European Journal of Operational Research 233 (2014) 408–419

Contents lists available at ScienceDirect

European Journal of Operational Research

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

A multi-criteria decision making model for advanced repair-to-order and disassembly-to-order system

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ARTICLE INFO

Article history:
Available online 21 September 2013

Keywords:
Sensor-embedded products
Disassembly-to-order
End-of-life management
Radio frequency identification (RFID)
Linear physical programming

ABSTRACT

Sensor-embedded products (SEPs) eliminate a majority of uncertainties involved in product recovery by providing item-based life-cycle information. This information includes the content of each product and component conditions, and enables the estimation of remaining useful life of the components. Once the data on the products are captured, it is possible to make optimal recovery decisions without any preliminary disassembly or inspection operations.

This paper presents a multi-criteria advanced repair-to-order and disassembly-to-order (ARTODTO) system for SEPs. ARTODTO system deals with products that are embedded with sensors and RFID tags. The goal of the proposed approach is to determine how to process each and every end-of-life product (EOLP) on hand to meet remaining life based product and component demands as well as recycled material demand while optimizing an aggregate objective function. Demands are met by disassembly, repair, and recycling operations. Outside component procurement option is used to eliminate the component and material backorders. A linear physical programming (LPP) model is proposed to optimize the multi-criteria ARTODTO system. The LPP approach is explained in detail and a case example is considered to illustrate its application.

1. Introduction

Rapid technological advancements have resulted in the availability of high-tech products at low prices so that it has become economically viable for customers to satisfy their desire for newer products even before their current products reach their technological ends of lives. Increased turnover of such products have led to early disposal of goods, depletion of virgin resources and disappearance of landfills resulting in huge environmental concerns. With the increase in public awareness about environmental issues, both environmental legislations and customers have forced manufacturers to manage their end-of-life products (EOLPs) in a responsible manner. Manufacturers try to comply with customer expectations and governmental regulations by incorporating the concept of product recovery with their production models. Product recovery decreases the use of virgin resources by recovering the remaining value trapped in EOLPs, in turn, providing economic benefits by creating new markets for recycled materials, used components and remanufactured products. However, product recovery is fraught with uncertainty as the conditions of returns are not always known. These uncertainties provide major challenges in product recovery (Fleischmann et al., 1997;Gungor & Gupta, 1999; Ilgin & Gupta, 2010b).

The management of EOLPs involves cleaning, disassembly, sorting, inspecting and recovery or disposal. The recovery may take one of several forms depending on the condition of EOLPs: viz., product recovery (refurbishing, remanufacturing, repairing), component recovery (cannibalization), and material recovery (recycling). A method that has gained attention in recent years is disassembly-to-order (DTO). DTO system aims to fulfill component and material demands by cannibalizing the EOLPs.

The main objective of DTO is to determine the optimum number of EOLPs to disassemble to fulfill the demand for components and materials such that a criterion or a combination of criteria of the system is satisfied. EOLPs, however, originate from many sources in which the products are subjected to various operating environments, usage patterns and customer upgrades. This causes an unpredictable/uncertain status in EOLPs leading to errors in DTO's outcome. Since the life cycle information of a product is unknown, inspection and testing become necessary to determine the conditions of EOLPs and their components. When a component turns out to be nonfunctional after testing, the time and effort made in disassembling and testing that component are wasted. This increases the backorders and prevents production planners from

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http://dx.doi.org/10.1016/j.ejor.2013.09.003

generating reliable recovery plans for the disassembly-to-order (DTO) system. Missing components also lead to unreliable recycling planning as planned number of components may not be harvested for recycling during disassembly.

Another popular recovery option is repair. EOLPs may need component replacement to be in "working order". This option usually requires disassembly of nonfunctional components and may involve disassembly of functional components due to disassembly precedence relationships. Depending on the condition of a recovered product, it may be sold in the market as a brand new or a used product. The components' replacement operations that need to be performed during the repair option vary widely depending on the condition of EOLPs. When there is no information available on the components' conditions, thorough testing is needed to determine that. If an EOLP is found not suitable for repair, the time and resources spent on determining that are wasted. It is clear that out of all EOLPs on hand, finding the EOLPs with minimal recovery costs requires testing of the whole EOLP inventory. That can be very expensive. However, emerging information technology devices, such as sensors and radio-frequency identification (RFID) tags, can be very helpful in mitigating such uncertainty.

RFID has recently gained importance in closed loop supply chain operations, including reverse logistics, disassembly and remanufacturing, as a means of communication and data storage (Cao, Folan, Mascolo, & Browne, 2009; Zhou & Piramuthu, 2011). Although passive RFID tags are sufficient for tracking purposes, active RFID tags with embedded sensors can provide a lot more information about the usage/condition of every single object. These products are referred to as sensor embedded products (SEPs). A sensor is a device that detects and keeps a log of the changes in the value of various measures such as temperature, pressure, vibration and converts them into useful information to provide the conditions of the components. Sensor embedded products (SEPs) are manufactured with sensors implanted in them to monitor their critical components while they are in use. Sensors collect dynamic field data while the product is being used. Dynamic field data or information generated during the use of a product consist of patterns of usage, number of use cycles, run time in each use cycle, and environmental conditions. Dynamic data also include service history on inspections and, replaced and repaired parts. SEPs mitigate storage and collection of both static and dynamic data on the product. Collected data can be used to predict failures (Ilgin & Gupta, 2010a), estimate the remaining useful lives of components, and recognize missing components as the products reach their ends of lives. In addition, using the static information stored on the RFID tags, type, release date, sale date, sale location, maintenance history and scheduled part replacements of an EOLP can be acquired without any inspection or disassembly operation. Decrease in uncertainty allows better planning which in turn leads to improvements in financial and environmental goals. Furthermore, these devices enable fulfillment of remaining life based component and product demands, thus allowing customers to state minimum remaining life requirements in their orders. This also helps determine the warranty levels that can be offered to customers on recovered items. Warranty costs are directly related to the remaining lives of recovered components and customer requirements. Because of the available sensor information, orders can be prepared so that they exceed the minimum remaining life requirements as much as possible minimizing the warranty claims.

In this paper, a multiple-criteria ARTODTO model for SEPs is proposed. The problem is formulated as a linear physical programming model. A case example of a residential air-conditioner (AC) ARTODTO system with disassembly precedence relationships among components is considered to illustrate the application of the methodology.

2. Literature review

2.1. Environmentally conscious manufacturing and product recovery

State of art in Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) is covered by the pair of papers by Gungor and Gupta (1999) and Ilgin and Gupta (2010b). Disassembly is one of the most popular research areas in ECMPRO owing to its importance in all recovery operations. Disassembly problems have been studied under four main areas, namely, scheduling (Barba-Gutiérrez, Adenso-Díaz, & Gupta, 2008; Duta, Filip, & Popescu, 2008), sequencing (Adenso-Diaz, Garcia-Carbajal, & Gupta, 2008; Moore, Güngör, & Gupta, 2001), disassembly line (McGovern & Gupta, 2007, 2010) and disassembly-to-order. Disassembly-to-order (DTO) research provides a strong basis to this study. The goal of DTO is to determine the optimum number of EOLPs to be disassembled in order to fulfill the demand for components and materials such that some desired criteria of the system (cost minimization, profit maximization, etc.) are satisfied. Kongar and Gupta (2002, 2006, 2009a, 2009b) presented preemptive goal programming (PGP), fuzzy goal programming (FGP), linear physical programming (LPP), and multi objective TS models for the DTO problem and illustrated their implementations to various cases. Gupta, Imtanavanich, and Nakashima (2009) proposed an artificial neural network model in order to solve the DTO problem. Langella (2007) developed a multi period heuristic considering holding costs and external procurement of items. Inderfurth and Langella (2006) developed two heuristic procedures to investigate the effect of stochastic yields on the DTO system.

Remanufacturing has also been researched recently by many authors because traditional production planning approaches fall short in a product recovery setting. Lage and Godinho Filho (2011) reviewed 76 journal articles published on production planning and control (PPC) in remanufacturing between 2000 and 2009. The authors also provided a comparative analysis between this literature review and the review conducted by Guide (2000). High degrees of variability in the quantity, quality and timing of returned products necessitate innovative planning techniques that can deal with uncertainty (Schultmann, Zumkeller, & Rentz, 2006). In general, a production planning system for remanufacturing assists managers in planning how much and when to disassemble, how much and when to remanufacture, how much to produce and/or order for new materials, and coordinates disassembly and reassembly (Guide, Jayaraman, & Srivastava, 1999). Georgiadis and Athanasiou (2010) presented the impact of two-product joint lifecycles on capacity planning of remanufacturing networks. Authors put emphasis on the inherent uncertainties of remanufacturing systems and propose a systems dynamics model and design of experiments for capacity planning. A recent study by Georgiadis and Athanasiou (2013) deals with long-term demand-driven capacity planning policies in the reverse channel of closed-loop supply chains (CLSCs) with remanufacturing, under high capacity acquisition cost coupled with uncertainty in actual demand, sales patterns, quality and timing of end-of-use product returns. Authors study the system's response in terms of transient flows, actual/desired capacity level, capacity expansions/contractions and total supply chain profit, employing a simulation-based system dynamics optimization approach. Kim, Song, Kim, and Jeong (2006) developed a mixed-integer programming model to maximize the remanufacturing cost savings by determining the quantity of products/parts processed in the remanufacturing facilities/subcontractors and the amount of parts procured from external sources. DePuy, Usher, Walker, and Taylor (2007) presented a production planning method which estimates the expected number of remanufactured units to be completed in each future period. This method