A closed-loop logistics model for remanufacturing

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Recoverable product environments are becoming an increasingly important segment of the overall push in industry towards environmentally conscious manufacturing. Integral to the recoverable product environment is the recoverable manufacturing system that focuses on recovering the product and extending its life through remanufacture or repair. Remanufacturing provides the customer with an opportunity to acquire a product that meets the original product standards at a lower price than a new product. The flow of materials and products in this environment occurs both from the customer to the remanufacturer (reverse flow), and from the remanufacturer to the customer (forward flow). Since most of the products and materials may be conserved, essentially this forms a closed-loop logistics system. We present a 0–1 mixed integer programming model that simultaneously solves for the location of remanufacturing/distribution facilities, the transshipment, production, and stocking of the optimal quantities of remanufactured products and cores. We also discuss the managerial uses of the model for logistics decision-making.

**Keywords:** distribution; environment; reverse logistics; mixed-integer programming; remanufacturing

**Introduction**

There are numerous ways to minimise the environmental costs of manufacturing, but the prevention of waste products avoids many environmental costs before they occur. A material recovery system; referred to as a recoverable product environment, includes strategies to increase product life consisting of: repair, remanufacturing, and recycling of products.\(^1\)\(^-\)\(^4\) In this study, the term recoverable product environment is used to describe the processes in a system that are designed to extend product life and recover materials via recycling at the end of the product life (Figure 1). A recoverable product environment is a closed-loop system incorporating traditional logistics forward flows with logistics channels reversed. In a closed-loop system new materials are needed to replace only materials which are not recovered by the system and the end-users are the source of input materials as well as customers of the system. A major part of the recoverable product environment is the recoverable manufacturing system that focuses on systems designed to extend product life cycles via remanufacturing and repair. These recoverable aspects are concerned with the management of the flow of materials (known as cores) from the consumer, transformation of these cores into products which satisfy the original quality and other standards (including for the procurement of new materials), and finally managing the flow of remanufactured products to distribution centers and/or the final customer. This is a closed-loop logistics system and it is this problem of product flows that we seek to address in this research.

We begin with a discussion of recoverable manufacturing systems and the associated logistics channels and a discussion of environmentally conscious supply chain management follows. In later sections we will present our model for closed-loop logistics and discuss its use as a management decision support tool.

**Recoverable manufacturing systems**

The term recoverable product environment is used here to describe the processes in a system designed to extend product life and ultimately recover materials via recycling at the end of the product life (Figure 1). Several authors have recognized the need for recoverable manufacturing systems and have cited the need for managerial support...
systems that recognise the inherent uncertainties contained in such a system. Vandermerwe and Oliff called for the development of manufacturing infrastructures to support recoverable manufacturing systems. Other authors have recognised the problem of developing reverse logistic systems as part of environmentally conscious supply chain systems required to support recoverable manufacturing systems.

The basis of a recoverable manufacturing system is remanufacturing. Remanufacturing offers several advantages as a form of waste reduction since it is profitable and environmentally conscious. Remanufacturing is the transformation of used units, consisting of components and parts, into units which satisfy exactly the same quality and other standards as new units. For a remanufacturing operation to function effectively, an organisation must be concerned with planning for the traditional forward flows of goods to the customer and the reverse flow of cores from end users (a closed-loop system). This work focuses on a closed-loop logistics model for use with a recoverable manufacturing system which will enable managers to make better decisions with respect to different factors including, but not limited to, the set of distribution/remanufacturing locations to be open and operate; what products to remanufacture and stock in these open distribution/remanufacturing locations; and in what quantities to stock them. The transportation of cores from customers to these distribution/remanufacturing locations and the remanufactured products from these locations to customers are other decisions to be made. We propose the use of a deterministic model to serve as a starting point in designing a reverse distribution network.

Environmentally conscious supply chain management

There are a growing number of companies interested in minimising the environmental impact of their products and services and an increasing interest in taking a proactive rather than an ‘end-of-pipeline’ approach. Many firms are becoming aware that clean products and processes produce less waste for disposal and this reduces direct costs, as well as potential liability costs. In the European Union, Germany has enacted the German Packaging Order and the German Recycling and Waste Control Act, which make the manufacturer responsible for avoiding waste.

These acts require companies to be concerned with the reverse flow of products from the consumer, as well as the traditional forward flow of products to the consumer. Such logistics systems become closed-loops, with the new material only being required when demand exceeds the supply of recoverable items.

It is expected that the rest of the European Union will follow Germany’s lead in environmental legislation and recently the International Organisation for Standardisation established a set of international standards (ISO 14000 and ISO 14001) for environmental management systems. This environmental focus is not limited to the EU, as Harrington reported on efforts for developing environmentally conscious supply chain systems at a number of companies in the US, including AT&T, Baxter Healthcare and Hewlett Packard. Unfortunately, there is very little literature to assist the practising manager in this area. Most of the research available simply identifies the need for closed-loop logistics models to be developed which explicitly recognise the complexities of incorporating reverse logistics flows.

Reverse logistics has been defined as ‘...all the activities required to move a product from a point of use to a point of disposition’.

A study by the Council of Logistics Management (CLM) reported that there are three key issues affecting reverse logistics: (1) the structure of the network; (2) the planning for material flows; and (3) the classification and routing of materials. A key aspect to recognise reverse flows is that the collection of goods from the marketplace is a supply-driven flow, rather than demand-driven flows seen in forward flow logistics systems. A supply-driven flow is outside of direct control by a company. For a company to obtain products for remanufacturing, the consumer must be willing to give up the product. This supply-driven flow creates a great deal of uncertainty with respect to the quantity, timing and condition of items. Since the supply of items for a recoverable manufacturing system may be out of the direct control of the company, predicting the quantity of goods available at any point in time may be difficult. Several authors have addressed the problems of forecasting returns: we refer the interested reader to these works. Despite these efforts at predicting return flows of items, most logistics systems are not designed for return flows.

There are few guidelines available for a company wanting to develop a closed-loop logistics system to support a recoverable manufacturing system. Jahre and Flygansvær developed a theoretic framework for logistics systems and proposed a set of managerial propositions based on a series of case studies. The most important aspect reported is that closed-loop systems provide for better control, reuse of products, in addition to recovering material. Jahre and Flygansvær also reported that the convenience of many product take-back locations, and the resulting higher return rates may be also obtained when returns are required to get a new item or an upgrade. Kooi et al. discusses the development of a reverse logistic model whose objective is to minimise the sum of transportation, processing, and facility investment costs. The model implicitly assumes that a product recovery and disposal strategy that balances supply and demand is already in place.

There is a large body of research on location models, some of which deserves mention here. Mathematical location models are designed to address a number of questions