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Production planning of a hybrid manufacturing–remanufacturing system under uncertainty within a closed-loop supply chain

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ABSTRACT

This paper deals with the production planning and control of a single product involving combined manufacturing and remanufacturing operations within a closed-loop reverse logistics network with machines subject to random failures and repairs. While consumers traditionally dispose of products at the end of their life cycle, recovery of the used products may be economically more attractive than disposal, while remanufacturing of the products also pursues sustainable development goals. Three types of inventories are involved in this network. The manufactured and remanufactured items are stored in the first and second inventories. The returned products are collected in the third inventory and then remanufactured or disposed of. The objective of this research is to propose a manufacturing/remanufacturing policy that would minimize the sum of the holding and backlog costs for manufacturing and remanufacturing products. The decision variables are the production rates of the manufacturing and the remanufacturing machines. The optimality conditions are developed using the optimal control theory based on stochastic dynamic programming. A computational algorithm, based on numerical methods, is used for solving the optimal control problem. Finally, a numerical example and a sensitivity analysis are presented to illustrate the usefulness of the proposed approach. The structure of the optimal control policy is discussed depending on the value of costs and parameters and extensions to more complex reverse logistics networks are discussed.

1. Introduction

The management of return flows induced by the various forms of reuse, or recovery of products and materials in industrial production processes has received growing attention throughout the last two decades among practitioners as well as scientists. This is due to the constant search for increased productivity, a better service to clients, as well as environmental concerns and the goals of sustainable development in general. Work in this area may be found as early as the 1900s. As an example, Amezquita and Bras (1996) analyzes the remanufacturing of an automobile clutch and Lund (1996) edited a comprehensive report on the remanufacturing industry. According to the American Reverse Logistics Executive Council, "*Reverse logistics can be viewed as the process of planning, implementing and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information, from the point of consumption back to the point of origin, for the purpose of recapturing their value or proper disposal*" (Rogers and Tibben-Lembke, 1998).

Accordingly, Fleischmann et al. (1997), point out that reverse logistics encompasses the logistic activities all the way from used products no longer required by the user to products again usable in a market. There is a major distinction between material recovery (recycling) and added value recovery (repair, remanufacturing). They describe the general framework of Reverse distribution systems, composed of the "Forward channel", going from the suppliers and through the producers and distributors to the consumers, and of the "Reverse channel", going back from the consumers through collectors and recyclers, to the suppliers or producers. 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 backward flow opposite to the conventional forward supply chain flow is the concern of the recently emerged field of "reverse logistics".

Reverse logistics systems have been classified into various categories depending on the characteristics that are emphasized. Thus several classifications may be found in the literature: Seaver (1994) focuses on design considerations for the different types of recovery operations based upon the Xerox Corporation

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experience; Fleischmann et al. (1997) propose a comprehensive review of quantitative approaches and distinguish the types of returned items; Rogers and Tibben-Lembke (1998) analyze trends and practices; Thierry et al. (1995) analyze the main options for recovery. Theses authors distinguish two categories or reverse logistic systems and four types or return items or services. The two categories of reverse logistic systems are *open and closed-loop systems*, depending on whether the return operations are integrated or not with the initial operation. The four categories of return items or services are the following: *reusable items* (such as returned products or pallets), *repair services* (where the products are sent back to the consumer after repair), *remanufacturing*, an industrial process in which used, end of life products are restored to like-new conditions and put back into the distribution system like the "new products" and the *recycling* of raw materials and wastes.

Many case studies and papers proposing models have been published in the area of reverse logistics as well as several reviews. See De Brito et al. (2003) for a review of case studies; Dekker et al. (2004) for a review of quantitative models for closed-loop supply chains; Geyer and Jackson (2004) who propose a framework to help identify and assess supply loop constraints and strategies and they apply it to the recycling and reuse of structural steel sections in the construction sector; and Bostel et al. (2005) for a review of optimization models in terms of strategic, tactical and operational planning, distinguishing weak and strong connections between forward and reverse flows. Special issues of journals have been devoted to the area of reverse, or closed-loop logistics: Verter and Boyaci (2007) edited a special issue journal on optimization models for reverse logistics; Guide and Van Wassenhove (2006, Parts 1 and 2) edited a two parts feature issue journal on Closed-Loop Supply Chains.

As can be seen from the numerous published literatures on reverse logistics, many industrial cases have been reported and many scientific planning or optimization models have been proposed. These cases and models differ by numerous characteristics. One of the the most complex situation is found in remanufacturing activities. Traditional areas for remanufacturing are the automotive or aeronautic sectors (machinery and mechanical assemblies such as aircraft engines and machine tools) as well as the remanufacturing of toner cartridges (see the report by Lund (1996) about the remanufacturing industry). An example is Hewlett-Packard, which collects empty laser-printer cartridges from customers for using them again (Jorjani et al., 2004). Other examples are described in the next section.

Individual repair requirements for every product returned, and coordination of several interdependent activities makes production planning a highly sophisticated task in this environment. In contrast with traditional manufacturing systems (forward direction), no well-determined sequence of production policies exist in remanufacturing (backward or reverse direction). This is illustrated by Sundin and Bras (2005) who describes a model of remanufacturing steps not following a specific order. In many cases, the original manufacturer is in charge of collecting, inspecting and refurbishing the used products prior to remanufacturing them.

Production planning in a hybrid context, involving manufacturing and remanufacturing activities, referred to as forward–reverse logistics in a closed-loop network, is very complex especially in the presence of uncertainties and under the consideration of the overall system's dynamics. Much of the work in the area of remanufacturing, or in the hybrid context, is devoted to the strategic design of the closed-loop system, or to the tactical or operational planning of production and management of inventories, considering discrete periods of time. See the next section for a more comprehensive review of literature related to the remanufacturing activities.

In this paper we address the area of an integrated combined manufacturing–remanufacturing system within a closed-loop supply chain subject to uncertainties. We study the production planning of such a hybrid system in a dynamic continuous time stochastic context. Uncertainties are due to machine failures and continuous time modeling seems to us a better framework to consider stochastic aspects than discrete-time. We found no such approach in the published literature on remanufacturing. We develop a generic stochastic optimization model of the considered problem with two decision variables (the production rates of manufacturing and remanufacturing machines) and two state variables (the stock levels of manufactured and remanufactured products). Our goal is to characterize optimal policies for the production rates of the new products as well as the remanufactured products, depending on the values of the model parameters and costs.

Our modeling approach could possibly be applied to many industrial cases such as those mentioned in this section or the next where machines can be subject to failures and their production rates can be continuously controlled. We feel the assumptions made can be acceptable, at least approximately, in many cases, but this should be verified as the first step of an industrial application. It is assumed in particular that the remanufactured products can be considered meeting the same quality level as the new products so that both type of products can be distributed like new. We also assume that the demand for new products is deterministic and known in advance and the proportion of returned products to be possibly remanufactured is a known proportion of demand. These assumptions are often made and discussed in Section 3.2 of this paper. Typical examples of applications might be the remanufacturing of copier cartridges, or aeronautical parts.

The rest of the paper is organized as follows. In Section 2, the literature review is presented. The model notations and assumptions are presented in Section 3. The control problem is also described in detail in Section 3. A numerical example and a sensitivity analysis (carried out to analyze the effect of the used products return ratio and the backlog costs), are given in Sections 4 and 5, respectively. Discussions of the results and directions for future works are presented in Section 6. The paper concludes with a short summary in Section 7.

2. Literature review

In this section, we focus on cases and models related to remanufacturing activities. A number of practical cases have been reported in various contexts of application. As mentioned above, many works have been devoted to the design of the network system or to production or inventory planning through discrete optimization models.

De Brito et al. (2003) discuss network structures and report cases pertaining to the design of remanufacturing networks by the original equipment manufacturers or independent manufacturers, the location of remanufacturing facilities for copiers, especially Canon copiers and other equipments and the location of IBM facilities for remanufacturing in Europe. They also present case studies on inventory management for remanufacturing networks of engine and automotive parts for Volkswagen and on Air Force depot buffers for disassembly, remanufacturing and reassembly. Finally, they present case studies on the planning and control of reverse logistics activities, and in particular inventory management cases for remanufacturing at a Pratt & Whitney aircraft facility, yielding decisions of lot sizing and scheduling.

As mentioned above, Bostel et al. (2005) propose a review of problems and models according to the hierarchical planning horizon and degree of correlation between forward and reverse flows. Strategic planning models are devoted to network design problems, while tactical and operational models address a number