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Planning decisions for recycling products containing hazardous and explosive substances: A fuzzy multi-objective model

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ABSTRACT

The rapid development of modern technology leads to the rapid consumption of natural resources, which in turn causes an increasing accumulation of waste materials. Manufacturers must now assume the responsibility for reclamation, recycling and disposal of their products that have reached the end of their life cycles. During the product recycling process, the detection and disposal of explosive substances must be performed with the utmost caution. This study proposes a fuzzy multi-objective linear programming model for use in planning of recycling processes for products that contain hazardous and explosive substances. Application of the proposed model has been carried out in a middle-sized factory, where various products that have completed their life cycles or has become inoperative are delivered to the factory at uncertain times from various warehouses. Results from the proposed model have been obtained using the system data to solve problems on various scales. A hybrid Monte Carlo simulation has been used to obtain Pareto-optimal solutions to solve the model. The planning model is shown to differ from the recycling production planning model in terms of its consideration of the explosion risk and the limitations and goals related to this risk; this model provides considerable flexibility for both the recycling process and the planning decisions taken for this process.

1. Introduction

The management of natural resources is important to use natural resources appropriately and achieve sustainability to protect the environment while maintaining continued technological development. Manufacturers are now expected to be aware of the potentially dangerous effects of their products on the environment. Green engineering refers to the efforts made to design and manufacture products in ways that minimize their footprints on the environment, both during and at the ends of their life cycles. At present, the most commonly applied practices to protect the environment and fight the accumulation of waste materials are reuse, remanufacturing, recycling and the use of environmentally-friendly approaches in product design and production. The determination of Waste Management Policy and its implementation is one of the most important topics of the EU Environmental Acquis. The principles adopted in the EU and based on the creation of an integrated waste management policy (Çevre ve Orman Bakanlığı, 2008). According to the European Statistical Agency Eurostat, the European Union's 27 countries produced 2.5 billion tons of waste and half was poured into landfill in 2008. The other half is recovered, recycled, reused or burned (Bilim Sanayi ve Teknoloji Bakanlığı, 2014). Under EU legislation on waste it is available in numerous legal regulations. All provisions in the EU Directive on hazardous waste management are reflected in the regulation on hazardous waste in Turkey. In Turkey, problems with recycling systems have been identified and solutions are investigated. The sector in order to ensure the achievement of sustainable and effective structure, "National Recycling Strategy Document and Action Plan" was formed (Bilim Sanayi ve Teknoloji Bakanlığı, 2014). Over 20 million tons of waste is produced by the manufacturing industry in Turkey. This amount is about 1.12 million tons of hazardous waste. 8% of this amount is recycled. 47% of this amount is disposed and 45% of this amount is reused (Çevre ve Orman Bakanlığı, 2008).

Recycling is gaining growing importance as the use of recycled materials becomes increasingly common in production, manufacturing industries and logistics. The recycling of hazardous and explosive products for a variety of uses is important for both the removal of the risks that these products pose and for the reuse of the materials. During the recycling of materials that have completed

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their product life cycles, the detection and safe decomposition of hazardous and explosive substances is essential. Therefore, numerous concerns including safety, economics, environmental factors and planning must be taken into consideration simultaneously. It is thus necessary to consider the risk of explosion along with profitability in the planning of recycling activities for products that contain hazardous and explosive materials, and efficient planning programs must then be devised accordingly.

Production planning is an important aspect of remanufacturing, which is one of the recovery processes involved in recycling. The remanufacturing system consists of three subsystems for disassembly, processing and reassembly. The coordination of these subsystems plays a critical role in successful production planning and control (Guide et al., 1999). Several studies on the planning and control of remanufacturing of returned products have been published in the literature (Fleischmann et al., 1997; Gungor and Gupta, 1999; Guide, 2000; Sbihi and Eglese, 2007). Many researchers proposed a model for production planning in remanufacturing systems (Li et al., 2006, 2007, 2009; Nakıboglu, 2008; Qu and Williams, 2008). For closed-loop system, the planning models were developed that involve the recycling and reuse of products (Shi et al., 2011; Jayaraman, 2006). Due to the lack of information, researchers have developed a fuzzy optimization model for remanufacturing systems. Generally, the uknown parameter is demand for returned products (Mula et al., 2010; Amin and Zhang, 2012; Su, 2014).

Unlike remanufacturing, recycling involves the transformation of expired products into raw materials by stripping the products of their qualities, rather than making them reusable by preserving the original design and workmanship. Numerous studies on the planning of both remanufacturing and recycling are available in the literature. These studies have mostly been conducted on production planning in the electronics and automotive industries. Williams et al. (2007) proposed a recycling planning model for tactical short-term decision making from the viewpoint of the processing and reprocessing of materials for use in the automotive industry in their study. Spengler et al. (2003) proposed a short-term recycling planning model for the recovery, disassembly and recycling of electronic waste in their study. Stuart and Lu (2000) proposed a model to help with decision making in the processing required for planning, reprocessing, preparation and inventory in the recycling of electronic products. Krikke et al. (1998) used stochastic dynamic programming to perform disassembly planning and cost analysis for planning of materials recycling. Simic and Dimitrijevic (2012) conducted a study of the production processes in a vehicle recycling factory to devise a production planning model on a tactical level for a vehicle recycling factory. Simic and Dimitrijevic (2013) subsequently developed a long-term planning model that considered the uncertainty in automotive industry recycling systems.

While several studies have been performed on production planning in recycling systems, no studies have been conducted to date on the recycling production planning of products that contain dangerous and/or explosive substances. The collection, transportation, recycling and disposal of products that contain dangerous substances constitute the core aspects of dangerous waste management. Dangerous waste management resources are typically studies of product transportation and routing decisions (Erkut and Verter, 1998; Nema and Gupta, 2003; Huang et al., 2004; Hicks et al., 2004; Emek and Kara, 2007; Alamur and Kara, 2007; Dadkar et al., 2008). Our study devises a model that aims to reduce the risk of explosion during the recycling process.

In the above-mentioned research literature, there is a gap as regards the need for a decision-making tool for planning decisions related to the recycling of materials with dangerous and/or explosive content. In this study, such a mathematical model, based on a real system, that is significant not only for the management and planning decisions that must be taken during the recycling of materials with dangerous and explosive content but also for the management of risks that may arise during the recycling process, has not been developed by the researchers in this area. Also, there has been little previous reference to the use of a fuzzy multi-objective model that considers the element of uncertainty in studies of this nature. This study has been performed such that the element of uncertainty in real recycling systems and multiple objectives are considered simultaneously.

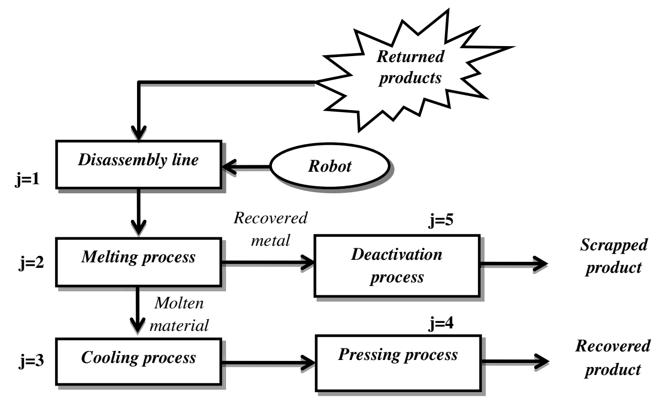

Fig. 1. Recycling process flow in the system under study.

The primary goal of the proposed model is to aid in the decision making processes involved in the planning and management of the recycling system. The study involves a real life application that enables the disposal and preparation for reuse of materials from products that have completed their life cycles. The linear programming model was only developed after the evaluation of the production planning activities had been performed and appropriate assumptions and the required parameters and constraints had been determined. In the model that has been developed in this study, a fuzzy multi-objective linear programming approach was devised to deal with the imprecise target values and the unpredictable intervals between and quantities involved in deliveries. The IBM ILOG CPLEX 12.0 Optimizer Solver has been used to solve the fuzzy multi-objective linear programming model.

The remainder of this study is organized as follows. Section 2 includes a detailed description of the system investigated in this study, and also provides explanations of the recycling activities, assumptions and features of the system. Section 3 presents the fuzzy multi-objective linear programming model used to plan management of the system. Section 4 elaborates on the solution approach used and the results. Section 5 provides results and discussion, while the final section discusses the results after a general review of the work and suggests directions for future studies.

2. System of application

The system under study is one in which dangerous and explosive substances are shipped from warehouses to a factory where they can be recycled. In this system, products that have reached the end of their life cycles or have become inoperative are returned to the factory from various warehouses at uncertain times and in uncertain quantities. The recycling process is completed after the returned products pass through a number of operations, such as disassembly and elimination of the risk of explosion. The recycling process produces two different outputs which are sold to interested buyers. The stages and the flow of the recycling system are shown in Fig. 1. As shown in Fig. 1, the returned products first pass through the disassembly line ($j = 1$). Because there is a risk of explosion at this stage, any explosive substances are separated from the product by a robot. However, the product may still contain some explosive