Journal of Cleaner Production 186 (2018) 180–190

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Optimal acquisition and remanufacturing policies considering the effect of quality uncertainty on carbon emissions

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ARTICLE INFO

Article history:
Available online 15 March 2018

Keywords:
Remanufacturing
Processing time
Quality uncertainty
Carbon emissions
Core acquisition

ABSTRACT

With the intensification of global warming, various policies are being proposed globally to reduce the emission of greenhouse gases, thereby causing the cost of carbon emissions to be an important factor in deciding the acquisition and remanufacturing policies. In a remanufacturing system, the highly variable quality of the end-of-life products not only results in uncertain remanufacturing costs, but also leads to different carbon emissions during remanufacturing. Therefore, in this study, a model considering the effect of quality uncertainty on carbon emissions is proposed to determine the optimal acquisition and remanufacturing policies of the independent remanufacturing system. To better depict the effect of quality uncertainty on carbon emissions and apply this property to the decision-making processes, the remanufacturing time is defined to describe the quality of acquired cores. Since the optimal sorting policy is independent of the remanufacturing quantity, the problem-solving process is divided into two sub-problems, namely, the sorting problem and remanufacturing problem. In the sorting problem, the optimal threshold of remanufacturing processing time is derived using a dichotomy method. In the remanufacturing method, the optimal acquisition quantity and remanufacturing quantity are obtained with the sorting policy derived above. In order to explore the difference with previous studies in which the effect of quality uncertainty on carbon emissions is ignored, numerical experiments between varied emissions case and fixed emissions case are employed to analyze and validate the effectiveness of proposed method. The results indicate that considering the effect of quality uncertainty on carbon emissions can effectively increases profit and reduces total carbon emissions for corporations. Moreover, the model considering the effect of quality uncertainty on carbon emissions exhibits a better adaptability to the variations in the external conditions.

1. Introduction

As a key part of sustainable development, remanufacturing increasingly attracts the attention of numerous researchers and practitioners because it can effectively assist in reducing resource consumption and environmental pollution (Laan and Salomon, 1997). From the corporate perspective, incorporating the remanufacturing operations into the business process can yield economic benefits (Smith and Keoleian, 2004). In addition, legislations that extend the accountability of the producer, necessitate the firms to take the responsibility for recycling and processing the waste-products; this has provided a strong motivation for the growth of the remanufacturing industry (Esty and Winston, 2009). However, in contrast with manufacturing, remanufacturing is more complex because of its high uncertainty, and corporations find it difficult to decide their acquisition and remanufacturing policies.

In practice, the quality of acquirable cores is variable. The uncertainty in the quality of the end-of-life products has been recognized as a critical factor directly affecting the remanufacturing cost (Gao et al., 2015; Deng et al., 2017). To maximize the profits of remanufacturers, a quality-based categorization of the acquired cores is required and a part of the cores should be scrapped or sold in the secondary market because of their poor quality. Thus, it is important for remanufacturers to decide the number of and which acquired cores to be remanufactured. However, the former depends on the volume of the cores that have been acquired (Teunter and Flapper, 2011). Galbreth and Blackburn (2010) also highlighted in their study that acquiring an appropriate quantity of used items that exceed the demand can reduce the negative effects of their uncertain quality. Hence, acquisition and remanufacturing

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https://doi.org/10.1016/j.jclepro.2018.03.150
0959-6526/

decisions should be analyzed in conjunction to adopt the corresponding optimal policies.

In addition, currently, the interest in environmental protection is growing worldwide, and the various related policies and legislations require a positive response from companies to reduce their pollutant discharge such as air emissions and solid-wastes. This lays more demands on the manufacturers and remanufacturers. In particular, carbon emissions have become an increasingly important influential factor because of the intensification of the greenhouse gas effect (Chang et al., 2015; Gong and Zhou, 2013). Some of the market-based mechanisms are designed to curb the industrial carbon emissions including mandatory carbon emission capacity, carbon tax, and carbon emission cap and trade (Wang et al., 2017). Of these three regulation policies, carbon tax has been proved to be more effective for reducing the carbon emissions and promoting the development of the remanufacturing industry (Liu et al., 2015; Yenipazarli, 2016). To follow these regulatory rules, remanufacturers should take the cost of the carbon emissions into consideration and adjust their existing strategies for resolving the acquisition and remanufacturing problems.

Thus, identifying an approach for determining the optimal acquisition and remanufacturing policies while considering the quality uncertainty as well as carbon emissions is becoming increasingly important. In a traditional manufacturing process, the carbon emissions because of production are fixed as the manufacturing procedure using the same raw materials is the same. However, in a remanufacturing process, better-quality acquired cores would require less time for remanufacturing and have lower greenhouse gas emissions, implying that the carbon emissions during remanufacturing production are drastically affected by the quality of the cores (Gao et al., 2015). Therefore, this study considers the effect of quality uncertainty on the carbon emissions. To comply with the rules of carbon emissions, their cost is incorporated in the decision-making process for the optimal acquisition and remanufacturing policies.

The remainder of this paper is organized as follows. Section 2 presents a brief review of the related research. Section 3 describes the specific problem and main components of the model. In section 4, the approach for solving the model is proposed. The varied and fixed carbon emissions cases are compared in section 5. Subsequently, in section 6, numerical examples are presented to demonstrate the theory and relate it with practical scenarios. Finally, in section 7, conclusions drawn from the study are summarized along with future research directions.

2. Literature review

Extensive research studies have been conducted regarding remanufacturing. For a comprehensive understanding, readers are referred to Souza (2013) and Subramoniam et al. (2009). This section is mainly focused on the efforts relevant to acquisition and remanufacturing problem.

In contrast with manufacturing, the acquisition and remanufacturing activities of remanufacturing firms are more complex, and further research is required to promote the development of the remanufacturing industry (Guide et al., 2003). Guide and Jayaraman (2000) studied the factors impacting core acquisition and proposed a formal framework for product acquisition management. Moreover, Guide (2000) highlighted the additional variety associated with remanufacturing and listed the characteristics that significantly convolute the production planning and control activities. However, the unpredictability of goods and repairable component yields makes it extremely difficult to determine the acquisition and remanufacturing policies which has been disclosed by DePuy et al. (2007). The quality uncertainty of the cores is one of the most important reasons for the unpredictability of goods and repairable component which can directly affect the remanufacturing cost as well as the optimal acquisition and remanufacturing policies. Therefore, the quality uncertainty needs to be incorporated into the decision-making process.

Summarizing the previously reported research, generally, two forms are used to describe the quality of acquirable cores, which are the proportional yield and a continuous variable, respectively. The former is the proportional yield of acquirable cores (Souza et al., 2002; Vorasayan and Ryan, 2006; Panagiotidou et al., 2013; Behret and Korugan, 2009; Van Wassenhove and Zikopoulos, 2010; Li et al., 2013; Galbreth and Blackburn, 2010). However, it is assumed that acquired cores were classified into several grades according to their quality before acquisition, and in each grade the cores were considered homogenous, which disregarded the associated quality variability inside each grade (Guide et al., 2003; Cai et al., 2014). The latter is a continuous variable that takes value into the interval $[0, 1]$ according to the different quality of the cores (Robotis et al., 2005; Ferguson et al., 2009). However, it is difficult to collect the data. To solve this problem, in some extended research(Simon et al., 2001; Guide et al., 2008; Galbreth and Blackburn, 2006), the continuous variable was defined based on specific characteristics such as the remanufacturing processing time or remanufacturing cost, so that it is easy for remanufacturers to obtain the relevant actual data. In this paper, the remanufacturing processing time is adopted to describe the quality of acquirable cores.

The above-mentioned studies mainly analyzed the core acquisition and remanufacturing process from an economic perspective. However, remanufacturing is also well-known for its potential to provide significant environmental benefits (Nikolopoulou and Ierapetritou, 2012; Krikke, 2011; Liao et al., 2018). In addition, the aggravation of global warming motivates firms to modify their approaches for selecting their acquisition and remanufacturing policies. Therefore, carbon emissions have attracted a lot of attention of various researchers, which have been considered into the decision-making process. For example, Bonney and Jaber (2011) regarded the vehicle emission cost as a fixed emission cost per shipment, and discussed its effect on the optimal production planning decisions. Furthermore, Liu et al. (2015) presented three kinds of carbon emission regulation policies to evaluate the remanufacturing quantity, which can help to improve the total profits. The three policies are mandatory carbon emissions capacity, carbon tax, and cap and trade, respectively. By numerical examples, the results showed that policy-makers favor the carbon tax policy. Moreover, Yenipazarli (2016) used the leader-follower Stackellberg game model to investigate the impact of emission taxes on the optimal production and pricing decisions. Yang et al. (2016) incorporated the quality uncertainty and carbon emission into the multi-product decisions. In general, these references have considered the quality uncertainty and emission cost in the decision-making process. However, the carbon emissions generated during remanufacturing process in these research are considered to be a fixed value for each remanufactured product, whereas carbon emissions are related to the quality of the cores in actual and high-quality acquired core implies low-carbon emission (Cao et al., 2012; Gao et al., 2015). Different carbon emissions mean different emissions cost, which can directly affect the profit of remanufacturers. Therefore, the relationship between the quality uncertainty and carbon emissions has to be considered in the acquisition and remanufacturing problem.

In this paper, the cost of the carbon emissions is incorporated into the model and the remanufacturing processing time is defined to describe the quality of the cores, which can be more accurate in describing the actual remanufacturing process. In addition, the remanufacturing processing time threshold is selected to make the