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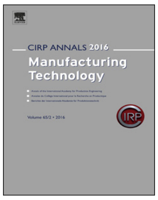

A location-allocation model for sustainable NdFeB magnet recovery under uncertainties

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ABSTRACT

Neodymium-iron-boron (NdFeB) magnets play a critical role in clean power products, e.g., electric vehicles and wind turbines. Since China has near monopolistic control of the supply of these magnets, many parties are interested in recovering end-of-life magnets for additional use cycles. Such a strategy requires a cost-effective approach to collect and process used magnets while maximizing the economic and environmental benefits. This paper employs fuzzy logic and non-dominated sorting genetic algorithm (NSGA-II) to solve a location-allocation problem for NdFeB magnet recovery under supply and demand uncertainties. A Pareto front is constructed to evaluate the performance of the proposed design.

1. Introduction

Neodymium-iron-boron (NdFeB) magnets have the strongest magnetic field per volume of all commercially available magnets. They are critical to many clean energy products, e.g., wind turbines and (hybrid) electric vehicles. The demand for rare earth elements (REEs), and in particular rare earth magnets, is growing quickly. China is responsible for 80–95% of the global supply of REEs, including NdFeB magnets [1]. The near-monopolistic Chinese control of the NdFeB magnet supply represents a significant supply risk for clean energy technology manufacturers.

One promising way to mitigate the supply risks and simultaneously protect the environment is to recover the value of NdFeB magnets from end-of-life (EOL) products. Currently, less than 1% of REEs are recycled at their EOL, but many companies are joining the NdFeB magnet recovery industry (e.g., Mitsubishi, Hitachi, and Urban Mining Company). A recent study revealed that NdFeB magnet-to-magnet recycling, which is a method to recycle all the materials in EOL magnets into new magnets, significantly reduces the raw material consumption and lowers the environmental footprint of NdFeB magnet production [2]. In order for the industry to thrive and reduce the life cycle impacts of NdFeB magnets, a holistic plan is needed to design the entire value chain of collecting, dismantling, recycling, and sale of recovered magnets.

Designing a reverse value chain is different than designing a forward supply chain. One of the most distinctive features of a reverse supply chain is the uncertainty of the system. Although building up the forward supply chain also involves uncertainties, the reverse value chain has greater uncertainties in terms of the collection of EOL products and the demand for recovered materials/products [3]. As a consequence, researchers have examined the uncertainty issues in the design of reverse logistics network using scenario-based analysis [3], probabilistic programming [4], and budget of uncertainty technique [5], etc.

There are many approaches to address these uncertainties; however, the fuzzy logic approach is particularly applicable in this scenario. For real problems, some model parameters can be only roughly estimated. Classically, vague data is often replaced with ‘average data’, while fuzzy logic offers the opportunity to model the subjectivity of variables as precisely as a decision maker can describe them [6]. Furthermore, it is sometimes difficult in practice to collect sufficient data to characterize the distribution of uncertain variables [7]. In this case, fuzzy logic is a promising alternative. Due to these advantages, fuzzy logic has been widely used to construct reverse logistics systems under uncertainties [8].

In this study, an optimization model is developed to quantitatively support the construction of the entire value recovery chain, consisting of collection, dismantling, recycling, and sale of recovered NdFeB magnets. The proposed model utilizes three objectives to design a profitable and environmentally friendly value recovery chain. A fuzzy approach is adopted to handle uncertainties in the collection of EOL products and the demand for recovered magnets. To find the Pareto optimal solutions and provide managerial decision options, a non-dominated sorting genetic algorithm (NSGA-II) is applied to a real world case study. To the best of our knowledge, this is the first research to address the uncertainties in the location and allocation model for NdFeB magnet recovery.

2. Model description

This paper solves a location-allocation problem for the recovery of NdFeB magnets. The reverse logistics system consists of four

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major stakeholders: (i) collection centers for acquiring EOL products, (ii) dismantlers for extracting NdFeB magnets from EOL products [9], (iii) recyclers for processing used magnets into a like-new condition (e.g., magnet-to-magnet recycling [10]), and (iv) customers that purchase the recovered magnets. Two types of products, hard disk drives and electric vehicle motors, are considered for EOL collection as they are the two most important sources of NdFeB magnets for recycling [11]. Although there are an increasing number of NdFeB magnets used in wind turbines, their EOL availability is not projected to be significant until around 2030 [11,12]. With the objectives of maximizing overall economic and environmental benefits, decisions should be made on (i) the locations of dismantlers and recyclers, and (ii) the optimal transportation flows among all the stakeholders. These decisions are made complicated by large uncertainties in the volatile supply of EOL products at collection centers and the unpredictable demand for recovered NdFeB magnets from the final customers, especially since this is a new and emerging business around the world.

2.1. Dismantlers' profit

The first objective is to maximize the profit earned by dismantlers when separating valuable components from EOL products. The total cost consists of EOL product acquisition costs (Eq. (1)), transportation costs (Eq. (2)), facility setup costs (Eq. (3)), and operating costs (Eq. (4)). Revenue (Eq. (5)) is achieved from selling dismantled components. Here, index k refers to the EOL product type (i.e., 0 for hard disk drive and 1 for electric vehicle motor), i refers to the collection center, j is the candidate dismantling facility, and r is a candidate recycling facility. Other variables are summarized in Table 1.

$$\text{Collection cost}: \ \Sigma_t\Sigma_j\Sigma_i\Sigma_k \, ac_k^t\tilde{s}_{i,k}^t I_{ij}^t \tag{1}$$

$$\text{Transportation cost}: \ \Sigma_t\Sigma_j\Sigma_i\Sigma_k \, tci_{ij}\tilde{s}_{i,k}^t I_{ij}^t \tag{2}$$

$$\text{Setup cost}: \ \Sigma_j \, scj_j \, OJ_j \tag{3}$$

$$\text{Operating cost}: \Sigma_t\Sigma_j\Sigma_i\Sigma_k \, ocj_{j,k}^t\tilde{s}_{i,k}^t I_{ij}^t \tag{4}$$

$$\text{Revenue}: \ \Sigma_t\Sigma_j\Sigma_i\Sigma_k \, p_k^t\tilde{s}_{i,k}^t I_{ij}^t \tag{5}$$

$$\text{Dismantler's profit}: f_1 = (5) - (1) - (2) - (3) - (4) \tag{6}$$

Table 1
Nomenclature for objective functions 1 and 2.

Notation	Description
ac_k^t	Acquisition cost of product k at time t ($/kg)
$\tilde{s}_{i,k}^t$	Supply of product k at collection center i at time t (kg)
I_{ij}^t	1, if EOL products are moved from collection center i to dismantler j at time t; 0, otherwise
R_{rs}^t	1, if recovered magnets are moved from recycler r to sales point s at time t; 0, otherwise
tci_{ij}	Transportation cost from collection center i to dismantler j ($/kg of EOL products)
tcj_{jr}	Transportation cost from dismantler j to recycler r ($/kg of EOL magnets)
tcr_{rs}	Transportation cost from recycler r to sales point s ($/kg of recovered magnets)
T_{jr}^t	Transportation volume from dismantler j to recycler r at time t (kg)
$\tilde{d}_s^t$	Demand for NdFeB magnets at sales point s at time t (kg)
scj_j	Setup cost of dismantler j ($/set-up)
scr_r	Setup cost of recycler r ($/set-up)
OJ_j	1, if dismantler j is ever open for operation; 0, otherwise
OR_r	1, if recycler r is ever open for operation; 0, otherwise
$ocj_{j,k}^t$	Operating cost of dismantler j for product k at time t ($/kg)
ocr_r^t	Operating cost of recycler r at time t ($/kg)
p_k^t	Price of dismantled components from product k at time t ($/kg of EOL product k)
p_{NdFeB}^t	Price of recovered NdFeB magnets at time t ($/kg)

'$\sim$' represents a fuzzy number.

2.2. Recyclers' profit

The second objective is to maximize the profit of recyclers from processing EOL NdFeB magnets into like-new conditions. The total cost consists of transportation costs (Eq. (7)), facility setup costs (Eq. (8)), and operating costs (Eq. (9)). Revenue (Eq. (10)) is obtained by selling recovered NdFeB magnets. Here, index s refers to a sales point (i.e., customer location). The remaining nomenclature is included in Table 1.

$$\text{Transportation cost}: \ \Sigma_t\left(\Sigma_r\Sigma_j \, tcj_{jr}T_{jr}^t + \Sigma_s\Sigma_r \, tcr_{rs}\tilde{d}_s^t R_{rs}^t\right) \tag{7}$$

$$\text{Setup cost}: \Sigma_r \, scr_r OR_r \tag{8}$$

$$\text{Operating cost}: \ \Sigma_t\Sigma_r\Sigma_j \, ocr_r^t T_{jr}^t \tag{9}$$

$$\text{Revenue}: \ \Sigma_t\Sigma_s\Sigma_r \, p_{NdFeB}^t\tilde{d}_s^t R_{rs}^t \tag{10}$$

$$\text{Recycler's profit}: f_2 = (10) - (7) - (8) - (9) \tag{11}$$

2.3. Environmental benefits from value recovery

The third objective is to maximize the overall environmental benefits of value recovery. A life cycle analysis showed that the NdFeB magnet recycling process significantly reduces the environmental footprint compared to virgin magnet production [2]. In addition, it minimizes transportation distances by utilizing domestic materials instead of importing them from overseas. With this background, the environmental impacts (abbreviated as E.I.) of recycling is expressed via Eq. (12), which include emissions from the recycling process and transportation. The environmental impacts of producing an equivalent quality and mass of virgin magnets, and the impacts of their importation are shown in Eq. (13). By subtracting Eq. (12) from Eq. (13), the relative environmental benefits of recycling are expressed as Eq. (14). The rationale is that if NdFeB magnets were not recovered and reused, the demand would be satisfied with new production that has a greater environmental burden. By promoting value recovery, environmental benefits (Eq. (14)) are achieved. Therefore, the goal from an environmental perspective is to satisfy as much demand as possible through recycling, while minimizing the transportation distances. The relevant nomenclature is defined in Table 2.

Table 2
Nomenclature for objective function 3.

Notation	Description
eii_{ij}	E.I. of transportation from collection center i to dismantler j (CO_2 equivalent (eq.)/kg)
eij_{jr}	E.I. of transportation from dismantler j to recycler r (CO_2 eq./kg)
eir_{rs}	E.I. of transportation from recycler r to sales point s (CO_2 eq./kg)
ei^r	E.I. of recycling (CO_2 eq./kg)
ei^{new}	E.I. of new production (CO_2 eq./kg)
ei_{import}	E.I. of transportation from overseas (CO_2 eq./kg)

$$\text{E.I. of recycling}: \Sigma_t[\Sigma_j\Sigma_i\Sigma_k \, eii_{ij}\tilde{s}_{i,k}^t I_{ij}^t + \Sigma_r\Sigma_j \, eij_{jr}T_{jr}^t + \Sigma_s\Sigma_r(ei^r + eir_{rs})\tilde{d}_s^t R_{rs}^t] \tag{12}$$

$$\text{E.I. of new production}: \ \Sigma_t\Sigma_s\Sigma_r(ei^{new} + ei_{import})\,\tilde{d}_s^t R_{rs}^t \tag{13}$$

$$\text{Relative environment benefits of recycling}: f_3 = (13) - (12) \tag{14}$$

2.4. Constraints

Given the aforementioned relations, a multi-objective location-allocation model is formulated with mixed integer linear programming (MILP). While the objective functions (Eqs. (6), (11), and (14)) orient the search direction toward optimal decisions, the constraints

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