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Interval-parameter semi-infinite programming model for used tire management and planning under uncertainty

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ABSTRACT

In the European Union, approximately 3.6 million tonnes of used tires are generated annually. Because used tires are not biodegradable, there is strong motivation to successfully manage this fast-growing waste flow. One of the most popular approaches for sustainable environmental stewardship of used tires is retreading. The problem investigated in this paper is to identify optimized purchasing, retreading, and inventory planning schemes of used tires in multiple tire retreading plants as well as allocation patterns of retreaded, reusable, and end-of-life tires that secure maximized profit within a multi-period planning horizon and under multiple uncertainties. This paper proposes an interval-parameter semi-infinite programming model for used tire management and planning. The underlying difference between this model and those developed in previous research is its ability to consider the effects of external impact factors related to complicated economic, environmental, and social activities on used tire management systems. Moreover, it can successfully handle real-life uncertainties of the used tire management systems expressed as functional and crisp intervals. A numerical example is provided to demonstrate the usefulness of the developed model. Flexible long-term purchasing, retreading, inventory, and allocation plans, which are adjustable with variations of external impact factors, are obtained. The presented model has advantages in addressing the dynamic complexity of used tire management systems by introducing the functional interval parameters associated with the price of a new tire as well as electricity and gas prices and labor costs in waste management and transportation sectors. Compared with the available models, the resulting solutions are far more robust because they are able to satisfy all possible levels of external impact factors. The presented model is beneficial for the tire retreading industry, which processes millions of used tires annually.

1. Introduction

Management of used tires is globally a crucial environmental problem (Hashemi, Chen, & Fang, 2014; Labaki & Jeguirim, 2017; Li, Xiao, Ferreira, & Cui, 2016; Oikonomou & Mavridou, 2009). Approximately 19.3 million tonnes of used tires are generated annually worldwide (Labaki & Jeguirim, 2017); this figure will rise in the near future along with the expected growth in the world's motor vehicle fleet. In the European Union, the quantity of used tires exceeded 3.6 million tonnes in 2013 (European Tyre, 2016), which corresponds to 5.92×10^8 tires (Hita et al., 2016). Because used tires are not biodegradable, there is a strong motivation to successfully manage this fast-growing waste flow, thereby mitigating its negative environmental impact.

Unlike waste electrical and electronic equipment (ElSayed, Kongar, Gupta, & Sobh, 2012; Iakovou et al., 2009; Kuo, 2013), end-of-life (EoL) photovoltaic modules (Fthenakis, 2009), EoL vehicles (Phuc, Yu, & Tsao, 2017), construction and demolition waste (Dodoo, Gustavsson, & Sathre, 2009), and other multi-component EoL products, used tires cannot be broken down into separate pieces. Their processing significantly differs from treatments of the aforementioned EoL products. In fact, one of the most popular approaches to sustainable environmental stewardship of used tires is retreading. Retreaded tires are used tires that have undergone a process designed to extend their service life (Boustani, Sahni, Gutowski, & Graves, 2010). At an acceptable processing cost, tire retreading successfully takes full advantage of the value that remains in the used tires. In this process, used tires are subjected to a sequence of value additive operations and are converted to reusable ones (Mondaln & Mukherjee, 2012). Several benefits associated with the tire retreading process include savings in cost (Amin, Zhang, & Akhtar, 2017; Machin, Pedroso, & de Carvalho,

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2017; Subulan, Tasan, & Baykasoglu, 2015) and energy (Boustani et al., 2010; Ferrao, Ribeiro, & Silva, 2008; Pedram et al., 2017), reduction in environmental pollution (Antmann, Shi, Celik, & Dai, 2013; Debo & Van Wassenhove, 2005), and non-renewable raw material utilization (Bunget, Shen, Gramling, Judd, & Kurfess, 2015; Mondaln & Mukherjee, 2012; Pedram et al., 2017; Uruburu, Ponce-Cueto, Cobo-Benita, & Ordieres-Meré, 2013).

Increases in environmental awareness have led to the search for economically attractive and environmentally responsive approaches to managing used tires. Although the relevant literature for our contribution originates from different streams of research, only that regarding used tire management systems is significant for our domain-oriented perspective. Owing to the increased importance of this subject, a considerable number of research papers have been published in the past decade. A detailed analysis of these papers is needed to identify the key directions for further development of this very important and dynamic research area. Lebreton and Tuma (2006) developed a linear programming model to assess the profitability of car and truck tire retreading process in Germany. Pehlken and Müller (2009) analyzed the separation process of recycling EoL tires and concluded that modeling such a process is a challenging task, because there are many uncertainties to identify. They highlighted that more research of this matter is needed. Dehghanian and Mansour (2009) proposed a three-objective linear programming model, which is able to simultaneously maximize economic and social benefits as well as minimize environmental impacts, in order to design a network of recycling plants for used tires in Iran. Kannan, Haq, and Devika (2009) formulated a linear programming model for minimizing the costs of a multi-echelon closed-loop supply chain for a tire manufacturer. Sasikumar, Kannan, and Haq (2010) developed a mixed-integer nonlinear programming model for maximizing the profit of a multi-echelon reverse logistics network for truck tire retreading. However, many modeling parameters (e.g. cost parameters) had been identified as deterministic, which limits real-world applicability of this model. Abdul-Kader and Haque (2011) had identified a tire, collection center, recycling plant and retreading plant as "agents" involved in the management of used tires and applied an agent-based simulation approach to tackle the used passenger car tire retreading problem. Mondaln and Mukherjee (2012) used a simulation approach to plan manpower deployment for labor intensive operations of the tire retreading process. Creazza, Dallari, and Rossi (2012) formulated a mixed integer linear programming model to optimize logistics network of the tire manufacturer Pirelli. Kop, Genevois, and Ulukan (2012) used the fuzzy Analytic hierarchy process to identify the most efficient EoL tire management option in a Turkish context. Vinodh and Jayakrishna (2013) applied the fuzzy Analytic hierarchy process for weighting criteria and VIKOR for selecting the best tire retreading process for an Indian manufacturing organization. De Souza and D'Agosto (2013) proposed a conceptual model of the reverse logistics chain of EoL tires and explored financial benefits of their sending to the cement industry. Pirachicán-Mayorga, Montoya-Torres, Jarrín, and Halabi Echeverry (2014) analyzed reverse logistics practices in Colombia and proposed a conceptual model of the used tire reverse logistics chain. Dhouib (2014) used the fuzzy MACBETH to assess alternatives in reverse logistics for used tires. Kannan, Diabat, and Madan Shankar (2014) presented a framework to analyze the motivating factors of EoL tire management in an Indian context and validated it with the assistance of the Interpretive structural modeling. Pehlken, Rolbiecki, Decker, and Thoben (2014) provided a concept for developing a model of EoL tire recycling plant based on Petri nets and neural networks. Dabic-Ostojic, Miljus, Bojovic, Glisovic, and Milenkovic (2014) presented a tool based on Bayesian networks for making decisions whether to retread used tires or not. Subulan et al. (2015) proposed a mixed-integer linear programming model for tire closed-loop supply chain and suggested that uncertainty analysis related to various modeling parameters definitely deserves future research efforts. Bazan, Jaber, and El Saadany (2015) presented a reverse logistics mixed-integer linear programming model for minimizing the costs of the tire retreading industry in Canada, which captured the costs for greenhouse-gas emissions and energy usage. Vorasayan (2016) used the two-player game theory approach to determine prices of a certified retreaded tire with warrantee and a noncertified retreaded tire under cooperative and non-cooperative schemes. Chang and Gronwald (2016) applied four different multi-criteria decision making methods to rank numerous used tires management alternatives and identified retreading as the best option. Amin et al. (2017) proposed a mixed-integer linear programming model for maximizing the profit of a tire remanufacturing closed-loop supply chain network in Toronto, Canada. They used a simplistic graphical tool to assess decisions under uncertain demand and returns. Pedram et al. (2017) presented a mixed integer linear programming model for maximizing the profit of a multi-echelon closed-loop supply chain of the tire industry in Tehran, Iran. They used a simple scenario-based approach to represent uncertainties in demand, return rate and quality of used tires. Afrinaldi, Taufik, Tasman, Zhang, and Hasan (2017) proposed a two-objective nonlinear programming model for creating an optimal preventive replacement schedule of a bus tire through minimization of its economic and environmental impacts.

A review of the literature reveals that numerous system analysis methods have been proposed for solving various problems of used tire management. However, a lack of research exists for uncertainties in used tire management systems. In addition, the literature clearly suggests that no attempt has been made to address used tire management problems through interval-parameter programming, which represents an extension of the classical linear programming problem to an inexact environment (Sengupta, Kumar Pal, & Chakraborty, 2001; Zhang & Xu, 2014). Interval-parameter programming is an alternative for handling uncertainties in the left- and right-hand sides of constraints and in the objective function, which cannot be expressed as distribution functions owing to the inadequate quality of available information. This approach does not require distribution information because the crisp interval, or the lower- and upper-bounded range of the real number, is acceptable for the uncertain input. On the contrary, the available models for management of used tires cannot address uncertainty related to functional-interval parameters. As an extension of conventional crisp intervals, the concept of functional intervals is proposed for addressing more complicated uncertainty (He, Huang, Tan, & Liu, 2008) because they include characteristics of intervals and functions. In fact, most of the real-life applications involve highly complex uncertainty. The need for introducing functional intervals in the used tire management problem primarily arises from the effects of external impact factors related to complicated economic, environmental, and social activities on the used tire management systems. In reality, the effects of the external impact factors on the components of the used tire management systems are too significant to be ignored. Thus, another significant limitation of the aforementioned system analysis methods is their inability to reflect the dynamic features of modeling parameters. Therefore, introduction of crisp and functional intervals into the modeling framework can provide a much more realistic representation of used tire management systems. Interval-parameter semi-infinite programming can address uncertainties expressed as crisp intervals and functional intervals with infinite objectives or infinite constraints. As a significant extension of previous efforts in the reviewed research area, an interval-parameter semi-infinite programming model for used tire management and planning is proposed in this paper by allowing the modeling parameters to be