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Quality management in product recovery using the Internet of Things: An optimization approach

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ABSTRACT

Internet of Things, by reducing or almost eliminating uncertainty regarding existence, types, conditions and remaining lives of components in an end-of-life product (EOLP), can mitigate planning of remanufacturing operations. Remaining useful life can be taken into account as a good measure of quality. Therefore, immediate determination of remaining useful life allows optimal recovery decisions to guarantee a minimum quality level on recovered products while satisfying various system criteria.

In this paper, a multiple objective advanced remanufacturing-to-order and disassembly-to-order (ARTODTO) system is proposed as an order-driven component and product recovery (ODCPR) system. In ARTODTO, device embedded products are remanufactured and disassembled to meet the product and component demands, recycled to satisfy the materials demands, stored to be re-used later, or disposed of. The objective of the system is to achieve multiple conflicting financial, environmental and quality-based goals. The problem is formulated as a mixed integer goal programming model that utilizes the Internet of Things. A numerical case example is considered to illustrate its implementation.

1. Introduction

Alarming increase in the use of natural resources and decreasing number of landfills have caused many environmental problems which have led to several government regulations that hold manufacturers responsible for their products after the products reach their end-of-lives (EOL). There are many advantages in managing EOLPs such as reduction in the use of virgin resources, landfill conservation, and cost savings stemming from the reuse of EOLPs, disassembled components and recycled materials. Management of EOLPs consists of a series of operations such as cleaning, disassembly, sorting, inspecting and recovery or disposal. Recovery options include remanufacturing, refurbishing, repairing, component recovery, and material recovery (via recycling). Conditions of collected EOLPs play a big role in determining the recovery option to choose. However, neither the quality nor the quantity of returning EOLPs is predictable. Hence, the outcome of the recovery operations is highly uncertain. This uncertainty is what makes quality management a challenging task in a reverse logistics (RL) setting. As one of the key elements of RL, remanufacturing exhibits, by far, the most difficult operations management problems. This is mostly because the variability and uncertainty associated with the quality of returned products lead to a huge variation in the product recovery operations and the quality of harvested components, spare parts and remanufactured products.

The "Internet of Things" has a potential to mitigate the planning of remanufacturing operations by reducing or almost eliminating uncertainty. The Internet of Things refers to uniquely identifiable objects (things) in a network structure. By means of this network, all objects can be monitored and tracked. Use of the Internet of Things has been proposed for various segments of supply chains including RL [1]. Radio-frequency identification (RFID) is considered to be the core component and the enabler of such a structure. 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 monitoring device that keeps a log of the changes in the value of various measures such as temperature, pressure and vibration. Sensor embedded products (SEPs) are built with sensors implanted in them to monitor their critical components while they are in use. By facilitating data collection during product usage, these embedded sensors help predict product/component failures [2] and estimate the remaining useful life of components as the products reach their end-of-lives. Remaining useful life can be taken into account as a good measure of quality allowing decision

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makers to construct sophisticated recovery models that guarantee a minimum quality level on recovered products while optimizing various system criteria.

Sensors and RFID tags, once incorporated with the products, can monitor the critical components throughout products' economic lives and deliver the collected lifecycle information when the products reach recovery facilities. In the beginning-of-life (BOL) phase, bill of materials, model and serial numbers, manufacturing date, location, warranty terms, maintenance instructions, and EOL processing guidelines (static data) are saved in the tags. In the middle-of-life (MOL) phase, sale date and customer number (static data), run cycles, working temperatures, failures, environmental sensory inputs such as dust, vibration, humidity levels (dynamic data), and maintenance information (e.g., dates, operations, center IDs, and technician IDs) are logged. By means of the central information sharing provided by the Internet of Things, item-level information is utilized to improve product design, provide on-time maintenance, and establish an early warning system in the BOL and MOL phases. EOL operations benefit the most from this information. Complete knowledge on the condition and quantity of EOLPs and remaining life determination eliminate costly preliminary disassembly and inspection operations, and enable optimal remanufacturing planning [3].

Advanced remanufacturing-to-order and disassembly-to-order (ARTODTO) is a system where SEPs are put through a series of recovery operations depending on their conditions such that the recovered product, component, and material demands are satisfied considering various system goals. Use of Internet of Things in an ARTODTO setting allows fulfillment of remaining life time based product and component demands, and affords customers the opportunity to state minimum quality (remaining functional life) requirements of their orders. Another advantage to being able to determine the remaining useful life of components is that the warranty levels on items can be defined based on real data rather than estimations. Warranty costs are strongly linked with the quality of recovered items and customer expectations/requirements. With the information provided by sensors, orders can be prepared so that they exceed the minimum quality requirements as much as possible to minimize the warranty claims.

In this paper, we propose an ARTODTO model for EOL processing of SEPs. The proposed model is formulated as a mixed integer goal programming model to achieve a variety of financial, environmental and physical goals. A dryer ARTODTO system with disassembly precedence relationships among components is considered to illustrate the methodology.

2. Literature review

The literature related to this study is reviewed under four subsections, namely, product recovery, quality issues in reverse logistics, sensor and RFID technologies and multi-criteria decision making.

2.1. Product recovery

An extensive overview of Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) is presented by Gungor and Gupta [4] and Ilgin and Gupta [5]. Together, this pair of papers explores the state of the art through 2009. Disassembly has been one of the hottest topics in product recovery area as a result of its importance in recovery operations. Disassembly problems have been studied under four main areas, namely, *scheduling* ([6,7,8–12]), *sequencing* ([13–17,18,19–21]), *disassembly line* ([22–24,25–29]), and *disassembly to order (DTO)* ([18,30–35]). Additional information about disassembly processes, problems and solution methods can be found in several other studies [36–39]. Majority of these papers mention uncertainty about quantity and quality of the returned products as one of the main issues to deal with and none of them proposed a complete system where uncertainty is reduced or eliminated.

2.2. Quality issues in reverse logistics

Quality assurance is one of the main challenges encountered in product recovery. Necessary recovery operations and quality of the recovered products are highly dependent on the quality status of the returned EOLPs. Quality of a returned product is determined by several factors during its life cycle. These factors could be maintenance frequency, upgrades, working conditions (light use, intensive use), environmental conditions (hot, cold, dusty, clean environments), etc. Similarly, the quantity of returning products is directly related to the willingness of the product holders to return their products. Although, buy-back campaigns or incentives can affect product holders' returning decision, it is still very difficult to estimate the number of returns. Moreover, even if it is correctly estimated, the number of reusable sub-modules/parts cannot be known before disassembly. In other words, because the quality of the returned products are not known in advance, the number of good quality parts recovered from the returned product is subject to uncertainty [40].

Quality of a return product can be defined in relation to that product's brand new condition. To this end, several dimensions of quality [41] such as features, conformance, serviceability, perceived quality and esthetics are not considered. Hence, performance, reliability and durability determine the quality of a returned product. In this study, we take remaining useful (i.e., performing as intended) life of a returned product as a measure to define quality. A recent book by Ilgin and Gupta [42] covers quality assurance and house of quality in a remanufacturing setting. Behret and Korugan [43] analyzed the effects of uncertainties in return quality in a hybrid (viz., remanufacturing and manufacturing) system via simulation. The authors concluded that as the return rate increases, remanufacturing operations dominate the system and the quality based classification of returns becomes much more important. van Wassenhove and Zikopoulos [44] investigated the effects of quality overestimation in an RL setting where the returned products are graded and classified based on a list of nominal quality metrics provided by the remanufacturer. Das and Chowdhury [45] proposed a mixed integer programming (MIP) model, which considers modular product designs and integrates an RL process for the collection of returned products, their recovery processes and production of products at different quality levels in order to maximize overall supply chain profit. Again, the quality levels are defined by indirect terms that do not necessarily measure quality. Nenes and Nikolaidis [46] proposed a multi period MIP model for the optimization of procurement, remanufacturing, stocking and salvaging decisions considering multiple suppliers and several quality levels of returned products. Nikolaidis [47] investigated the profitability of remanufacturing used products using an MIP model assuming the returns might be in several different quality conditions. A recent book examines the relationship between various quality issues and several areas of reverse logistics [48]. Chouinard et al. [49] proposed a stochastic programming model for designing supply loops considering five return product quality states (i.e., unknown, new, good condition, deteriorated or damaged, and failing). Denizel et al. [50] presented a stochastic programming approach considering certain probabilistic quality scenarios. Pochampally and Gupta [51] implemented the six-sigma quality approach for the selection of potential recovery facilities in reverse supply chains. Kim [52] introduced the quality embedded remanufacturing (QRS) and proposed a multi-agent approach and a real-time scheduling mechanism for