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Life cycle inventory policy characterizations for a single-product recoverable system

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ABSTRACT

This paper investigates the optimal inventory policies over the life cycle of a remanufacturable product. The product is produced through manufacturing or remanufacturing. Benefiting from the long-run optimal policies found through Markov decision analysis, the optimal or near-optimal policy characterizations with practical structure are determined for every life cycle stage under several setup cost configurations. The effects of changes in the demand and return rates on the optimal inventory policies are investigated through these policies. Further, a performance comparison with a PULL strategy is provided. The performance of these long-run policies is evaluated as well in a finite-horizon setting, and the importance of frequent policy revision over the product life cycle is illustrated numerically.

1. Introduction

Due to environmental regulations or concerns, as well as the potential economical benefits of product recovery, manufacturers have incorporated product recovery activities into their manufacturing process. Many manufacturers accept product returns which they can reprocess through some product recovery options, for example, repair, refurbishing, remanufacturing, cannibalization or recycling (Thierry et al., 1995).

Production planning and inventory control of recoverable manufacturing systems has gained significant interest among researchers due to its challenging nature. When product returns and recovery activities are taken into consideration, two additional complexities are present compared with the traditional manufacturing systems (Inderfurth and Van der Laan, 2001). First, due to uncertainty in the amount or quality of product returns, an additional stochastic impact has to be considered. Second, coordination among the regular procurement (e.g. purchasing or manufacturing of new products) and recovery activities (e.g. remanufacturing of returned items) is required.

There have been a growing number of studies related to the stochastic inventory control problem of the manufacturing/remanufacturing systems. In these systems, customer demand is satisfied by either manufacturing of new items or remanufacturing of returned items. Remanufacturing is considered as a recovery activity that transforms a returned item into a like-new item. Remanufactured products have usually the same quality as the new products and are sold for the same price, but they are less costly.

Examples of remanufacturable 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).

Two main approaches are observed in the literature regarding the stochastic inventory control problems for manufacturing/remanufacturing systems. One approach is to investigate the structure of optimal inventory policy using dynamic programming techniques. This approach has been used in only a couple of papers, which provide the optimal policy structures for a periodically reviewed recoverable system where setup costs are not considered and lead times for manufacturing and remanufacturing operations are either zero or identical (Simpson, 1978; Inderfurth, 1997). The second approach is to find optimal or near-optimal parameter values of a predetermined policy structure using several techniques such as queuing theory, Markov decision process (MDP), enumeration techniques, simulation or heuristics (Kiesmuller, 2003; Kiesmuller and Minner, 2003; Kiesmuller and Scherer, 2003; Mahadevan et al., 2003; Van der Laan et al., 1996, 1999a, 1999b; Van der Laan and Salomon, 1997; Van der Laan and Teunter, 2006).

The latter approach has been widely used for both periodically and continuously reviewed recoverable inventory systems due to its simplicity and its applicability to more comprehensive,

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larger-scale models. A drawback of this approach is that the predetermined policy is not guaranteed to be optimal or even near-optimal, and to our knowledge, the papers that use this approach do not provide a numerical evaluation of the predetermined policy compared with the optimal policy.

Most of the studies regarding the inventory control of periodically reviewed recoverable manufacturing systems do not consider setup costs for manufacturing or remanufacturing. Recently, Ahiska and King (2008) provide a Markov decision process-based analysis to find optimal or near-optimal inventory policy characterizations for a single product recoverable system without pre-specifying the structure of the inventory policies beforehand. They investigate the system under several cost configurations, including non-zero setup costs. They show that the existence of setup cost for either manufacturing or remanufacturing has a significant effect on the optimal policy structure.

This paper aims to determine near-optimal, if not optimal, inventory control policies over different stages of the entire life cycle of a remanufacturable product, e.g. a printer cartridge. The recoverable system under consideration is a periodically reviewed, single-product, stochastic, manufacturing/remanufacturing system with two stocking points, namely recoverable inventory of returned items and serviceable inventory that includes newly manufactured items as well as remanufactured items. Both zero and non-zero setup costs for manufacturing and remanufacturing are considered.

To our knowledge, there is only one paper that investigates the inventory policies through the product life cycle with product recovery as an option. Van der Laan and Salomon (1997) consider two pre-determined control strategies, PUSH and PULL, for which they find the long-run optimal parameter values that correspond to different life cycle stages. However, they do not indicate how well these control strategies perform compared with the optimal policy.

In this paper, inventory policy structures are not determined a priori. They are determined after observing the long-run optimal policies for each stage of the life cycle. First, the optimal inventory policies that correspond to different stages of the product life cycle are characterized, that is, defined in a structured way using a few control parameters. Then, the quality of the characterization is evaluated through comparison with the optimal cost. The effects of a change in demand and return rates on the policy structure, as well as policy parameter values, are investigated. Later, the performance of these long-run policy characterizations is evaluated in a finite-horizon setting. Further, the importance of frequent policy revision is investigated.

Note that it is important to know the structure of the optimal policy because most real inventory problems are large-scale and it might not be computationally possible to determine the optimal policy. However, if the structure of the policy is more or less known beforehand, then optimal or near-optimal values of its parameters can be found using any of several tools such as simulation, heuristics, enumerative search techniques, etc. Another advantage of characterizing the optimal policy is that it enables a clear interpretation of the policy. For instance, the effects of changes in system parameters on the policy can be seen clearly through characterization.

In Section 2, the system under consideration is presented, and the Markov decision process (MDP) formulation is provided. In Section 3, the product life cycle analysis is introduced. In Section 4, the optimal or near-optimal long-run policy characterizations are determined for every stage of the product life cycle under different setup cost configurations. In Section 5, a performance comparison with the PULL strategy considered by Van der Laan and Salomon (1997) is provided. Section 6 provides performance evaluation of the long-run policy characterizations in a finite-horizon setting. The importance of frequently revising the inventory policies over the product life cycle is illustrated numerically in Section 7. Conclusions are provided in Section 8.

2. System description and MDP formulations

This paper analyzes the inventory control problem of a single-product recoverable manufacturing system throughout the entire product life cycle. As can be observed from Fig. 1, there exist two stocking points, *recoverable inventory* and *serviceable inventory*, and two supply modes, *manufacturing* and *remanufacturing*. Recoverable inventory includes customer returns that are considered for remanufacturing. Remanufactured products are assumed “like new” in that they have the same quality and price as the new ones and customers are indifferent between remanufactured products and newly manufactured products. Customer demand is satisfied from serviceable inventory, which includes newly manufactured items as well as remanufactured items. Both manufacturing and remanufacturing operations have a one period lead time. Backordering is allowed up to a certain level, beyond which an unsatisfied demand is lost. A returned item is disposed if the recoverable inventory is full. Note that the recoverable inventory capacity can be set sufficiently large if disposal of returned items is not allowed.

The problem is defined as finding the optimal inventory policy (the manufacturing and remanufacturing strategy that have the smallest cost) in each life cycle stage. The system is formulated as a discrete-time Markov decision process (MDP).

An MDP model is a stochastic sequential-decision model defined by a set of system states, a set of decisions to make, an immediate reward function to optimize and a matrix that defines the probability of going from one state to another in one transition under a selected decision (Puterman, 1994). The MDP model formulated for this problem is briefly described below. For detailed information regarding the MDP formulation, refer to Ahiska and King (2008).

The system state is defined by the net serviceable inventory level (i.e. on-hand serviceable inventory minus backorders) and the recoverable inventory level. I_t and J_t represent the net serviceable inventory level and the recoverable inventory level at the beginning of period t, respectively. These inventory levels at any time cannot exceed the stock capacities of $I_{\max}$ and $J_{\max}$, respectively. Further, if the lower bound for the serviceable inventory level, $I_{\min}$, is negative, then its absolute value indicates the maximum allowable backordered demand. Note that $|I_{\min}|$ can be set arbitrarily large if lost sales are not allowed in the system.

The decisions to be made are how many items to manufacture and remanufacture at the beginning of each period based on the system state. Clearly, the feasible pairs of manufacturing and remanufacturing decisions for a state should be determined considering the system capacities, i.e. storage as well as production capacities. Let the beginning-of-period t serviceable and recoverable inventory levels, I_t and J_t, form the state S_t. For state S_t, the feasible pairs of manufacturing and remanufacturing decisions are calculated as follows.

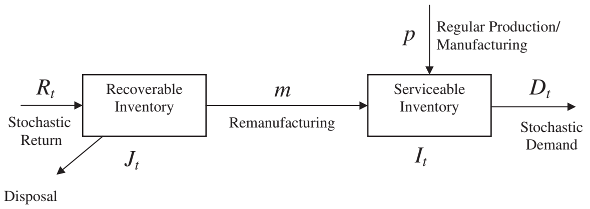

Fig. 1. The recoverable manufacturing system.