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Optimal sorting policies in remanufacturing systems: Application of product life-cycle data in quality grading and end-of-use recovery

Ardeshir Raihanian Mashhadi [a], Sara Behdad [a,b,*]

[a] Mechanical and Aerospace Engineering, University at Buffalo, State University of New York, Buffalo, NY, USA
[b] Industrial and Systems Engineering, University at Buffalo, State University of New York, Buffalo, NY, USA

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ABSTRACT

The quality of used products returned to recovery facilities is often highly uncertain. Quality grading and sorting policies are immediate solutions that are used in remanufacturing systems to handle this source of variability in incoming products. The sorting policies offered in the literature so far are mainly based on external criteria such as market trends, corporate policies and assessment of the product's physical condition. In this study, we offer a new sorting method based on both product's internal factors such as future reusability of components, product identity data, and product health status as well as external factors such as market trends. The purpose of this paper is to improve decision making in remanufacturing operations by integrating the product life cycle information, particularly product usage phase data, into determining both optimal sorting policies and End-of-Life/End-of-Use (EoL/EoU) decisions. To achieve this, two related analyses are conducted: first, a reusability index is derived for each product unit based on the reusability of its components, product features, and the product usage phase information. Second, the reusability index is used as a quality measure to derive the optimal EoU decision for each product category. Clustering algorithms are employed to identify similar products that could go through the same recovery process. A data set of hard disk drive Self-Monitoring Analysis and Reporting Technology (S.M.A.R.T.) coupled with simulated data has been analyzed to illustrate the application of the model. The proposed framework helps decision makers include product identity data in the EoU recovery decision making under the quality heterogeneity.

1. Introduction

As the manufacturing industry is moving toward a more resource-constrained economy, the notion of resource security and sustainability of manufacturing systems requires more attention. One solution proposed to improve the sustainability of manufacturing systems is to adopt the concept of a circular economy, in which new approaches are employed to keep the product value within the same manufacturing system through facilitating end-of-use recovery and remanufacturing operations [1]. However, remanufacturing operations suffer from many challenges including several sources of uncertainty in addition to the traditional uncertainties exist in the manufacturing frameworks [2]. For instance, unlike manufacturing systems, the condition of products acquired in remanufacturing facilities is highly variable. The quality level directly determines the buyback price, corresponding to the operational efforts required to remanufacture them. Therefore, quality grading of the incoming products in remanufacturing systems is a critical challenge, since the high level of uncertainty and variability cripples the planning efforts in remanufacturing operations.

In order to develop a proper quality grading system in remanufacturing facilities, two general steps are needed. First, an accurate measure should be defined to assess the quality of incoming products and second the measure should be employed to sort and categorize the products with the aim of maximizing the profit out of EoU recovery decisions.

Currently, two common quality assessment approaches are used in the industry. The first approach is based on the physical inspection of returned products. This approach may require full disassembly of the product, which is a labor-intensive process and is not cost efficient [3]. The second approach, which is more common in the consumer electronics industry, is the nominal quality grading based on the product appearance and basic functionalities [4]. The latter lacks the proper accuracy as assessing the quality

* Corresponding author.
E-mail addresses: ardeshir@buffalo.edu (A. Raihanian Mashhadi), sarabehd@buffalo.edu, sarabehdad@gmail.com (S. Behdad).

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based on appearances, market trends, corporate policies and basic features may not reveal a comprehensive condition of the product.

Overall, quality grading and product sorting policies have been the point of attention in the closed-loop supply chain literature [5–7]. There is a consensus in the literature that suggests proper quality grading prior to remanufacturing decisions ultimately improves the profit [7,8]. However, these studies are founded upon similar assumptions regarding a priori knowledge of the statistical distributions of the product quality or error free inspections. Therefore, new approaches are still needed to overcome these assumptions. To fill this gap and further to use the opportunities available through improvements of data science and advancements in the sensing technologies during recent years, data-driven approaches have been proposed to utilize product life cycle information for reusability and quality assessment purposes [9–11]. The main idea of such studies is to integrate one or several sensors in the product to record data over its usage cycle. Then, these data are used to determine the real-time product quality level or predict its failure. The same source of data can be used to identify the product's quality grade or its reusability potential for EoU decision making [12].

Although the idea of using product sensor data for EoU recovery decisions has already been discussed in the literature, no effort has been made to implement this idea. Research is still in the early stage in this field. Therefore, there is a need for a comprehensive quality assessment model that allows using product life cycle data with the aim of simultaneous consideration of both internal and external product information such as product features and conditions as well as market trends in sorting decisions. In addition, the proposed models should be able to handle product lifecycle data, independent of how and where data are collected, sensors data or other collection methods. Furthermore, more research should be conducted regarding the impact of product life cycle data on the EoU decision making process and the way that product identity data should be employed. In many cases, even if the product identity data for each unit of the product are available, it is not practical to tailor remanufacturing operations for each individual product, unless some sort of clustering and grouping is used to minimize the remanufacturing operational costs.

The current paper contributes to the literature by addressing the above mentioned gaps. First, we propose a method that uses product life cycle data (e.g. product identity data) to determine product quality conditions and quantify the future reusability. Second, we show how products with similar quality levels can be clustered to facilitate decision making in remanufacturing operations, and finally we illustrate how best EOU decisions will be made for each product cluster. A product reusability index has been proposed based on the product critical component features and life cycle information. The reusability index defines the quality level of the product. Clustering algorithms are used to sort and group the products based on their quality level and an optimization problem is defined to determine the best recovery operation for each cluster. The application of the proposed method has been shown in a case study of computer hard drives.

The rest of this paper is organized as follow: Section 2 provides a review of the literature on the quality grading and the integration of product life cycle information in EoU recovery decisions. Section 3 discusses the proposed method including the quality assessment step, sorting policy and the EoU decision model. Section 4 provides a case study of personal computers. Section 5 presents the sensitivity analysis on the model results and finally, Section 6 concludes the paper.

2. Background: quality grading models and sorting policies

Since the uncertain condition of returned products significantly affects the testing, disassembly and EoU recovery decisions, addressing the uncertainty in the quality of returns prior to remanufacturing is becoming critical. It has been shown that as the product sorting and acquisition process improves, the profitability of recovery operations improves as well [13]. This section strives to provide a review of studies that address the issue of uncertain quality returns in EoU recovery literature.

2.1. Different approaches in modeling uncertainties in the quality of returns

Generally, two types of modeling approaches have been employed in the literature to address the uncertainty in the quality of returned products [14]. The first category of studies considers a fraction of remanufacturable products in each batch of returns. The second group of studies represents the quality of returns by using a continuous random variable between zero and one with known probability distribution.

To mention a few studies, Pishvaee et al. [15] assumed that an inspection stage separates the products into two groups: recoverable (high quality) and unrecoverable (low quality) products. Fathi et al. [16] considered an inspection based quality assessment system where the quality of a product is defined based on the expected processing time required for remanufacturing it. Therefore, products are separated into two groups; those that have a processing time less than a threshold value and those that have a processing time greater than the threshold. The latter will be rejected for remanufacturing.

Zikopoulos and Tagaras [5] also assumed that the quality of the product is determined after inspection and defined nominal quality grades to investigate the impact of uncertainty in the quality of returns on the profit of the operations. Similarly, Denizel et al. [6] considered nominal quality grades based on inspection for a multi-period remanufacturing system. Ferguson et al. [8] used a real number varying between zero and one to model the quality of the product. Galberth and Blackburn [17] and Panagiotidou et al. [14] used known statistical distributions to formulate the uncertainty in the quality of returns. Aligned with the previous studies, Subulan et al. [18] developed a stochastic mixed integer linear programing model for a lead/acid battery closed-loop supply chain. They considered an uncertain quality level for batteries where the ratio for inappropriate condition of the batteries is stochastic. Francie et al. [19] studied a hybrid manufacturing/remanufacturing system for printer cartridge industry where products are separated into two categories based on their quality levels.

2.2. Integration of product life cycle data into end-of-life recovery decisions

Regardless of the mathematical approach to model the uncertainty in the quality of the products, a more practical challenge is to define the measure to represent the quality level. Although using nominal quality grading approaches based on the product appearances and basic features is more common in the industry (readers may refer to [4,20] as examples of quality assessment in web-based trade-in programs), utilization of product life cycle information to represent its quality level seems more promising, as it brings more accuracy and flexibility into the recovery operations.

The idea of using life cycle sensor data for quantifying the reuse potential in electronic products was first introduced by Scheidt and Zong [12]. They emphasized the advantages of having a modular design and introduced an "identification unit" for each module to record the life cycle data. In their model, the data were accessi-