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Designing an environmentally conscious tire closed-loop supply chain network with multiple recovery options using interactive fuzzy goal programming

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ABSTRACT

Significant environmental problems have been caused by the growth in the volume of used tires each year. In addition, remanufacturing and recycling options related to the end of life for tires are crucial issues at present because of difficulties related to the degradation of these scrap tires in the environment and the economic benefits of material and energy recovery. Thus, effective collection, storage, recycling, and appropriate disposal methods are required for used tires without damaging the environment by designing an efficient closed-loop supply chain network. Based on this motivation, we present a holistic modeling approach for a tire closed-loop supply chain using mixed integer linear programming. Alternative recovery options such as remanufacturing, recycling, and energy recovery are considered simultaneously in the model. The main objective of this study was to develop a multi-objective, multi-echelon, multi-product, and multi-period logistics network design model in a more holistic manner while also considering environmental issues. To quantify the environmental impact and the closed-loop supply chain, we used a life cycle assessment-based and damage-oriented method (eco-indicator 99). We applied the model to an illustrative case study and an interactive fuzzy goal programming approach was utilized to solve the proposed fuzzy multiple-objective network optimization model. In order to obtain the best profit values and to satisfy the environmental indicator targets, we examined the effects of some parameters (factors) within the profit and damage function using an experimental technique based on the Taguchi design. Experimental runs were conducted using the optimization solver in ILOG OPL Studio 6.3 and the results were evaluated based on Taguchi's (S/N) ratios, analysis of means graphs, interaction graphs, and analysis of variance with MINITAB 14.

1. Introduction

More than one billion brand new tires are manufactured each year by approximately 500 producers throughout the world [1]. In addition, millions of scrap tires are disposed of each year, which presents an enormous disposal problem that causes health hazards and environmental damages [2,3]. The chemicals leached from old tires are hazardous to human health because they cause water and air pollution [4]. Vast amounts of used tires are disposed of all over the world using traditional

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methods that are not environmentally friendly, thus the development of alternative recovery methods has become a vital issue in the last decade. Furthermore, managing used tires effectively and balancing the forward and reverse flows in a value chain are challenging tasks for the tire industry. Thus, designing an economically and ecologically optimized closed-loop supply chain (CLSC) network is a prerequisite for tire producers to facilitate increased environmental responsibility and sustainable development.

In this study, we examine different recovery options simultaneously, such as remanufacturing, recycling, and energy recovery, and we present a holistic modeling approach for coordinating an integrated tire management system that recovers the value of scrap tires. Our model aims to maximize the total CLSC profit and to minimize the total environmental impact along the CLSC. Most previous studies that investigated the optimal tire supply chain configuration were only cost- or profit-oriented, although a few studies have emphasized environmental perspectives in CLSCs based on life cycle assessment analysis. For example, Sasikumar et al. [5] formulated a mixed integer nonlinear programming model for maximizing the profit of a multi-echelon, multi-period, reverse logistics (RL) network based on a real-world case of truck tire retreading. They considered the remanufacturing option as well as the recycling of defective tires simultaneously in their model. Comprehensive descriptions of four suitable recovery processes (heat generation in thermoelectric plants or in cement kilns, ground rubber applications, such as use as an asphalt additive, direct reuse in civil engineering works, and recycling through pyrolysis) for used tires were given by Ferrer [6], where a decision rule that determined the appropriate times for retreading a tire was also proposed to maximize the utilization of tires. The sustainable recovery network model of Dehghanian and Mansour [7] only considered scrap tire processing in plants and energy recovery in cement plants. Lebreton and Tuma [8] developed a mathematical model for assessing the profitability of tire remanufacturing, where the return probability and quality levels were also considered in their model. Boustani et al. [9] conducted a tire remanufacturing energy savings analysis in four interrelated contexts, i.e., transformational technological changes in tires, transitional technological changes in tires, degradation of efficiency (rolling resistance), and product variations. They utilized life cycle assessment models as an analytical methodology. An agent-based simulation model was developed by Abdul-Kader and Haque [10] to investigate the environmental benefits of tire retreading and to sensitize the government regulators by generating different scenarios. The results of their study showed that significant decreases could be achieved in the raw material consumption and scrap rate. Subulan and Tasan [11] proposed a profit-oriented mixed integer linear programming model for a tire CLSC with multiple recovery options and time periods, where they extended their model by considering environmental issues [12].

There is a lack of environmental considerations in previous cases of CLSC network modeling, thus we employed the eco-indicator 99 methodology to quantify the environmental impact throughout the tire CLSC. This method incorporates a quantitative life cycle assessment in order to formulate an appropriate environmental measure to guide strategic decision making in supply chains [13]. The eco-indicator methodology is more advantageous than other methods because it uses a systematic method to perform the subjective procedure when assigning and scoring the relative importance of different impact categories [14]. In addition, this method yields an assessment of the environmental impact related to a product or manufacturing process using a single indicator/index [7]. Thus, this method has been used in a wide variety of applications, especially the design of chemical supply chains. Moreover, Coca-Cola Hellenic calculates its ecological footprint throughout the value chain using the eco-indicator 99 method [15].

The main aim of this study was to develop a multi-objective, multi-echelon, multi-product, and multi-period network design model for a tire CLSC with multiple recovery options, time periods, and green image in a more holistic manner. The end users of this method are considered to be the responsible managers of CLSCs in tire manufacturing companies and logistics service providers.

The remainder of this paper is organized as follows. In Section 2, we described relevant studies of the main modeling characteristics/features utilized in RL and CLSC network design. In addition, we review previous applications of the eco-indicator 99 method in supply chain design and planning. In Section 3, we explain the details of the problem, including the model formulation, assumptions, and parameters. In Section 4, we present an application of the proposed model to an example problem inspired by a case in Turkey. This section also contains detailed explanations of the solution methodology and interactive fuzzy goal programming. In Section 5, we present an evaluation of the computational results using the Taguchi experimental design method. In Section 6, we give our conclusions and suggestions for future research.

2. Relevant literature

2.1. Review of the main modeling characteristics/features in RL and CLSC network design

In this section, we compare our model with previous studies in terms of the main characteristics or features handled in the mathematical model development phase. A selective overview of the most relevant studies is provided in Table 1 based on the main features identified by Alumur et al. [16]. In addition to these nine main features, six modeling features are included to facilitate more realistic RL and CLSC network design. These features comprise the integration of forward and reverse flows (CLSC concept), multi-objectivity, vehicle type/transportation mode, production, recycling, remanufacturing technology selection, environmental issues, and uncertainty modeling approaches. Thus, a multi-period CLSC network design model was developed in order to overcome some of the drawbacks discussed by [16] and to consider the dynamic nature of the problem. Including these additional features in the proposed model makes our model more holistic and it represents an