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Inventory optimization in a one product recoverable manufacturing system

S. Sebnem Ahiska [a], Russell E. King [b,*]

[a] Industrial Engineering Department, Galatasaray University, Ortakoy, 34357 Istanbul, Turkey
[b] Edward P. Fitts Department of Industrial and Systems Engineering, North Carolina State University, Raleigh, NC 27695, USA

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ABSTRACT

Environmental regulations or the necessity for a 'green image' due to growing environmental concerns, as well as the potential economical benefits of product recovery, have pushed manufacturers to integrate product recovery management with their manufacturing process. Consequently, production planning and inventory control of recoverable manufacturing systems has gained significant interest among researchers who aim to contribute to industrial practice. This paper considers inventory optimization of a single product recoverable manufacturing system where customer demands are satisfied through either regular production (manufacturing) of new items or remanufacturing of returned items. We present robust, implementable characterizations of the optimal manufacturing/remanufacturing inventory policies found using Markov decision processes. We extend the results in the literature by considering setup costs and different lead time cases for manufacturing and remanufacturing.

1. Introduction

In recent years, manufacturers have paid growing attention to reuse activities that provide material waste reduction via recovery of used products. Motivation behind product recovery activities is two-fold: growing environmental concerns and potential economical benefits. In several countries environmental regulations make manufacturers responsible for the whole product life cycle, a common example of these regulations being take-back obligations after usage (Fleischmann et al., 1997). But even in the absence of such regulations, the expectations of environmentally conscious consumers put pressure on companies to consider environmental issues in their manufacturing process. A green image has become a powerful marketing tool and provides a significant competitive advantage in the global market. Reuse of products or materials can be economically attractive in addition to contributing to sustainable development. Disposal costs have increased significantly in recent years due to depletion of incineration and land filling capacities.

With product recovery, the considerable value incorporated in the used product is regained resulting in energy, material and labor savings. Remanufactured products often have the same quality as new products and are sold for the same price. Examples of remanufactured products include mostly high-value components such as aircraft or automobile engines, aviation equipment, medical equipment, office furniture, machine tools, copiers, computers, electronics equipment, toner cartridges, cellular telephones, single-use cameras, etc. (Thierry et al., 1995; Fleischmann et al., 1997; US EPA, 1997; Guide et al., 1999; Toktay et al., 2000).

Recoverable manufacturing systems can be defined as closed loop systems with discarded items used in place of externally supplied virgin materials to the extent possible in the fabrication of new products (Guide et al., 2000). These systems are capable of dealing with product returns via several product recovery options that can be categorized as direct reuse, repair, refurbishing, remanufacturing, cannibalization and recycling with respect to increasing degree of required disassembly level (Thierry et al., 1995). There are several review papers that emphasize the challenges of considering product recovery. Thierry et al. (1995) describe strategic issues that manufacturers face in implementing product recovery management policies. Fleischmann et al. (1997) provide a systematic review of reverse logistics issues and mathematical models for dealing with returns in distribution planning, production planning and inventory control areas. Guide et al. (2000) discuss the complicating characteristics of recoverable manufacturing systems including uncertainties in timing, quantity and quality of returns, the need for balancing demands with returns, disassembly need for returned products, the requirement of a reverse logistics network, material matching restrictions and stochastic routings for materials to be used in recovery operations.

Two main additional sources of complexity appear in inventory control of recoverable manufacturing systems compared with traditional inventory systems. First, due to uncertainty of the product returns, an additional stochastic impact needs to be considered. Second, product recovery (e.g. remanufacturing) must

* Corresponding author. Tel.: +1 919 515 5186; fax: +1 919 515 1543.
E-mail addresses: sahiska@gsu.edu.tr (S.S. Ahiska), king@ncsu.edu (R.E. King).

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be coordinated with regular procurement (e.g. manufacturing) which complicates the inventory control situation.

In recent years, the challenges faced when dealing with returns in the context of production planning and inventory management have gained considerable attention in the literature. The literature can be categorized as deterministic versus stochastic recoverable systems. Further, stochastic product recovery models can be classified into periodic versus continuous review models. We focus here specifically on periodically reviewed stochastic recoverable manufacturing systems.

Two main approaches are observed in the literature regarding inventory management of stochastic recovery models. One approach, which has been rarely used, is to investigate analytically the structure of optimal control policy using dynamic programming approaches (e.g., Simpson, 1978; Inderfurth, 1997). A second approach is to find optimal or near-optimal values for the parameters of a predetermined reasonable control policy structure. (e.g. Kiesmuller, 2003; Kiesmuller and Minner, 2003; Kiesmuller and Scherer, 2003; Mahadevan et al., 2003; Van der Laan et al. 1996, 1999; Van der Laan and Salomon, 1997; Van der Laan and Teunter, 2006). However, it has the drawback of considering a pre-determined policy that is not guaranteed to be optimal. In these works, it is not indicated how far the predetermined policy is from the optimal policy.

Periodic review models describe practical situations in a suitable way, however, only a few studies have been provided in the literature which considered periodic review models in the context of product recovery. Kiesmuller (2003) considers a pre-determined periodic review PULL policy for a stochastic manufacturing/remanufacturing system with two stocking points, and provides a comparative analysis to justify the use of separate inventory position definitions for the manufacturing and remanufacturing decisions. The optimal parameter values of the policy are calculated through grid search and simulation. Kiesmuller and Minner (2003) provide simple newsvendor type heuristic formulae to calculate the parameter values. Mahadevan et al. (2003) employ a periodic review PUSH policy to analyze a similar recoverable inventory system. They develop several heuristics based on traditional models to find the parameter values of this pre-determined policy.

Only a couple of papers emphasize the determination of optimal control policy structures for a one product recoverable system. Simpson (1978) generates the optimal policy structure for a finite-horizon problem with two stocking points using a dynamic program. The optimal policy structure, which is defined by the repair-up-to level, purchase-up-to level, and scrap-down to level, is valid under a 0-lead time assumption for repairing and purchasing activities. More recently Inderfurth (1997) addresses the problem with and without stock keeping of returned items. He uses stochastic dynamic programming to derive optimal decision rules for procurement, remanufacturing and disposal. For the case without stock keeping of recoverable items, he formulates optimal policy structures for different lead time cases; however, for the case where recoverable items can be stocked, he provides the optimal policy structure only for the case of equal lead times and no setup cost for manufacturing and remanufacturing. He states that if there exist fixed costs of remanufacturing or manufacturing, the policies provided may no longer be optimal. Kiesmuller and Scherer (2003) consider the optimal policy structures provided by Inderfurth (1997) under equal lead times for manufacturing and remanufacturing, and provide a method for exact computation of the policy parameters and a couple of heuristic methods. As pointed out by Kiesmuller (2003), the case with unequal lead times is quite complex and the optimal policy structure is not known even without fixed costs of manufacturing or remanufacturing.

To our knowledge, no work exists in the literature which conducts an analysis to find optimal policy structure in the existence of fixed cost for manufacturing and/or remanufacturing in the context of periodic-review inventory control. Further, none of the work that uses a pre-determined policy structure for inventory optimization indicates how well the considered policy structure characterizes the optimal inventory control policy.

This paper considers inventory optimization of a periodically reviewed single product stochastic manufacturing/remanufacturing system with two stocking points, recoverable and serviceable inventories. Lead times and setup costs for manufacturing and remanufacturing are considered. The system is modeled using Markov decision processes, and an empirical study is conducted to determine optimal or near optimal policy characterizations under several cost configurations and different lead time cases for manufacturing and remanufacturing. Policy characterization can be defined as the description of the policy in a structured way using a few parameters. Clearly, characterization of the optimal policy is important, because it makes it easier to interpret the optimal policy. In this paper, the performance of policy characterizations under several cost configurations is evaluated numerically considering the percentage deviation from optimal cost. In addition, the effects of a change in system parameters including setup costs on the optimal inventory policy are investigated using the policy characterizations. Results indicate that the existence of setup cost for either manufacturing or remanufacturing has a significant effect on policy structure, and the policy characterizations we provide represent well the optimal policies with a maximum deviation of 1% from optimal cost in almost all cases.

The rest of the paper is organized as follows: In Section 2, the recoverable manufacturing system under consideration is presented and the inventory optimization problem is formulated as a discrete Markov decision process under different cases for manufacturing and remanufacturing lead times. In Section 3, the experiments to be performed are described. Sections 4–6 include the policy characterizations determined under several cost configurations for the three lead time cases considered, i.e. the case where manufacturing and remanufacturing lead times equal one period; the case where remanufacturing lead time is two periods and manufacturing lead time is one period; and the case where manufacturing lead time is two periods and remanufacturing lead time is one period, respectively. Further, in Section 7, a sensitivity analysis is provided regarding the effect of changing the coefficient of variation of demand distribution on policy structure or policy parameter values. Finally, concluding remarks and suggestions for further research are given in Section 8.

2. Problem description and formulations

This paper considers a one product stochastic manufacturing/remanufacturing system with two stocking points: serviceable inventory and recoverable inventory, as illustrated in Fig. 1. Serviceable inventory includes finished products that are ready for sale while recoverable inventory includes no longer needed used products returned to manufacturer, which are considered for remanufacturing. Serviceable inventory can be replenished in two ways. One is the production of new items using externally supplied new materials or parts referred to as *regular production* or *manufacturing*. The other is the recovery of returned items via *remanufacturing*. A remanufactured product is considered as a 'like new' item that has the same quality and selling price as a new one.

The system is investigated under three lead time cases. First, lead times for manufacturing (l_p) and remanufacturing (l_m) operations are assumed to be one period, i.e. orders that start at the beginning of a period end at the end of the same period. In the second case, l_p=1 and l_m=2 and in the third case, l_p=2 and l_m=1.