Journal of Cleaner Production 170 (2018) 559–569

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Economic lot scheduling problem in a remanufacturing system with returns at different quality grades

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ARTICLE INFO

Article history:
Received 10 May 2017
Received in revised form
18 September 2017
Accepted 18 September 2017
Available online 19 September 2017

Keywords:
Remanufacturing
Lot scheduling
Returns
Quality grading
Acquisition management

ABSTRACT

An increasing number of companies and researchers have realized the value of quality grading in the remanufacturing process. In this research, we consider a lot scheduling problem for remanufacturing with returns divided into different quality grades. The remanufacturing rate increases as the quality grade increases and holding costs for serviceable products are higher than returns. The objective is to minimize the average total cost by optimizing the acquisition lot size and scheduling the remanufacturing sequence. We first schedule the remanufacturing sequence for an independent remanufacturing system, and we subsequently extend the model to a hybrid manufacturing and remanufacturing system. It is demonstrated that the given models can be applied not only to deterministic situations, where the proportion of each quality grade is constant, but also to stochastic situations, where the proportion of each quality grade is uncertain. Finally, we confirm the value of the scheduling remanufacturing sequence and analyse the sensitivity of the relevant parameters through numerical examples. The results show that the benefit of scheduling the remanufacturing sequence is to take advantage of the low holding cost for storing inexpensive returns and postponing the remanufacturing process to the time when they are needed. The value of scheduling a (re)manufacturing sequence is prominent when the quality and production rate of returns are scattered and the difference in the holding cost of products and returns is relatively large. In the hybrid manufacturing and remanufacturing system, the greater the recovery rate is, the more obvious the value of scheduling is.

1. Introduction

Driven by economic incentives, environmental constraints and societal pressure, an increasing number of manufacturing enterprises are undertaking remanufacturing operations. Remanufacturers must manage a number of product recovery activities, including used-product acquisition, reverse logistics, product disposition, remanufacturing operations, and remarketing (Guide and Wassenhove, 2001). In particular, acquisition management activities have to control the uncertainty in the timing, quantity, and quality of returned products (cores) because the returns may come from different kinds of customers and channels. To tackle this difficulty, remanufacturers commonly classify the cores into several categories according to their quality. Pitney–Bowes suggested three quality levels corresponding to good, better, and best (Ferguson et al., 2009), while ReCellular established a nominal quality metric for grading mobile telephones, which includes six quality levels (Guide and Wassenhove, 2001). At the same time, many studies have also confirmed that grading returns into different quality classes helps to reduce remanufacturing costs. For example, Aras et al. (2004) reported that cost savings due to categorization can easily reach 10%, and Ferguson et al. (2009) showed that a policy of grading returns into different quality classes improves total profits over a system without grading by approximately 4%.

At present, quality grading has been extensively incorporated into the study of remanufacturing, e.g., quality and process control (Liu et al., 2015; Su and Xu, 2014), acquisition and remanufacturing policies (Cai et al., 2014), inventory (Zhou et al., 2011) and lot sizing (Panagiotidou et al., 2017). However, most studies have only noted that grading helps to reduce the remanufacturing cost but ignore its

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https://doi.org/10.1016/j.jclepro.2017.09.184
0959-6526/

impact on the production rate. Although quality grading effectively controls the uncertainty of the remanufacturing rate, but it may make the output speed and inventory levels unstable if it only produces in accordance with the order of the quality level. Take the recovery of telecommunications equipment for cable TV as an example. The remanufacturing rate and output rate of the used cables are very different because the types of cables vary widely. As a market leader in the provision of reverse logistics, DTC International provides operators with a recycling service for investment recovery of surplus telecom copper cable infrastructure. At DTC, the waste cable is often inspected and graded prior to processing to making sure there is no risk of contamination, while improving the efficiency and stability of output.

This research establishes economic lot scheduling models with different quality levels of returns to explore the value of scheduling the remanufacturing sequence in terms of production costs and inventory control. Many studies have noted that the quality of returns does affect the remanufacturing rate (Gharbi et al., 2008; Manna et al., 2017; Pellerin et al., 2009). For simplicity and without losing generality, we suppose the remanufacturing rate increases as the quality level increases. The remanufacturer may not only determine the production sequence of manufacturing and remanufacturing, but needs to schedule the remanufacturing process for different qualities of returns. In the market, there are two remanufacturing systems: the independent remanufacturing system and the hybrid manufacturing/remanufacturing system; therefore, we establish two models for both remanufacturing systems. The objective is to minimize the average total costs per unit time through optimizing the lot sizes of returns (raw materials) and the (re)manufacturing sequence. The contributions of this research are as follows: first, quality grading is introduced into the lot scheduling problem; second, two models are established that can be applied to the independent and hybrid remanufacturing systems; third, the value of scheduling the remanufacturing sequence is demonstrated, and the sensitivity of relevant parameters are analysed by numerical examples. The results show that the value of scheduling the (re)manufacturing sequence is prominent when the quality and production rate of returns are scattered and the difference in the holding cost of products and returns is relatively large. In the hybrid manufacturing and remanufacturing system, the greater the recovery rate is, the more obvious the value of scheduling is.

The rest of this research is organized as follows. Section 2 presents the main recent related literature. Section 3 provides the optimal policy for the economic lot scheduling problem with multiple quality grades of returns. Numerical examples are illustrated in Section 4, and the study's conclusions are summarized in Section 5.

2. Literature review

This research is closely related to two streams of research literature: the economic lot scheduling problem (ELSP) and the economic lot scheduling problem with returns (ELSPR).

The ELSP issue is the problem of accommodating cyclical patterns when several items are manufactured at the same facility, and its objective is to determine the lot sizes of each item and the production sequence to minimize the holding and setup costs per unit time (Elmaghraby, 1978). ELSP has attracted much attention since it was introduced by Rogers in 1958 (Rogers, 1958), because it can be widely applied to many production situations such as bottling, plastic production, textile production, paper production, among other operations (Giri et al., 2003). Several comprehensive reviews regarding the ELSP issue can be found in Santander-Mercado and Jubiz-Diaz (2016) and Elmaghraby (1978).

The economic lot scheduling problem with returns (ELSPR) evolved from ELSP. The earliest study on ELSPR is by Schrady (1967). He developed a heuristic procedure for determining the lot sizes of remanufacturing, and established a $P(n_1, 1)$ policy with n_1 remanufacturing lots and one manufacturing lot. Teunter (2001) extended Schrady's cycle patterns to a cycle with several manufacturing lots and one remanufacturing lot, a $P(1, n_2)$ policy. Choi et al. (2007) generalized the $P(n_1, n_2)$ policy by treating the sequence of orders for newly purchased products and setups for the recovery process within a cycle as a decision variable. Several extensions have been proposed that relax some of the assumptions made to date. For example, Teunter (2004) relaxed the assumption of an instantaneous manufacturing and remanufacturing process to derive more general expressions for the manufacturing and remanufacturing lot sizes. Konstantaras and Papachristos (2008) improved Teunter's work by developing an exact solution that leads to the optimal number of manufacturing and remanufacturing lots. Tang and Teunter (2006) explored the multi-product economic lot scheduling problem for a hybrid remanufacturing line, considering policies with a common cycle time for all products, and with one manufacturing lot and one remanufacturing lot for each product during a cycle. Afterwards, Teunter, et al (Teunter et al., 2008, 2009). developed a mixed integer programming formulation for the ELSPR, and gave a corresponding exact algorithm and heuristics algorithm for finding the optimal common-cycle-time policy. More recently, Bae et al. (2016) proposed a heuristic algorithm based on a time-varying lot sizes approach to identify production frequencies, production sequences, production times, and idle times for several items subject to returns at a single facility. Benkherouf et al. (2016) optimized the production, remanufacturing and refurbishing activities in a finite planning horizon with a stochastic recovery rate and demand rate.

According to Tang and Teunter (2006), the ELSPR is more complex than the ELSP. In the traditional ELSP, at least for low utilization problems (high capacity compared to expected demand), the lot size influence the inventory level and most schedules lead to the same stock level patterns and average stock levels (Zanoni et al., 2012). However, in the ELPSR system, there are two inventories: recoverable inventory and serviceable inventory. The sequencing of lots within a production cycle influences the inventory holding cost because the holding costs of recoverable items and serviceable products are usually not equal. According to Paul (2000), the holding cost typically includes two major components. The first comprises all direct costs associated with inventory itself, including costs for physical handling, insurance, refrigeration, and warehouse rental. The second component is the financing cost, which reflects that holding inventory ties up capital. In the remanufacturing system, the direct cost for returns is not higher than for serviceable products because the products usually require better storage conditions, while the financing cost for returns is lower than for the serviceable products because the returns have a lower quality than serviceable products. Therefore, the holding cost of returns is usually smaller than that of serviceable products. Interested readers are referred to Teunter et al. (2000), Teunter and Laan (2002) and Çorbacıoğlu and van der Laan (2007) for some general discussions on how to set the holding cost in a remanufacturing system.

Although the ELSPR issue and returns quality grading have been receiving increasing attention in recent years (Aras et al., 2004; Cai et al., 2014; Ferguson et al., 2009; Jing, 2016; Liu et al., 2015), few