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Fuzzy multi-objective recoverable remanufacturing planning decisions involving multiple components and multiple machines ☆

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ABSTRACT

The demand for customization is gradually increasing given that recycled materials no longer meet customer demands for new products. Meeting the needs of a particular customer may require release of numerous new materials and recycled materials to minimize both total production costs and total CO_2 emissions. The lot-sizing production-to-order problem is to optimize the lot size for each potential lot release. This study focuses on the relationship between new materials and recycled materials under varying production cost, machine yield and capacity and energy consumption. Fuzzy multi-objective linear programming (FMOLP) models are used to analyze factors in the relative cost-effectiveness and CO_2 emissions. The proposed model evaluates cost-effectiveness and CO_2 emissions and integrates multi-component and multi-machine functions for remanufacturing systems. The analytical results can help managers during decision making by enabling systematic analysis of the potential cost-effectiveness of recoverable remanufacturing.

1. Introduction

In recent years, resource depletion and waste have increased rapidly. Therefore, many countries have begun considering environmental issues such as reverse logistics and the recycling, reuse and remanufacturing of products. Aside from adhering to strict environmental laws, businesses must actively strive to lower the environmental impacts of their products. The most effective approach is implementing effective methods of product recycling, reuse and remanufacturing. Reverse logistics enables user-end recycling of obsolete products by dismantling, cleaning, and restoring them in a repetitive cycle of reuse and remanufacture. For example, end-user recycling by Hewlett–Packard recovers empty toner cartridges and prepares them for repeated use (Jorjani, Leu, & Scott, 2004). Therefore, including appropriate use and remanufacturing of recyclable materials in the design of production systems is an important contemporary issue that must be solved.

As the trend in customization increases, some recycled materials can no longer meet customer demands. Another consideration is creating value-added products by combining new and recycled materials in remanufacturing methods (Li, Chen, & Cai, 2007). Remanufacturing processes require a tradeoff between the cost and CO_2 emissions of new and recycled materials. That is, new materials have a high purchasing cost but a short processing time, which reduces energy use. In contrast, recyclable materials have low purchasing costs but a long processing time, which results in high energy use. Therefore, when companies consider the differences in cost and CO_2 emissions they compromise by simultaneously considering the cost of new materials and the cost of remanufacturing recycled materials.

In practice, decision makers must simultaneously consider multiple objectives such as lowest total cost and lowest total CO_2 emissions. However, most research on this topic tends to focus on a single objective. In actual real lot-sizing production-to-order problems involving recoverable remanufacturing systems, input data or parameters such as forecasting demand, resources, costs and objective function are often imprecise or fuzzy because some information is incomplete, unavailable, or unobtainable. These factors result in a fuzzy objective function. For example, the objective function of annual production costs may be \$0.5 million, and the objective function of annual CO_2 emissions may be 5 metric tons. To minimize the effects of this imprecision, a set of fuzzy multi-objective models is needed to produce a set of compromise solutions.

In this study, a novel FMOLP model is also used to solve the lot-sizing problem of recoverable remanufacturing with multiple components and multiple stages in uncertain environments. The proposed FMOLP model simultaneously optimizes both total

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production costs and CO_2 emissions considering customer demand, machine capacity, lot sizes released and CO_2 emissions constraints. That is, the model simultaneously achieves the targets of low carbon emissions and low cost. The original FMOLP model simultaneously minimizes total production costs and CO_2 emissions with reference to multiple components and multiple machines.

The remainder of the paper is organized as follows: Section 2 presents a literature review; Section 3 formulates the fuzzy multi-objective recoverable remanufacturing planning decision model; Section 4 assesses the feasibility of the proposed model in the case of remanufactured toner cartridges. Finally, Section 5 concludes the study.

2. Literature review

Remanufacturing is a major line of research in the green operations literature. The techniques used in this study to minimize energy and resources for flow systems and to minimize the use of virgin materials are based on the green manufacturing and remanufacturing literature (Srivastava, 2007).

2.1. Recoverable manufacturing/remanufacturing

Recoverable manufacturing systems minimize the environmental impact of industry by reusing materials, reducing energy use, and reducing the amount of industrial products contained in landfill (Guide, Jayaraman, Srivastava, & Benton, 2000). Richter and Weber (2001) formulated the reverse Wagner/Whitin model with additional variable manufacturing and remanufacturing costs to optimize inventory. Koh, Hwang, Shon, and Ko (2002) proposed a model for analyzing an inventory system with recycled products and newly purchased products for procurement as well as the optimal inventory level of recoverable items. Konstantaras and Papachristos (2008) proposed a closed form expression of the optimal solution for the Koh et al. (2002) model. Teunter and Haneveld (2002) considered the appliance remanufacturing problem of controlling parts inventory in the final phase of service. They also proposed a partly graphical method of calculating the optimal inventory policy.

Bhattacharya and Guide (2006) examined the problem of optimal retail order quantities from the perspective of a manufacturer of new products and from the prospective of a remanufacturer of used and unsold products. Jayaraman (2006) proposed an analytical approach to production planning and control for closed-loop supply chains with product recovery and reuse. The approach included a linear programming model called the remanufacturing aggregate production planning model for aggregate production planning and control. Choi, Hwang, and Koh (2007) developed a mathematical model of an inventory system in which stationary demand can be satisfied by recovered products and newly purchased products.

Chung and Wee (2008) analyzed how green product design, the new technology evolution, and remanufacturing affect production-inventory policy. They also developed an integrated deteriorating inventory model that considered the value of the green-component life-cycle during remanufacturing in semi-closed supply chains. Zhou and Wang (2008) designed a reverse logistics network model that simultaneously considered both repairing and remanufacturing options. Bao, Tang, and Ji (2008) investigated the bimodal properties of disassembly/purchasing lead time distribution in a remanufacturing system. They proposed a minimum relative entropy method of estimating how bimodal distribution affects system performance. Behret and Korugan (2009) analyzed a hybrid remanufacturing-manufacturing system that allows for different quality levels for return flows. They also proposed a multi-stage inventory control model that considered uncertainties in remanufactured products, including quality, return rates, and return time.

Konstantaras, Skouri, and Jaber (2010) developed an inventory system that combined inspection, sorting, recovery (remanufacturing), and ordering of new items for a recoverable product in a reverse logistics environment. Ahiska and King (2010b) analyzed inventory control for a single-product recoverable manufacturing system for the entire product life cycle. Piñeyro and Viera (2010) investigated the lot-sizing problem using different demand streams for new and remanufactured items. They provided a mathematical model for solving the problem and developed a Tabu-search-based method for finding the near-optimal solution.

For production-remanufacturing inventory systems, Konstantaras and Skouri (2010) developed inventory models for cases of shortage and no shortage for a single product recovery system with variable setup numbers. Chung and Wee (2011) developed an integrated production-inventory deteriorating model that considered the greening operation process and life-cycles in a green supply chain inventory control system. Teunter, Douwe, and Flapper (2011) studied problems and decision making related to acquisition and remanufacturing. Lot acquisition decisions were optimized under consideration of uncertainty, multiple quality and multinomial quality distribution. Feng and Viswanathan (2011) evaluated a deterministic model of product recovery in a manufacturing system. They proposed two lot-sizing policies and developed two heuristics for solving the problem. In a mathematical model for green product mix decisions, Tsai et al. (2012) incorporated capacity expansion features by using a linear programming technique that references machine hour constraints, direct labor constraints, direct material constraints, CO_2 emission constraints and product-level constraints. Amin and Zhang (2012) designed a multi-objective mixed-integer linear programming model for optimizing a closed-loop supply chain network of disassembly, refurbishing and disposal sites. The objective of network configuration was to optimize the number of products and materials in each section of the network.

2.2. Remanufacturing planning decisions problem

Van der Laan and Salomon (1997) developed a stochastic inventory system with production, remanufacturing, and disposal operations to solve inventory control problem. Their stochastic inventory system attempts to minimize the total expected system costs. Van der Laan, Salomon, and Dekker (1999) later examined how lead-time duration and lead-time variability affect total expected operational costs in a system with manufacturing/remanufacturing operations. Guide, Kraus, and Srivastava (1997) designed a simulation model with remanufacturing facility, disassembly release mechanisms, and priority dispatching rules to solve a disassembly scheduling problem. Guide (1997) derived a simulation model for solving the scheduling policies problem with priority dispatching rules and drum-buffer-rope in a recoverable manufacturing system. Richter and Sombrutzki (2000) proposed a reverse Wagner/Whitin's model to solve a remanufacturing planning and inventory control problem, which attempts to minimize the total production costs.

Dobos (2003) developed a two-store reverse logistics model with continuous disposal to solve a production and inventory control problem in order to minimize the sum of the holding costs in retail stores and costs of manufacturing, remanufacturing and disposal. Kiesmüller (2003) designed a mathematical model with lead time, deterministic and dynamic demand, and return rates to solve a inventory control problem in a single product recovery system. Seliger, Franke, Ciupek, and Basdere (2004) developed a discrete-event simulation model for solving the process and facility planning problem in mobile phone remanufacturing, with the objective of maximizing the profit margin. Kim, Song, Kim, and