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Robust optimal policies of production and inventory with uncertain returns and demand

Cansheng Wei [a], Yongjian Li [b,*], Xiaoqiang Cai [c]

[a] College of Information Technical Science, Nankai University, Tianjin 300071, PR China
[b] Business School, Nankai University, Tianjin 300071, PR China
[c] Department of Systems Engineering and Engineering Management, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong

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ABSTRACT

We consider an inventory and production planning problem with uncertain demand and returns, in which the product return process is integrated into the manufacturing process over a finite planning horizon. We first propose an inventory control model for the return and remanufacturing processes with consideration of the uncertainty of the demand and returns. Then a robust optimization approach is applied to deal with the uncertainty of the problem through formulating a robust linear programming model. Moreover, properties on the robust optimization model are studied, and an equivalent robust optimization model based on duality theory is obtained which allows the solutions to be derived more efficiently. Finally, we provide a set of numerical examples to verify the effectiveness of the approach and analyze the effects of the key parameters on the solutions.

1. Introduction

In the manufacturing industry, product recovery has been given an increasing attention with the aims to protect the environment and to save production costs in the supply chain. For example, some car manufacturers such as BMW have set up a recovery process for the reuse of end-of-life cars, and manufacturers of products such as one-off cameras(Kodak) and toner cartridges(Xerox) are also undertaking remanufacturing activities. In these examples, the remanufacturing process is integrated into the manufacturing process of the new products. The management of any company with remanufacturing of returned products often finds that they have to deal with two major uncertainties: the uncertainty with the market demand for the new product and the uncertainty with the quantity of the returned product. In particular, there is a great uncertainty involved in the collection process of the returned product, which may affect significantly the entire inventory and production planning decision.

Generally, in a manufacturing/remanfuactring hybrid system, it is required to determine, in the presence of the above-mentioned uncertainties, the quantities of new product to be manufactured, the quantities of returned product to be remanufactured or disposed off, and appropriate inventories of the sellable and returned products, over the planning horizon so that the total production and inventory cost is minimized. Such a problem is hard to solve efficiently, especially in a multi-period environment. It is much complicated by the difficulty to forecast the returned products, because the used products are usually returned through different channels, from different customers in different circumstances. In many cases, information on the probabilistic distribution concerning the quantity of a returned product is not available (Trebilcock, 2002; Fleischmann et al., 1997), and what we can estimate is just the likely mean and its possible maximum/minimum values. Considering this inherent difficulty in remanufacturing with returned products, in this paper we will adopt the robust optimization approach to tackle a multi-period inventory and production planning problem with uncertain market demand and uncertain quantity of the returned product. As it is well known, robust optimization is particularly powerful in dealing with uncertain variables with only known intervals, which is different from stochastic optimization which needs distributional information on the random variables.

Many studies have discussed production planning and inventory control problems with consideration of the product return process by using stochastic optimization approach. Two early models have been proposed by Heyman (1977) and Simpson (1978), respectively. Heymand considers a continuous time problem with the stochastic returns independent of the demand, while Simpson considers a periodic situation with mutually dependent stochastic demand and returns. Simpson also proposes an optimal structure of purchasing, repairing, and junking policies. Inderfurth (1997) investigates optimal procurement,

* Corresponding author. Tel.: +86 22 23505341; fax: +86 22 23501039.
E-mail addresses: liyongjian@nankai.edu.cn, nkyjli@gmail.com (Y. Li).

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remanufacturing, and disposal policies through a dynamic programming method. Erwin et al. (1999) study a hybrid system by comparing the "push" and "pull" control strategies in the manufacturing process with consideration of the remanufacturing process. Dobos and Richter (2004) examine a production/recycling system with predetermined production-inventory policy and assume that there is no difference between newly produced and recycled items. Inderfurth (2004) shows how the manufacturing and remanufacturing decisions can be coordinated in order to maximize the total expected profit with new and remanufactured item substitution.

Recently, Kim et al. (2006) propose a supply planning model for a remanufacturing system of reusable parts in reverse logistics. They develop a general model to maximize the total cost savings by optimizing the quality of the parts to be remanufactured and the quantity of parts purchased from outside supplier. Geyer et al. (2007) introduce a strategic model of a production system with remanufacturing, which is subjected to limited components durability and a finite life cycle. They demonstrate the necessity to carefully coordinate the production cost structure, collection rate, product life cycle, and component durability to maximize cost savings. Jaber and Saadany (2008) consider the optimal production, remanufacturing and disposal decisions when the lost-sales demand for the manufactured item is different from that for the remanufactured one. Mukhopadhyay and Ma (2008) give a model to derive the joint procurement and production decision in a hybrid system where both the returned and new parts serve as inputs of the system and the demand and quality are uncertain. Yang (2004) studies a production control problem with random raw material supply, which shares some similarity with the problem with uncertain product returns. Yang's model involves, however, only one manufacturing process.

The multi-echelon inventory system with remanufacturing is also the focus of many studies. DeCroix et al. (2005) study a series inventory system with stochastic demands and returns over an infinite horizon, and they prove that an optimal stationary echelon base-stock policy can be derived under the condition of nonnegative demand. An assembly system with product or component returns is studied by DeCroix and Zipkin (2005). They show that returns may disrupt the long-run balance in two main ways. Conditions on the item-recovery pattern and restrictions on the inventory policy are proposed to maintain the balance. DeCroix (2006) identifies the optimal policy structures of the remanufacturing/ordering/disposal activities for a multi-echelon inventory system, and decomposes the system into a sequence of single-stage systems. The echelon base-stock policy in each downstream stage and a three-parameter simple structure in most upstream stages are derived.

Scarf (1958) appears to be the first attempting to apply a distribution-free approach to solve the newsboy problem. He considers the optimal policy corresponding to the worst distribution in a set of distribution functions with the same mean and variance. Gallego and Moon (1993), Moon and Silver (2000), Hesham and Hassan (2005), and others extend Scarf's work. For the finite-period problem, Gallego et al. (2001) consider inventory models with discrete distributions that are incompletely specified. They propose an inventory policy that minimizes the maximum expected cost over the class of demand distributions.

A robust optimization method that incorporates an uncertain data set is proposed by Soyster (1973), who deals with uncertain parameters by considering their worst cases. However, the result from Soyster's model is very conservative because only the worst case parameters in the uncertain set are considered. Since then, optimization under uncertainty has received greater attention. Mulvey et al. (1995) propose that a solution is robust when it is close to the optimal value in all uncertain scenarios. They also point out that a model is robust if it remains "almost" feasible for all scenarios, and present a robust optimization model. For the important generic convex optimization problem, Ben-Tal and Nemirovski (1998) first show that the corresponding robust convex program is either exact or approximate if the uncertain set is ellipsoidal. Ben-Tal and Nemirovski (2000) study a linear program with uncertain data using the method of Ben-Tal and Nemirovski (1998). Further, Ben-Tal et al. (2004) extend the method by considering a linear program with both nonadjustable and adjustable variables. Bertsimas and Sim (2004) flexibly adjust the level of conservation of the robust solutions in terms of the probabilistic bounds on constraint violation. An attractive aspect of their method is that the new robust formulation is also a linear optimization problem. Iyengar (2005) is the first to present robust dynamic programming, and argues that a robust dynamic program is equivalent to a stochastic zero-sum game with perfect information.

Regarding applications of robust optimization, Escudero et al. (1993) consider production planning and outsourcing policies using scenarios to characterize the uncertainty in demand. Gutierrez and Kouvelis (1995) develop a robust optimization approach to international sourcing to ensure that the sourcing network is relatively robust concerning the potential exchange rate change. Ben-Tal and Nemirovski (2002) survey the main results of robust optimization that is applied to uncertain linear, conic quadratic, and semidefinite programming problems. They discuss some applications, especially, for problems of antenna design, truss topology design, and stability analysis/synthesis, in uncertain dynamic systems. Bertsimas and Thiele (2006) are the first to use the above robust methods to solve inventory problems in supply chain management. Ben-Tal et al. (2005) consider a two-echelon multi-period supply chain problem, and Adida and Perakis (2006) apply the robust method to dynamic pricing and inventory control problems based on flow models. Two critical issues have been given great attention in the existing studies of applying robust optimization to practical problems. The first is how to ensure the optimal solution meets the constraints of the problem under consideration with an acceptable probability; and the second one is how to reduce the sensitivity of the optimal solution to the support interval of the uncertain variable if its lower and upper bounds are hard to be estimated accurately.

To the best of our knowledge, there does not seem to be any work reported in the previous literature on integrated manufacturing, remanufacturing, and disposal policies using the robust optimization approach. However, as we have discussed above, uncertainty in the product return process is very complicated, and is prevalent in remanufacturing activities. In this paper, we will apply a robust optimization approach to tackle an inventory control and production planning problem in which the product return process is integrated into the manufacturing process over a finite planning horizon, where it is assumed that the demand and returns are uncertain with only intervals being known. Our contributions include:

(1) A robust optimization model is developed, which treats both the quantity of returns and the market demand as uncertain variables, with only upper and lower bounds being known. Such a model captures the decision needs in situations with very uncertain information on the returns and the demand. Our model exhibits a linear programming structure, and can be solved efficiently by any powerful linear programming algorithms. We further derive an equivalent model based on duality theory, which allows the solutions to be derived more efficiently.