Computers & Operations Research 43 (2014) 225–236

Contents lists available at ScienceDirect

Computers & Operations Research

journal homepage: www.elsevier.com/locate/caor

A heuristic solution procedure for the dynamic lot sizing problem with remanufacturing and product recovery

M. Fazle Baki [a,*], Ben A. Chaouch [a], Walid Abdul-Kader [b]

[a] Odette School of Business, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4
[b] Industrial and Manufacturing Systems Engineering, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4

ARTICLE INFO

Available online 16 October 2013

Keywords:
Lot-sizing
Product returns
Remanufacturing
Heuristic
Dynamic programming

ABSTRACT

Here we discuss the lot sizing problem of product returns and remanufacturing. Let us consider a forecast of demands and product returns over a finite planning horizon — the problem is to determine an optimal production plan. This consists of either manufacturing new products or remanufacturing returned units, and in this way meets both *demands* at minimum costs. The costs of course are the fixed set-up expenses associated with manufacturing and/or remanufacturing lots and also the inventory holding costs of stocks kept on hand.

In addition to showing that a general instance of this problem is NP-Hard, we develop an alternative mixed-integer model formulation for this problem and contrast it to the formulation commonly used in the literature. We show that when integrality constraints are relaxed, our formulation obtains better bounds. Our formulation incorporates the fact that every optimal solution can be decomposed into a series of well-structured blocks with distinct patterns in the way in which set-ups for manufacturing and remanufacturing occur. We then construct a dynamic programming based heuristic that exploits the block structure of the optimal solution. We also propose some improvement schemes as well. Finally, our numerical testing shows that the heuristic performs very well as intended.

1. Introduction

Today, the terms "reuse" and "remanufacture" are no longer considered alien terms by many manufacturers and retailers alike [12]. In fact, a growing number of companies are beginning to see the business value of having a green reputation, actively demonstrating to their customers that they care about the environment [26]. For instance, "Cradle-to-cradle" manufacturing has been embraced as the new style of manufacturing that provides recycling and remanufacturing of all components. What this means is, from the first use of one product to the reuse of parts in other products [12–15].

The literature on remanufacturing and product recovery has rapidly grown in the past 15 years and now encompasses a large number of contributions [12,14,15,26]. This healthy growth in research contributions has been spurred by two major trends. First, recent environmental laws and take-back regulations have forced both manufacturers and retailers to become more environmentally conscious. Second, the growing concern of the general public in the rapid deterioration of the environment (dwindling natural resources, escalating pollution levels and so on) has also forced companies to improve their corporate image by managing their businesses for the good of the environment [26].

As a result, companies are now seeking better ways to manage and optimize their reverse logistics systems. This trend has led to the development of a number of quantitative models dealing with various aspects of these systems from designing an efficient reverse logistics network [9] to better managing stocks of returned products [13] and lastly in choosing optimal lot sizes in production planning and control for remanufacturing [28, 29]. Useful survey papers that discuss both the strategic and tactical issues of managing product returns for remanufacturing can be found in Fleischmann et al. [8], Guide et al. [12], Guide and Van Wassenhove [14, 15], Blackburn et al. [5] and Srivastava [26].

In this paper, we focus on one important tactical aspect of manufacturing for reuse. Namely, we consider production-scheduling applications to an environment with fluctuating demand requirements for an item that can be met either by manufacturing new items or by remanufacturing returned products. Returns are often referred to as cores or virgin items in the literature. The number of core units available for remanufacture also varies with time. A recently acquired core can be remanufactured immediately into a like-new item or carried in inventory for future reuse. A production schedule will specify how many new units of product to make and how many cores to remanufacture during each period over the planning horizon. After all, there are costs of holding the resultant

* Corresponding author. Tel.: +1 519 253 3000; fax: +1 519 973 7073.
E-mail addresses: fbaki@uwindsor.ca (M. Fazle Baki), chaouch@uwindsor.ca (B.A. Chaouch), kader@uwindsor.ca (W. Abdul-Kader).

0305-0548/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.cor.2013.10.001

inventories of cores as well as the finished items. Not to mention, there are also fixed set-up costs associated with batch production. The objective is to find a schedule that minimizes the total set-up and holding costs while satisfying all demand requirements in a timely way.

Having thus stated our purpose, we have organized the paper as follows: in Section 2, we discuss a commonly used mixed-integer linear programming (MILP) formulation (since a number of authors alluded to the fact that the problem is NP-hard, we give proof to show that a general instance of this problem is indeed NP-hard); in Section 3, we review the literature related to the MILP model; in Section 4, we develop an alternative MILP formulation of this problem and discuss its advantages over the original formulation; in Section 5, we propose a computationally efficient heuristic method that can be used to solve the problem; in Section 6, we provide ample numerical testing to illustrate the performance of the alternative model and heuristic; and to end off, in Section 7, we conclude with some remarks.

2. Model statement

As stated above, a number of operations researchers have examined the impact of remanufacturing and product recovery on the lot-sizing problem with deterministic time-varying demands (see [21,22,11,4,32,29,23,1617]). To better relate our contribution to this literature, we begin by stating a typical mixed-integer model formulation of the problem. Table 1 summarizes the notation that will be used throughout the paper.

Table 1
Notation.

General	
N	Planning horizon
i	Index for periods in the planning horizon, $i=1,\ldots,N$
D_i	Number of products demanded in period i
R_i	Number of products returned at the beginning of period i
K^S	Set-up cost to manufacture new units (or serviceables)
K^R	Set-up cost to remanufacture a returned unit
h^S	Holding cost to carry a unit of serviceable inventory from period i to period $i+1$
h^R	Holding cost to carry a returned unit in inventory from period $i$to period $i+1$
Mixed integer linear programming (MILP) formulations	
d_{ij}	Cumulative demand from period $i$to period j
r_{ij}	Cumulative returns from period $i$to period j
Q_i^S	The quantity of products manufactured in period i
Q_i^R	The quantity of products remanufactured in period i
I_i^S	Inventory in units of serviceables left over at the end of period i
I_i^R	Inventory in units of returns left over at the end of period i
y_i^S	Binary variable$=1$ if new products are manufactured in period$i$; 0 otherwise
y_i^R	Binary variable$=1$ if returns are remanufactured in period$i$; 0 otherwise
x_{ij}^S	Binary variable$=1$ if manufacturing occurs in period$i$and next in period$(j+1)$; 0 otherwise
x_{ij}^R	Binary variable$=1$ if remanufacturing occurs in period$i$and next in period $(j+1)$; 0 otherwise
Constructive heuristic	
D_i^S	The part of demand $D_i$in period $i$satisfied by manufacturing new products
D_i^R	The part of demand $D_i$in period $i$satisfied by remanufacturing returned products
γ_i	The target end-of-period inventory of returned products for period i
$e'_{ij}(s,t)$	Total manufacturing cost in period i to meet demands D_k^S for $k=i,i+1,\ldots,j$
$f_j(s,t)$	The minimum total set-up and holding costs of meeting the demands $D_i^S$by manufacturing only from period s through$j$
$e''_{ij}(s,t)$	Total remanufacturing cost in period i to meet demands D_k^R for $k=i,i+1,\ldots,j$
$g_j(s,t)$	The minimum total set-up and holding costs of meeting the demands D_i^R by remanufacturing only from period s through j
$c(s,t)$	Optimal total set-up and holding costs of satisfying the demands D_i from period s through t

Let us consider a forecast of demands D_i and returns R_i over the planning horizon N. The basic problem is to choose Q_i^S and Q_i^R, namely, the quantities to be manufactured and remanufactured in period i, so as to satisfy all demands at minimal costs. Demand is met either from newly manufactured products or from the remanufacturing of some returns or both. The total costs include the fixed set-up costs of manufacturing and remanufacturing and the inventory holding costs for serviceables and returns. Without loss of generality, let the initial inventories $I_0^S=0$ and $I_0^R=0$ and define

$$y_i^S=\begin{cases}1 & \text{if new products are manufactured in period } i\\ 0 & \text{Otherwise}\end{cases}$$

$$y_i^R=\begin{cases}1 & \text{if returns are remanufactured in period } i\\ 0 & \text{Otherwise}\end{cases}$$

The complete model (P) is then

$$\text{Min} \sum_{i=1}^{N}\{h^S I_i^S+h^R I_i^R+K^S y_i^S+K^R y_i^R\} \quad (1)$$

s.t.

$$I_i^S=I_{i-1}^S+Q_i^S+Q_i^R-D_i \quad \forall i=1,2,\ldots,N \quad (2)$$

$$I_i^R=I_{i-1}^R+R_i-Q_i^R \quad \forall\ i=1,2,\ldots,N \quad (3)$$

$$Q_i^S\le\left(\sum_{j=i}^{N}D_j\right)y_i^S \quad \forall\ i=1,2,\ldots,N \quad (4)$$

$$Q_i^R\le\left(\sum_{j=i}^{N}D_j\right)y_i^R \quad \forall\ i=1,2,\ldots,N \quad (5)$$

$$y_i^S,y_i^R\in\{0,1\},Q_i^S,Q_i^R,I_i^S,I_i^R\ge 0 \quad \forall\ i=1,2,\ldots,N$$

Constraints (2) and (3) in (P) are inventory balance equations for serviceables and returns, respectively. Constraints (4) and (5) in (P) insure that if a set-up is not performed in a period, then the quantity made in that period is zero, but if a set-up is undertaken in period i, the bound $\sum_{j=i}^{N}D_j$ on the quantity produced is appropriately chosen so that the two constraints are redundant. The objective function (1) is to minimize the total set-up and carrying costs over the planning horizon N.

The formulation shown in (P) presumes the following sequence of events. In each period we first observe returns and then we decide how much to manufacture or remanufacture. Then the demand is observed and satisfied and holding costs are assessed based on the remaining stocks of serviceables and returns at the end of the period.

3. Review of the literature related to model (P)

Richter and Sombrutzki [21] study model (P) (presented in Section 2) with the additional restriction that enough product returns are available at the start of the planning period to cover demands over the entire horizon. This assumption makes it possible to transform model (P) to a problem instance that preserves the all-important "zero-inventory property." This property states that replenishments are to take place in a given period only if the starting inventory in that period is zero. As a result of this, the authors show that optimal solutions can be calculated