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Full Length Article

Modeling operation and inventory for rare earth permanent magnet recovery under supply and demand uncertainties

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ABSTRACT

Rare earth permanent magnets (REPMs) play an essential role in various applications such as renewable energy production, and aerospace and defense related products. Rare earth elements (REEs) such as neodymium and dysprosium are used in REPMs, and the supply of these REEs has experienced volatility. To mitigate this risk, REEs may be recovered from end-of-life (EOL) products such as computer hard disk drives (HDDs). To facilitate REE/REPM recycling, this paper develops an operation and inventory management strategy to explore the profitability 1) under uncertain market supply and 2) with varying component/material values whose demand also faces significant uncertainties. The resulting strategy provides recommendations for the ordering and processing quantities associated with REPM containing products. An upper bound solution on the recovery profit was proposed to assess the performance of the developed strategy. We found that the proposed strategy helps increase the overall profit, and its performance is close to the upper bound. Finally, several scenarios were evaluated to examine how market conditions affect profit. To the best of authors' knowledge, this research is the first study on REPM recycling that provides a promising strategy to the relevant industry.

1. Introduction

Rare earth elements (REEs), such as neodymium and dysprosium, are used to make rare earth permanent magnets (REPMs). REPMs are used extensively in motors, actuators, and generators for applications such as automobiles, hard disk drives (HDDs), and wind turbines. REPMs offer the benefit of a smaller and compact design compared to other magnet materials such as alnico and ferrite, since they have a substantially stronger magnetic field per volume [1,2]. In addition, REPM motors have been reported to have less environmental impact than ferrite motors [3].

While REEs in general and REPMs in particular offer exciting performance related properties, recent history has shown their supply to be uncertain. At present, over 80% of the world's REEs [4] and REPMs [5] are produced in China. Over the last two decades, demand for REEs has increased [6] and environmental concerns associated with their production have intensified. Perhaps owing to these factors, China has imposed export duties and quotas, and reduced the number of licensed manufacturers, which has limited the REE availability to the rest of the world [7,8]. REE prices have fluctuated considerably over the last two decades. For example, the price of neodymium oxide rose from $10 per kg in 2001 to $239 per kg in 2011, and then dropped to $80 per kg in 2014 [9]. Given the indispensable nature of REEs for a variety of applications, supply and price volatilities constitute a great challenge. Responses to this challenge include: i) diversifying new sources of REEs, ii) developing substitute materials, and iii) employing reuse and recycling. These responses call for anticipating criticalities and preparing for them in the long term, as opposed to just suffering the criticalities when they occur.

There are advantages to using recycled REEs as opposed to utilizing virgin sources. Securing virgin sources is extremely capital-intensive, requiring about $100 million to $1 billion [10] to setup an operation to extract and process rare earth ores. It takes between 8 and 15 years to construct a mine and another 10–20 years to achieve full-scale REE production [11]. Production knowledge is limited outside of China, and the production cost is often lower in China than other countries, which represents a barrier to new competitors entering the market [12]. The environmental consequences of REE production are significant: greenhouse gas emissions, water contamination, and resource depletion [13,14]. When REEs are extracted, by-products such as thorium or uranium are often produced. There are environmental and health risks asso-

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ciated with radioactive elements, and their management increases the cost of REE production [10]. With recycled REPMs, the potential supply of material can be as large as the in-use stock of REPMs – for some REEs (neodymium, dysprosium, praseodymium, and terbium), the in-use stocks are almost four times the annual extraction rate of the individual elements [15]. In particular, it has been reported that HDD recycling is the most feasible way to collect large quantities of neodymium (not only because of the feedstock abundance but also for the techno-economic feasibility of recycling REEs from HDDs), as compared with other products such as direct drive wind turbines, most of which are not yet available for EOL recycling [16]. Rademaker et al. [34] also confirmed that HDDs would remain the predominant recycling source for neodymium for the next 10 years, followed by the automotive and wind turbine sources. HDDs are an important source of REEs [17], as they use the most REPMs within electronic goods [18]. In addition to a meaningful mass of REPM content (the manufacture of HDDs requires 6000 to 12,000 tons of REPMs per year), HDDs have several advantages in recycling since they i) are relatively easy to identify, ii) have a rapid turnover (~5year life), and iii) are often already removed from Waste Electronics and Electrical Equipment (WEEE) [17]. Moreover, recycling of REPMs from HDDs is better than producing new REPMs from an environmental point of view [19,20]. In particular, NdFeB magnet-to-magnet recycling was reported to have significantly less environmental impact than virgin production [20].

In spite of the economic and environmental promise of recycling REEs, few researchers have examined the economics associated with REE recovery. Du and Graedel [22] estimated the weight of REEs used in products in the U.S., Japan, and China at two points in time: 1995 and 2007. Shi et al. [23] assessed the Japanese demand and in-use stock of dysprosium, and investigated the dysprosium life cycle from extraction to disposal. Guyonnet et al. [24] modeled the REE material flow in the EU-27, and developed a method that uses a possibilistic representation of uncertain data to estimate the import and export of REEs and in-use stock. Hart [25] developed a model to predict the demand for REPMs in the U.S. and rest of the world from 2010 to 2020. The material flow of neodymium and dysprosium from REPMs in Japan was identified by Sekine et al. [26]. The economic feasibility of recycling hybrid electric vehicle motors and air conditioner motors was also evaluated and showed that it is profitable to recycle REPMs from hybrid electric vehicles but not so for air conditioners [26].

Reverse logistics and the supply chain network can affect the success of a value recovery system. Akçalı and Cetinkaya [27] reviewed literature on inventory and production planning (I&PP) for closed-loop supply chain systems and found most literature in stochastic I&PP focused on durable products for which manufactured and remanufactured products are perfectly substitutable. Govindan, et al. [28] revealed that about 48.9% of the existing literature studied the nondeterministic aspect of demand, 37.8% on uncertain supply (returned products), and 6.7% on changing prices, while some considered two or more of the uncertainties simultaneously. Teunter and Flapper [29] proposed mathematical models to determine the optimal acquisition and remanufacturing quantity under EOL product quality and demand uncertainties. Minner and Kiesmüller [30] presented a mathematical model to determine the optimal buy-back price of EOL products and the number of products for manufacturing, remanufacturing, inventory, and disposal. Sutherland et al. [31] developed a simulation model for the operation of a de-manufacturing facility, including inventory, with uncertainties in EOL product quantity, recovery rate, and selling price, and proposed an optimal selling policy that maximized profit.

There are two fundamental contributions of this paper. First, we developed an operation and inventory model for EOL HDD dismantling that yields multiple subcomponents, each having different economic value and uncertain market demand. As noted above, the existing research focused on remanufacturing that has 1:1 or n:1 relationship between EOL supply and recovered product demand (with n being the number of components necessary to manufacture a product). This assumption does not apply to EOL HDD industry that has a 1:n relationship (with n being the number of output components and materials). In fact, EOL HDDs, especially those from datacenters, are typically recycled than remanufactured due to data security risks. The specific outputs of HDD dismantling are shown in Fig. 1, which include printed circuit board (PCB), REPM, and other metal parts. Second, our model considers both stochastic supply and demand for REPM recovery from EOL products, unlike most literature that focused on one type of uncertainty. To better understand the market dynamics, we surveyed several HDD and REPM recyclers in the U.S. to gauge current market for the supply, component demand, and associated costs and revenues, which are not available in the literature. These features distinguish our paper from the literature and highlight the unique contribution of this paper.

The main idea and contribution of this paper is also depicted in Fig. 2. Currently, less than 1% of REEs from used products are recycled at their end of life, meaning that more than 99% of REEs are either disposed or lost during the recycling of other materials (for example, REEs could end up in the slag during ferrous materials recycling). For EOL processors, used products serve as the supply of 'raw materials' to be processed. However, difficulties may arise due to uncertainties in supply quantity, quality, and timing. Market demand for each recovered component and material is also different and uncertain, which challenges EOL processors in managing their production and inventory.

This paper examines the complexities attributed to uncertainties in EOL HDD supply and market demand for different components as illustrated in Fig. 2. An operation and inventory management strategy was proposed to maximize profit under demand and supply uncertainties. Section 2 is devoted to model development for the optimal order, processing, and service quantities. An upper bound profit was derived and compared to the proposed inventory decisions to assess the performance. Subsequently, several scenarios were examined for their impacts to the overall system.

2. Inventory management under supply and demand uncertainties

Equation (1) shows the cost model by Cong et al. [32] where the annual cost (TC) for REPM value recovery was calculated as the sum of the used product purchase cost (C_p), dismantling cost (C_d), inventory cost (C_h), transportation cost (C_t), and facility cost (C_f).

$$TC = C_p + C_d + C_h + C_t + C_f \quad (1)$$

The model assumes an infinite supply of EOL products and that all components and materials recovered during EOL processing are sold (i.e., demand equals processing rate). However, market demand and supply can both be envisioned as random variables. Supply shortages may lead to idle processing lines (which incur costs even while idle) and lost sales opportunities (and angry customers), while supply overages may lead to increased inventory costs. Likewise, demand shortages will drive up costs associated with inventoried components and recovered materials, while excessive demand that cannot be met may jeopardize customer relationships. As a result, an effective inventory management strategy is necessary to minimize costs and/or maximize profit.

In a forward supply chain, where products flow from manufacturer to consumer, uncertainty in customer demand mainly affects a manufacturer in terms of the quantity of raw materials to order and the quantity of final goods to produce. In a reverse supply chain,