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The economic lot-sizing problem with remanufacturing and one-way substitution

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ABSTRACT

We investigate a lot-sizing problem with different demand streams for new and remanufactured items, in which the demand for remanufactured items can be also satisfied by new products, but not vice versa. We provide a mathematical model for the problem and demonstrate it is NP-hard, even under particular cost structures. We also show the key role that remanufacturing plays in the problem resolution. With the aim of finding a near optimal solution of the problem, we develop and evaluate a Tabu-Search-based procedure. The numerical experiment carried out confirms the success of the procedure for different cases.

1. Introduction

The economic lot-sizing problem with remanufacturing and final disposal options (ELSR) refers to the problem of finding the quantities to produce, remanufacture, and dispose in each period over the planning horizon such that all demand requirements of a single item are satisfied on time, minimizing the sum of all the involved costs. The main difference with the traditional economic lot-sizing problem (ELSP) is that the demand can be also satisfied by recovering used items returned to the origin. Governmental and social pressures as well as economic opportunities have motivated many firms to become involved with the return of used products for recovery (Gungor and Gupta, 1999; Guide, 2000; Fleischmann, 2001; Brito et al., 2002). Remanufacturing can be defined as the recovery of returned products, after which the products are as good as new (Gungor and Gupta, 1999; Hormozi, 2003). Remanufacturing tasks often involve disassembly, cleaning, testing, part replacement or repairing, and reassembling operations. Products that are remanufactured include automotive parts, engines, tires, aviation equipment, cameras, medical instruments, furniture, toner cartridges, copiers, computers, and telecommunications equipment.

However, possible downgrading in the remanufactured products may cause that they are offered at an inferior market price than the new ones, i.e. they are not identical from the consumer's viewpoint. Then, it makes sense to assume different demand segments for remanufactured and new items. Industrial applications where segmented market for manufactured and remanufactured occurs include photocopiers, tires and personal computers (Ayres et al., 1997; Ferrer, 1977; Maslennikova and Foley, 2000; Inderfurth, 2004). Since the demand requirements must be fulfilled on time, the case where the available returned items in a certain period are not sufficient to meet the demand requirements for remanufactured products must be considered. To address this problem, a manufacturer's market strategy is to allow substitution of remanufactured products by new ones, possibly maintaining the selling price of the remanufactured products in order to avoid losing potential customers (Bayindir et al., 2007; Inderfurth, 2004). Thus, we can consider the substitution necessary rather than desirable. On the other hand, as we will see further in a numeric example of Section 3.1, allowing substitution can result in cost savings, even when the returns are sufficient to fulfill the requirements of remanufactured products in any period and the remanufacturing costs are favorable. As it is noted by Inderfurth (2004), when manufacturing and remanufacturing processes are sharing common manufacturer resources and/or the different markets are interconnected by substitution, it is necessary to coordinate manufacturing and remanufacturing decisions.

In this paper we investigate the economic lot-sizing problem with products returns under the circumstances described above, i.e. two independent demand streams for remanufactured and new items, respectively, and where the substitution for the remanufactured items is allowed. We refer to this problem as the Economic Lot-Sizing Problem with Remanufacturing and Final Disposal options and one-way Substitution (ELSR-S). We provide a mathematical model for the problem and show it is NP-hard, even under stationary cost parameters. We also show that in order to optimally solve the ELSR-S, we can focus on the remanufacturing activity. Considering this last result, we suggest a Tabu-Search-based procedure for solving the ELSR-S, exploiting the key role that the remanufacturing plays in

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the problem resolution and employing the divide and conquer principle in order to obtain the plans for the different activities. The procedure can be considered as an extension of that presented in Piñeyro and Viera (2009) for the traditional ELSR, i.e. when substitution is not allowed. To the best of our knowledge, this is the first time that a metaheuristic, and in particular the Tabu Search, is used for solving this kind of problem.

The remainder of this paper is organized as follows. Section 2 is devoted to the literature review. In Section 3 we provide the problem definition and the respective mathematical model. We also show the relevance that remanufacturing plays in the ELSR-S resolution and certain effects of the substitution in its determination. In Section 4 we present the Tabu Search procedure suggested for solving the ELSR-S. The computational analysis is provided in Section 5. Finally, Section 6 is devoted to our conclusions and several directions for future research.

2. Literature review

To the best of our knowledge, the first to study a deterministic and dynamic inventory-system with product returns are Richter and Sombrutzki (2000). They provide an extension to the well-known algorithm of Wagner and Whitin (1958) for the particular case that the number of returns in the first period is sufficient to satisfy the total demand over the planning horizon. In Richter and Weber (2001), the previous work is extended for including variable costs. The same problem with less restrictive assumptions in the returns flow is analyzed in Golany et al. (2001). They introduce a Network Flow formulation for the problem and demonstrate that it is NP-hard for the case of general concave cost functions. They also provide an exact algorithm of $O(T^3)$ for the case of linear function costs. The NP-hard result is extended in Yang et al. (2005) for the case of stationary concave cost functions, and a heuristic procedure of $O(T^4)$ is proposed for the ELSR. Finally, van den Heuvel (2004) demonstrates that the problem is NP-hard in the particular case that the cost functions are composed of both setup and variable costs for the activities and variable cost for the holding inventory. This last result is valid even when the setup and variable costs are stationary. Teunter et al. (2006) suggest several heuristics for the economic lot-sizing problem with the remanufacturing option (final disposal is not considered). Two versions of the problem are analyzed: with joint and separate setup costs for production and remanufacturing, respectively. For the case of joint setup costs, an algorithm of $O(T^4)$ time based on a dynamic programming approach is provided. For the other case, the authors "conjecture that the problem with separate set-up costs is NP-hard". Finally, Piñeyro and Viera (2009) propose and evaluate a set of inventory policies specially designed for the ELSR, under the assumption that remanufacturing used items is more suitable than disposing of them and producing new items. In addition, a Tabu Search based-on procedure for the problem is developed. The policies as well as the Tabu Search procedure are based on the divide and conquer principle and exploiting the key role that remanufacturing plays in the ELSR resolution.

We also note that the continuous review version of the inventory problem with product returns has received a lot of attention. Relevant and recent works examples are as follows. Minner and Kleber (2001) determine optimal conditions for a continuous time model along with an algorithm tested under different return scenarios. In Teunter (2004) new and simple formulas are derived for determining the optimal lot sizes of production and recovery. He also presents a detail analysis of different policies. Minner and Lindner (2004) analyze the continuous review inventory system with returns, showing for example that a policy with non-identical lot sizes may be better than those with identical lot sizes. In addition, more realistic and complex situations have been considered recently. Examples are the papers of Konstantaras and Papachristos (2006) and Pan et al. (2009). They analyze the inventory problem with returns allowing demand backlogging and considering capacity constraints, respectively. However, substitution is not allowed.

Since the ELSR is a relatively new problem, the works dealing with both remanufacturing and substitution are very scarce. Inderfurth (2004) suggests and analyzes a profit model for the single-period hybrid manufacturing/remanufacturing system with product substitution. Optimal policies are derived for the problem taking into account different initial inventory values, costs configurations and positive lead-times values. Bayindir et al. (2005, 2007) propose profit models in order to investigate the effect of substitution on the optimal utilization of remanufacturing option under capacity constraint. Several observations and managerial insights are derived for the numerical experiment carried out by the authors. A multi-product version of the problem tackled in this paper is studied by Li et al. (2006), without considering the final disposal of used items and without distinction among produced and remanufactured items. They provide a dynamic programming approach to obtain the optimal solution for the particular case of large quantities of returned products. Based on this approach, an approximate procedure is suggested for the general case of $O(TQ)$ time, where T is the number of periods and Q the numbers of products. A detailed analysis of the procedure is reported, considering also the effect of the substitution.

The main contribution of this paper is to analyze a deterministic and dynamic inventory-system with product returns and one-way substitution, considering (1) multi-period, (2) no special constraints about the returns flow, (3) different storages for produced and remanufactured items, and (4) the final-disposal option.

3. Problem definition

We investigate the single-item economic lot-sizing problem with remanufacturing and final disposal options and different demand streams for new and remanufactured products, where in addition the requirements for the remanufactured items can be also satisfied by new items, but not vice versa (i.e. one-way substitution). Fig. 1 shows a sketch of the flow of items for this inventory system.

We assume that the demand and return values are known in advance for each period over the finite planning horizon of long $T>0$, and no relationships are assumed among them. Two different demand streams are considered. One of them is for new items, and the other for remanufactured items. This means that new and remanufactured items are not identical for the consumer's viewpoint. It is also assumed that the customer accepts substitution, i.e. the demand for remanufactured items can be satisfied by remanufacturing used items returned to origin and/or producing new ones. Backlogging demand is not allowed for both new and remanufactured items. Infinite capacity for producing, remanufacturing and disposing is assumed. Nevertheless, we note that the sum of the remanufacturing and final disposal quantities in a certain period is bounded by the amount of used items available in that period. The producing, remanufacturing, and final disposal lead-times are assumed to be zero. The inventory level in a certain period for used, remanufactured or new products is determined at zero-time and after all activities. When a positive amount is produced, remanufactured, or disposed in a certain period, set-up and unit costs are incurred