see e.g. Murthy and Ma, 1991). For product recovery systems these considerations are even more relevant.

Thierry (1997) compares different MRP approaches for remanufacturing with respect to their behaviour under uncertainty. A simulation study is presented to compare safety stock levels required to guarantee a given service level under stochastic demand, returns, and yields. Thierry concludes that introducing a separate BOM for used products specifying the expected amount of reusable components is the most appropriate method. Predicting safety stock levels turns out to be very difficult since they depend in a complex way on various parameters.

5.2.2. Shop floor control in remanufacturing

A particular characteristic of remanufacturing is non-standard shop floor routing due to individual repair requirements for every core. This element of uncertainty has been addressed by Guide et al. (1996, 1997a, b) in a number of simulation studies. These investigations are based on a case study of an overhaul centre for military aircraft engines, a job shop environment concerned with repair operations on parts of disassembled cores.

In this setting Guide et al. (1997a) investigate the influence of different parts release policies from disassembly into the remanufacturing shop and of different priority rules for queue control at the work centres. They conclude that these policies do not have a significant influence on the performance of the remanufacturing system and suggest simple policies based on the order of disassembly. It is worth noting that batching policies do not seem to perform well in this context since the batches are split up due to differences in repair requirements. The fact that time–phased release of parts based on expected repair times does not perform any better than other policies leads Guide et al. to question the value of MRP for remanufacturing. They state that remanufacturing is incompatible with the need for standardization that is fundamental for MRP.

As an alternative to MRP Guide (1996) proposes scheduling according to the drum–buffer–rope concept (Schragenheim and Ronen, 1990). Following the philosophy of synchronous manufacturing a continuous work flow is sought by focusing control on production bottlenecks.

Guide et al. (1997b) investigate the impact of uncertain shop floor routings on capacity planning. They propose modifications to traditional rough cut capacity planning techniques by introducing discount factors to account for uncertain reusability and repair requirements. The techniques are again tested by simulation.

5.3. Summary

In this section we have reviewed production planning issues in reverse logistics. A generic new set of questions arises with respect to the selection of the most attractive reuse options. We have stressed the strong link of this topic with engineering and product design.

Extended approaches are required for the scheduling of production activities related with product and material reuse. Two aspects add complexity to this task, namely an additional disassembly level and high uncertainty with respect to timing, quantity, and quality of the return flow. These aspects notably affect reuse options with a high level of conservation of original product structures, such as remanufacturing. As stated earlier, modern information technology may provide means for reducing the level of uncertainty.

While consensus is rather broad that traditional MRP systems fail to handle these aspects adequately, few alternatives have been proposed in the scientific literature. In particular, the integration of the increased uncertainty has not received much research attention so far.

It is the overall impression that production planning in a reuse context has not yet been well investigated. While some specific aspects have received more attention in a number of case studies, a comprehensive framework has not been established. Contrasting this with the large number of practical examples of industrial reuse activities we conclude that scientific research significantly lags behind current practice in this field.

6. Conclusions

In this survey we have addressed the logistics of industrial reuse of products and materials from an Operational Research perspective. Reuse occurs in a large diversity of forms and not all reuse activities necessarily require new planning approaches. Traditional methods from the fields of distribution planning, inventory control, and production planning can readily be applied to a number of planning problems arising in this new context. This is also the approach prevalent in current industrial practice.

However, not all reuse activities fit into the traditional setting. In the preceding sections we have pointed out situations that require new planning methods. Specifically, it is the interaction of the new reverse material flows and the traditional forward flows that adds complexity to the systems involved. In a number of situations these two flows cannot be treated independently but have to be considered simultaneously to achieve adequate planning. A second general observation is the increasing uncertainty in systems involved in reuse. Used products are a far less homogeneous and standardized input resource than traditional raw materials and new parts. To handle this uncertainty adequately is one of the major tasks in the planning of reuse activities. Modern information technology may play an important role in this context.

As a scientific field reverse logistics is still rather young. The results published to date are rather isolated. Comprehensive approaches are rare. This stands in sharp contrast with the large number of practical examples of industrial reuse activities, as documented by case studies and trade publications, and with the interest in the technical aspects of recycling and reusability. Finally, we note that research on reverse logistics has been confined to rather narrow views on single issues. The influence of return flows on supply chain management is a topic that deserves further research efforts.

With this survey we hope to contribute to a better understanding of the issues in reverse logistics and to encourage further research in this field. In view of environmental consciousness and legislation, the importance of industrial reuse activities is increasing rapidly. Operational researchers can make an important contribution to carrying out the ecologically required changes in industrial production in an economically attractive way.

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