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On the optimal control of manufacturing and remanufacturing activities with a single shared server

Simme Douwe Flapper [b], Jean-Philippe Gayon [a,*], Lâm Laurent Lim [a]

[a] Grenoble-INP/UJF-Grenoble 1/CNRS, G-SCOP UMR5272, Grenoble F-38031, France
[b] Technische Universiteit Eindhoven, P.O. Box 513, 5600 MB Eindhoven, Netherlands

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ABSTRACT

We consider a single-product make-to-stock manufacturing–remanufacturing system. Returned products require remanufacturing before they can be sold. The manufacturing and remanufacturing operations are executed by the same single server, where switching from one activity to another does not involve time or cost and can be done at an arbitrary moment in time. Customer demand can be fulfilled by either newly manufactured or remanufactured products. The times for manufacturing and remanufacturing a product are exponentially distributed. Demand and used products arrive via mutually independent Poisson processes. Disposal of products is not allowed and all used products that are returned have to be accepted. Using Markov decision processes, we investigate the optimal manufacture–remanufacture policy that minimizes holding, backorder, manufacturing and remanufacturing costs per unit of time over an infinite horizon. For a subset of system parameter values we are able to completely characterize the optimal continuous-review dynamic preemptive policy. We provide an efficient algorithm based on quasi-birth–death processes to compute the optimal policy parameter values. For other sets of system parameter values, we present some structural properties and insights related to the optimal policy and the performance of some simple threshold policies.

1. Introduction

The reuse of products and materials is not a recent discovery. However, it is only during recent decades that product recovery and reverse logistics have gained increasing importance as a profitable and sustainable strategy for companies around the world (see e.g. Dekker, Fleischmann, Inderfurth, & van Wassenhove, 2004; Srivastava, 2007). Reusing may be motivated by economical, legislative or environmental reasons. As stated in Thierry, Salomon, van Nunen, and van Wassenhove (1995), there are several options to recover a product. Via remanufacturing, a product is completely recovered and its quality after remanufacturing is as good as that of a new product. Remanufacturing complicates inventory control. Integrating this reverse flow of used products affects both the materials planning and the inventory control of the supply chain. Indeed, managers have to take into account the uncertain flow of used products and they have to coordinate the remanufacturing stage with the regular mode of procurement (Inderfurth & van der Laan, 2001).

Coordination between manufacturing and remanufacturing operations is a central issue (Van der Laan, Salomon, Dekker, & van Wassenhove, 1999). The company has to decide who takes care of each operation, when and how much to manufacture or to remanufacture. In our model, we consider a single server that can perform manufacturing and remanufacturing operations. The server can switch at any time between these two operations. As stated in Ferrer and Whybark (2000), shared resources increase the flexibility of the system but also the complexity of the coordination. The study of Tang and Teunter (2006) is an example of a concrete application of a hybrid manufacturing and remanufacturing system with a shared resource. Their research was motivated by a company which manufactures and remanufactures car parts. New and remanufactured parts are processed in the same facilities by the same workers. In their study, the remanufactured products represent approximately 30% of the annual sales. Trebilcock (2002) discusses a catalog retailer that has to prepare and ship around 65,000 products weekly. Around 15% of the products come back to the retailer. In this case, managers can ask some workers for a few days to inspect, clean and repack returned products. This type of situation (where workers switch between manufacturing and remanufacturing to satisfy customer orders) may be modeled by a hybrid system as described in our study.

In this paper, we consider a hybrid manufacturing–remanufacturing system. Manufacturing and remanufacturing operations are executed by a single shared ressource. This situation can be found in small companies or in dedicated specialized units within companies dealing with complex products (like large medical systems

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* Corresponding author. Tel.: +33 4 76 57 47 46.
E-mail address: jean-philippe.gayon@grenoble-inp.fr (J.-P. Gayon).

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and dedicated copiers), when both manufacturing and remanufacturing require deep understanding of the product. Remanufactured and new products can equally well be used to satisfy customer demand. The times to manufacturing and remanufacturing a product are exponentially distributed. Demand and used products arrive via mutually independent Poisson processes. We consider the situation where products are manufactured or remanufactured one by one. The objective is to minimize discounted or average costs (holding, manufacturing, remanufacturing, backorder) over an infinite horizon. We do not include neither setup times and costs nor disposal option. These limits of our model our discussed in Section 8.

More generally, our problem can be seen as a production-inventory control with two supply channels. The first supply channel is completely controlled while the second supply channel is autonomous and random. For example, car companies like DaimlerChrysler can get very easily low quality (often less expensive) engines that are supplied by dealers in the context of take back programs or internet offers. However, it is much more difficult and uncertain to get high quality (often more expensive) engines.

To the best of our knowledge, the problem described in this paper has not been studied before. In particular it is the first paper to investigate an hybrid system with a shared resource in a stochastic environment. For the problem described above, we characterize the optimal manufacture–remanufacture policy for certain sets of system parameter values and provide for these sets an efficient method to calculate the optimal values of the policy parameters. For other sets of system parameter values, we provide insights into the optimal policy structure. We also present a sensitivity analysis for several system parameters.

In Section 2, we review the literature and our contributions. In Section 3, a detailed description and mathematical formulation of the problem is given. In Section 4, we derive several characteristics of the optimal policy structure for different sets of parameter values. In Section 5, we provide an efficient method to calculate the optimal values of the policy parameters. In Section 6, we present some insights into the optimal behavior of the system for sets of parameter values for which it is not possible to derive the optimal policy structure. Based on these insights, we introduce in Section 7 some simple heuristics that we compare with the optimal policy. In Section 8 we conclude the paper and indicate directions for further research.

2. Literature review

There is a vast literature on inventory control with product returns (see e.g. Fleischmann et al., 1997; Fleischmann, Kuik, & Dekker, 2002; Ilgin & Gupta, 2010; Pokharel & Mutha, 2009). Hybrid manufacturing and remanufacturing systems have received growing attention in recent years (see e.g. Van der Laan et al., 1999; Teunter, van der Laan, & Vlachos, 2004).

In a deterministic environment, only a few authors consider a shared capacity for manufacturing and remanufacturing. The first deterministic model involving product returns is introduced by Schrady (1967). He considers an EOQ setting with constant demand and returns rates, infinite manufacturing and remanufacturing rates, different holding costs for recoverable and serviceable items and different fixed costs. For the class of $(1,R)$ policies that alternates a manufacturing lot and a fixed number R of remanufacturing lots, he is able to derive EOQ formulae. Several papers consider variants of Schrady's model. Nahmias and Rivera (1979) considers a variant with a finite recovery rate. Teunter (2001) includes a disposal option for returned products. Teunter (2004) investigates $(1,R)$ policies and $(P,1)$ policies where the server alternates between manufacturing P lots and remanufacturing 1 lot. He obtains optimal lot-sizes for both manufacturing and recovery operations. These formulae are valid for both finite and infinite manufacturing and remanufacturing rates. Tang and Teunter (2006) study the multi-product economic lot scheduling problem with returns. Like previous papers, manufacturing and remanufacturing operations are performed on the same shared production line. Due to the complexity of this multi-product problem, the authors restrict their study to common cycling policies with one manufacturing lot and one remanufacturing lot in each cycle. The problem is formulated as a mixed-integer problem.

In a periodic review setting, several authors present models with stochastic demand and returns but they do not consider a shared capacity for manufacturing and remanufacturing. Simpson (1978) considers a system where returns are held in a separate buffer until they are remanufactured or disposed of. He characterizes the optimal policy for the case with zero manufacturing and remanufacturing lead times. Inderfurth (1997) considers positive and identical manufacturing and remanufacturing leadtimes. He also shows that the optimal policy may have a very complex structure when lead times are different. Li, Zhang, Chen, and Cai (2010) include fixed manufacturing costs and fixed disposal costs. Zhou, Tao, and Chao (2011) investigate a situation where returns can have different quality levels. DeCroix (2006) extends the results of Inderfurth (1997) to a multi-stage series system where products are remanufactured at the upstream stage. Fleischmann and Kuik (2003) study the optimal policy structure for a single stock point with a stochastic demand that is either positive or negative in each period. They show the average-cost optimality of an (s,S) policy. Teunter and Vlachos (2002) study the necessity of a disposal option for a hybrid manufacturing and remanufacturing system with constant lead times over a finite time horizon. By using simulation, their results show that a disposal option leads to an important cost reduction only if the demand rate is low, the recovery rate is high and remanufacturing is almost as expensive as manufacturing. The authors also notice that it is more difficult to find the optimal policy when considering a disposal option for product returns.

As far as we know, Heyman (1977) is the first who investigates a continuous-time inventory control model with product returns. He assumes zero lead times, linear costs and a disposal option. Heyman (1977) shows that the optimal disposal policy is a threshold policy and derives an explicit formula for this threshold. The author also indicates that introducing a remanufacturing lead time requires a new variable (the remanufacturable inventory) resulting in a very complex model. Vercraene and Gayon (2013) consider a variant of Heyman (1977) where the manufacturing leadtime is exponentially distributed and there is no disposal option. They prove the optimality of a base-stock policy to control the serviceable inventory and derives an exact formula for the optimal base-stock level. Muckstadt and Isaac (1981) introduce a hybrid system with nonzero lead times for both procurement and remanufacturing. The authors investigate a simple (s,Q)-rule for the procurement policy and returns are remanufactured as long as returned products are available. Since an exact analysis is difficult, an approximation is given for the steady-states distribution of the system. Fleischmann et al. (2002) consider an inventory system with Poisson demand and returns, fixed procurement leadtime and zero remanufacturing processing time. They show that the optimal policy to minimize the total average cost is an (s,Q)-policy. Van der Laan et al. (1999) investigate an inventory system where manufacturing and remanufacturing occur simultaneously. They consider constant leadtimes, stochastic demands and returns, fixed set-up costs per batch and linear holding costs for the remanufacturable and serviceable inventories. They compare systems without remanufacturing with push and pull controlled hybrid systems with remanufacturing. Ching, Li, and Xue (2007) suggest a new approach to analyze a hybrid system with remanufacturing under continuous-review with Markovian assumptions. The serviceable inventory is controlled