Environment, Development and Sustainability (2021) 23:5794–5821
https://doi.org/10.1007/s10668-020-00847-2

A stochastic multi-objective closed-loop global supply chain concerning waste management: a case study of the tire industry

Zahra Ghasemzadeh[1] · **Ahmad Sadeghieh**[1] · **Davood Shishebori**[1]

Received: 5 February 2020 / Accepted: 1 July 2020 / Published online: 8 July 2020

Abstract

Today, growth in the population and the use of vehicles have led to a growth in the production of waste tires and subsequently the creation of environmental concerns. Thus, choosing common strategies (such as retreading, recycling, burning, and disposal) to deal with these wastes and improve environmental conditions has become one of the most significant concerns of today's industries. In this study, a mixed-integer linear programming model has been used to develop a stochastic closed-loop supply chain network design (SCND). The proposed formulation has two objectives: (i) minimizing Eco-indicator 99 and (ii) maximizing profit in a multi-product, multi-echelon, and multi-period problem for tires. It is implemented in a practical case study in tire production industry. Also, uncertain parameters such as the return rate of products, demand, and the percentage of tire material provided by external suppliers are considered as possible scenarios. The improved version of the augmented ε-constraint, named AUGMECON2, is applied to solve the proposed problem. Finally, comprehensive sensitivity analysis is carried out to measure the efficiency. Obtained results represent that concerning global factors, an optimal closed-loop SCND can be very different and the problem is sensitive to the customs duty rate and exchange rate parameters. Besides, without considering the limitations of supplying raw materials by external suppliers, profits can increase by about 12%.

Keywords Closed-loop supply chain · Network design · Multi-objective · Tire · Shortage · Global factors · Eco-indicator 99 · Waste management · Uncertainty

1 Introduction

Transportation is one of the largest energy-consuming sectors in the world, and with increasing urbanization and the expansion of decorated lifestyles, the use of vehicles and the average mileage of each vehicle have risen recently. One of the resulting consequences is the production of waste tires that are environmentally harmful. Every year,

---

✉ Davood Shishebori
shishebori@yazd.ac.ir

[1] Department of Industrial Engineering, Yazd University, Yazd, Iran

approximately one million tons of tire material are disposed of in the world. Some conventional methods (e.g., burning, stockpiling, and landfilling), adopted for disposing and managing these hazardous wastes, are proved to have a higher amount of adverse impact on the health of human beings, environment, and ecological systems (Yadav and Tiwari 2019). Due to their high stability, waste tires are highly detrimental to the environment and distort the face of nature.

As we know, a truck tire consumes about 22 gallons of oil and the retreading process saves up to 70% of the crude oil consumption. New tires use four times more material than retreaded tires, and the amount of energy used to produce them is three times that of retreaded tires (Tanzadeh and Haghighat 2012). As a result, the disposal of end-of-life tires has become a controversial economic and environmental dilemma and there is an urgent need to improve the value of worn-out tires. Accordingly, ways of managing this issue, which can significantly enhance their value, are being sought universally.

As another significant point, the study of several closed-loop supply chains with regard to global factors can play a critical role in enhancing their performance. In today's dynamic business environment, the competition is no more among firms, however, among supply chains to gain competitive advantages. This causes to global supply chain (khai loon 2014). In several countries, some percentages of raw materials for tires are supplied through other countries, making decision makers need a global supply chain. Customs duties (tariffs on products when they are transported between countries) and exchange rates (between currencies) are two significant global factors that they are considered here.

The prominent goal of this study is to formulate a multi-objective, multi-product, multi-period, and multi-echelon mathematical model for the tire supply chain such that the most practical factors such as uncertainty, product shortage, the percentage of the raw materials received from the foreign supplier, customs duty, and exchange rates are considered simultaneously. This model is applicable for tire manufacturing companies and products with cycles similar to those of the tire manufacturing industry.

The remainder of the current study is organized as follows. In Sect. 2, the primary relevant studies and research gaps are discussed. In Sect. 3, the details of the problem including some definitions, assumptions, and mathematical formulation are explained. In Sects. 4 and 5, the suggested method for solving the proposed multi-objective stochastic model is described. In Sect. 6, a case study is discussed and applied to test the proposed approach. Finally, the conclusions and future studies are stated in Sect. 7.

2 Literature review

Based on the topic discussed in the present study, the literature is reviewed in two streams.

2.1 Tire closed-loop supply chain

Dehghanian and Mansouri (2009) developed a three-objective mathematical model for designing a sustainable waste tire recovery network. Their goals include balancing social and environmental impacts and economic issues. Using the Eco-indicator index and the analytic hierarchy process (AHP) method, they computed the parameters of environmental and social impacts. Sasikumar et al. (2010) focused on the reverse chain of end-of-life tires and provided a formulation to maximize the profit of a multi-echelon SCND. In their study, the maximum allowed distance between the initial centralized points and the customers is determined by using the sensitivity analysis. Their model has single objective, single product and certain demand, and the retreading of the truck tire is considered as a case study. Subulan et al. (2015) designed a multi-configuration logistics network that addresses environmental issues through the Eco-indicator 99 index. They solved their multi-objective model via interactive fuzzy goal programming. In their study, demands for new tires, retreading and the rate of return of end-of-life tires are assumed as fixed parameters. Considerations such as external suppliers with global factors (customs duty and exchange rates) are not seen in their study. Hassanzadeh Amin et al. (2017) presented an optimal multi-period, multi-product, and single-objective model to maximize profits and solve the model with MILP. They used the decision tree method to assess the net present value under the conditions of uncertainty of demand and return of the product. Pedram et al. (2017) examined a case study for automobile tire and used the "Scenario Analysis" technique and GAMS (General Algebraic Modeling System) 24.0.1 software to maximize profits and manage waste (by retreading tires) to reduce pollution. Their model has single period; the distribution and retailer locations, the collection, recycling, and retreading centers are predetermined and fixed. For the first time, Sahebjamnia et al. (2018) studied a sustainable tire closed-loop SCND and formulated a multi-objective MILP formulation. For large-sized networks, they implemented hybrid metaheuristic algorithms. In their study, the single-period model is used and certain parameters are considered. Also, Fathollahi-Fard et al. (2018) proposed a three-echelon formulation for designing the location and allocation of a tire closed-loop SCND. Shi et al. (2019) introduced a new closed-loop supply chain mode which hypothesizes some barriers for such a mode exist for the whole supply chain from the remanufacturers' management and government support. Yıldızbaşı et al. (2020) assessed the social sustainable supply chain indicators using an integrated approach of fuzzy technique for order preference by similarity to an ideal solution (TOPSIS) and fuzzy AHP. They studied the automotive industry in Turkey to assess them in terms of social sustainability.

2.2 Global supply chain with regard to waste management

Meixell and Gargeya (2005) reviewed operations management formulations in global supply chains.

They emphasized that a few formulations have modeled according to the practical issues in the design of global supply chain formulations. They classified papers based on global considerations, such as corporate income tax, exchange rates, currency, tariffs, and non-tariff trade barriers. Liu and Papageorgiou (2013) addressed the production, distribution and capacity planning of global supply chains with regard to customer service level, cost, and responsiveness simultaneously. They developed a multi-objective mixed-integer linear programming (MILP) formulation with total lost sales, total flow time, and total cost as essential objective functions. Lee et al. (2017) studied how firms make plant location and inventory level decisions to serve global markets. They investigated not only differences in transportation costs, wages, and subsidies across countries but also competition and exchange rate changes among firms. Hassanzadeh Amin and Baki (2017) designed a mathematical formulation for a closed-loop SCND by considering global factors, including customs duties and exchange rates. The formulation is a multi-objective MILP model under uncertain demand. In this model, only one strategy for waste management is considered and product shortage is not considered.

Zerang et al. (2018) studied a closed-loop global supply chain in which the manufacturer manipulates both manufacturing from raw materials and remanufacturing from the second-hand products collected by third party simultaneously. They assumed that the market demand depends on marketing efforts and selling price. Koberg and Longoni (2019) identified the critical elements of sustainable SCND in global supply chains and proposed a systematic review of SCND in global supply chains. They concluded some useful outcomes along environmental, social and economic dimensions. Rezaei and Maihami (2019) studied a closed-loop global supply chain which is structured to sell the products in a first and a secondary market. As a significant point, they applied the game theory in sustainability in a new competitive SCND structure. Cohen and Lee (2020) identified the reaction strategies of firms to changes in government policy that are relevant to global manufacturing and logistics. This includes policy changes, such as tariffs, taxes, content requirements, and investment incentives. Boronoos et al. (2020) developed a multi-objective MILP formulation for a closed-loop green global SCND problem. Their formulation minimizes the total robustness costs and total CO_2 emissions in both forward and reverse directions, simultaneously. Abdolazimi et al. (2020) designed a multi-level closed-loop supply chain network under deterministic and uncertain conditions to maximize the time delivery, and minimize total costs, and environmental impacts under the uncertainty of some parameters. They studied their proposed approach in a tire production factory.

2.3 Research gap

Although many researchers have considered different aspects of the closed-loop SCND with a variety of significant practical factors such as batteries, iron and steel, and hospital waste, only a few studies have focused on developing a stochastic multi-objective closed-loop global SCND formulation with particular focus on the tire production processes. In most papers, the uncertainty of parameters such as return rates and demand has not been considered. Accordingly, to fill the research gap in the literature, the current study develops a closed-loop global SCND formulation, including demand uncertainty and product return rates. In the suggested model, critical factors such as dividing suppliers into internal and external categories, forcing manufacturers to buy a percentage of raw material from external suppliers, and considering the shortage of customer demand are included. A summary of the literature review is provided in Table 1 to determine the contribution of the current study.

3 Problem description

This paper, considering waste management, studies the issues of today's world and adds the necessary flexibility to the model. It specifically addresses the tire life cycle with two objectives: the first is maximizing total profits, and the second is minimizing the Eco-indicator 99. The tire life cycle in the network, as shown in Fig. 1, can be divided into the two following categories.

(I) In the forward direction, the manufacturers produce raw materials from internal or external suppliers whereby, in the case of import of raw materials, the external suppliers bear the customs costs and exchange rates. (It should be noted that in some countries, a percentage of tire raw materials is imported.) Then, after the production, the tires are transferred to the distribution points and the retailers receive the products from the distributors according to their periodicity. Due to limitations of supplier capacity, this may not be possible for the last requests.

Table 1 Summary of recent studies

Reference	Year	Multi-period	Multi-product	Multi-objective	Facility capacity	Uncertainty	Global factors	Shortage	Close-loop SCND	Location decisions for facilities			
										Distribution points	Centralized return point	Retreading	Recycling
Dehghanian and Mansouri	2009	✗	✓	✓	Multi-level capacities	✗	✗	✗	✗	✗	✗	✓	✓
Sasikumar et al	2010	✓	✗	✗	Capacitated	✗	✗	✗	✗	✗	✓	✗	✗
Subulan et al	2015	✓	✓	✓	Modular capacities	✗	✗	✗	✓	✓	✓	✓	✓
Hassanzadeh Amin et al	2017	✓	✓	✗	Capacitated	✓	✗	✗	✓	✗	✗	✗	✗
Pedram et al	2017	✗	✓	✗	Capacitated	✓	✗	✗	✓	✓	✓	✓	✗
Sahebjamnia et al	2018	✗	✓	✓	Capacitated	✗	✗	✗	✓	✓	✓	✗	✓
Fathollahi-Fard et al	2018	✗	✓	✓	Capacitated	✗	✗	✗	✓	✓	✓	✗	✓
Shi et al	2019	✓	✓	✗	Multi-level capacities	✗	✗	✗	✓	✓	✓	✗	✓
Boronoos et al	2020	✗	✗	✓	Un capacitated	✓	✓	✗	✓	✓	✗	✗	✓
This paper	2020	✓	✓	✓	Capacitated	✓	✓	✓	✓	✓	✓	✓	✓

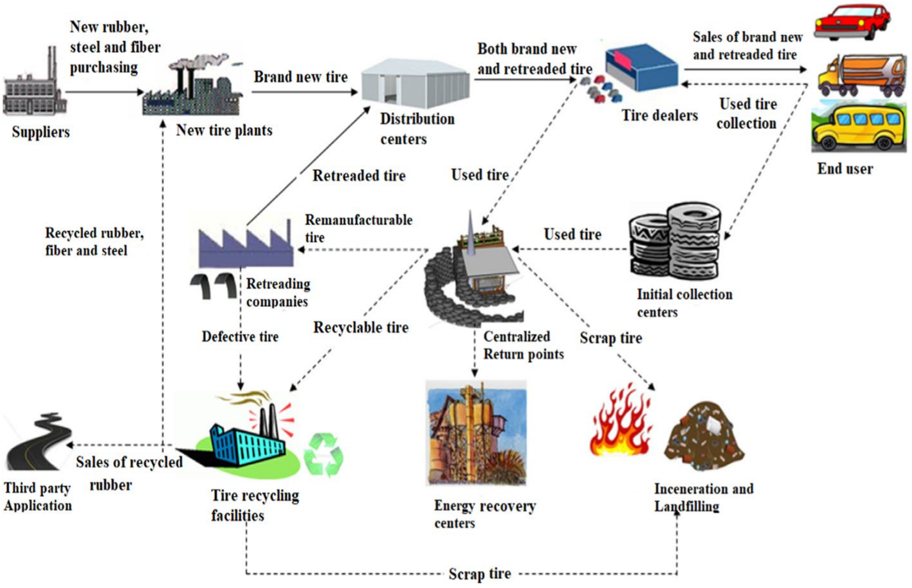


Fig. 1 A closed-loop supply chain of tire [2]

(II) In the reverse direction, waste tires are transmitted by dealers and initial collection centers to centralized return sites for inspection and waste management. To attract and retain customers, the policy is that customers receive new tires with a discount rate if they return tire waste. After the inspection, according to the quality level, the used tires are transferred to retreading, recycling, cement or electricity plants, and landfill centers.

In order to better clarify of practical conditions of the proposed problem, in the following subsections, two significant topics (i.e., several recovery options of the end-of-life tires and the Eco-indicator 99) are explained briefly.

3.1 End-of-life tires and several recovery options

Different recovery options can be discussed as follows.

(I) *Direct reuse:* Reuse is one of the most significant waste prevention strategies. Although the importance of preparation for reuse is evident, preparation centers for reuse are not common in the traditional waste SCND (Gusmerotti et al. 2019).

(II) *Retreading:* Up to 80% of the cost of tire materials can be saved via the retreading process (Debo and Wassenhove 2005). The significant point is that retreaded tires and newly produced tires have approximately the same mileage. However, they can be sold with a 30–50% discount (Sasikumar et al. 2010).

(III) *Recycling:* This process informs the recovery of materials from granulate tires (Panagiotidou and Tagaras 2005; Shakhsi-Niaei and Esfandarani 2019).

(IV) *Preparing for waste tire modified concrete production:* The rubber tire particles can be used in concrete to replace mineral aggregates. This method is applied in some leading countries (Karabash and Cabalar 2015; Cabalar and Karabash 2015; Akbarimehr et al. 2019).

(V) *Recovery of energy:* Studies emphasize that the energy of 242 million scrap tires equals 12 million barrels of oil. Accordingly, they can be used for electricity generation (Subulan et al. 2015).

(VI) *Disposal*: In order to manage tire waste, landfilling is the least preferred option (Ferrao et al. 2008).

All of the above-discussed recovery options, except (I) and (IV), are considered in the proposed formulation to reflect the real-world conditions of the proposed practical case study more accurately. In this way, the most widely used recovery methods are evaluated to save production time and minimize damage to nature and the preservation of raw materials, the need for the import of raw materials from abroad will decrease and national production will increase.

3.2 The methodology of Eco-indicator 99

The methodology of Eco-indicator 99 is a life cycle assessment-based approach and damage modeling, which is applied for estimating and quantifying the environmental effects of a product or process. These predetermined guides, used by designers and production managers, apply the Eco standard indicator to measure the environmental aspects of the product. In this approach, the main damages are categorized into three divisions (Pishvaee and Razmi 2012):

- Human health: production of carcinogenic substances.
- Ecosystem quality: climate change, ozone layer degradation, and acidity of the earth.
- Sources depletion: consumption of fossil fuels and minerals.

In the methodology, the environmental effects, studied in the product life cycle, include the following phases: (1) raw material attainment, (2) production, (3) transportation/distribution, (4) use, (5) end-of-life collecting, (6) end-of-life processing, (7) energy recovery, (8) remanufacturing, (9) recycling, (10) storage/warehousing, and (11) disposal (Subulan et al. 2015).

In the Eco-indicator 99 calculation, the utilization of tires by end users is ignored in the proposed mathematical model, because it does not affect on decision making.

3.3 Assumptions

According to the realistic conditions of the practical case study and the proposed problem, the main assumptions are organized as follows.

- The lead times of transportation between the stages are ignored.
- Shortages for dealers are allowed.
- The sale price of new tires is cheaper if end-of-life tires are left with the tire dealer.
- The number of tires returned from a predetermined tire dealer is a fraction of the maximum demand of that dealer.

- All facilities have a limited capacity.
- The locations of manufacturers and suppliers are predefined and fixed.
- In all the stages of the closed-loop SCND, the cost parameters do not change throughout the several time periods. This is except for the cost of the initial setup for the established factories.
- The cost of the initial setup grows seasonally, such that it becomes more expensive to establish a new factory over time.
- Since a percentage of tire raw materials is imported, for those suppliers who are abroad, the customs duty and exchange rates are included.
- All production, distribution, collection, recycling, and retreading centers are in a country, and only suppliers can be considered as being internal and external.

3.4 Mathematical programming model

The nomenclature, parameters, and decision variables are defined in "Appendix". The multi-objective, multi-product, multi-period, and multi-echelon closed-loop SCND design is formulated as the following mathematical model.

Equation (1) represents the profit function obtained from the difference between income and expenses.

$$MaxZ1 = TREV - (TOP + TFC + TRMC + TPRC + TTC + TRC + TCC + TMPC + TIC + TDC + TSC) \tag{1}$$

Equation (2) shows the total revenue of the CLSC, which is obtained by selling end-of-life tires for energy recovery, retreaded tires, new brand tires, and recycled materials for other usages.

$$\begin{aligned} \text{TREV} = & \sum_{p}\sum_{d}\sum_{r}\sum_{v}\sum_{t}\sum_{s} p_s \cdot \alpha_{ps} \cdot X2_{pdrv(t-1)s} \cdot SL1_p \\ & + \sum_{p}\sum_{d}\sum_{r}\sum_{v}\sum_{t}\sum_{s} p_s \cdot (X2_{pdrvts} - (\alpha_{ps})X2_{pdrv(t-1)s}) \cdot SL2_p + \\ & \sum_{a}\sum_{d}\sum_{r}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X3_{adrvts} \cdot SL3_a + \sum_{p}\sum_{k}\sum_{w}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X5_{pkwvts} \cdot SL4_p + \\ & \sum_{c}\sum_{n}\sum_{t}\sum_{s} p_s \cdot Qs_{cnts} \cdot SL5_c \end{aligned} \tag{2}$$

Equations (3) and (4) represent the overall fixed operating and setup costs for the facilities.

$$\text{TOP} = \sum_{l}\sum_{t} Oc1_l \cdot Y1_{lt} + \sum_{d}\sum_{t} Oc2_d \cdot Y2_{dt} + \sum_{k}\sum_{t} Oc3_k \cdot Y3_{kt} + \sum_{n}\sum_{t} Oc4_n \cdot Y4_{nt} \tag{3}$$

$$\begin{aligned} \text{TFC} = & \sum_{l}\sum_{t} F1_{lt} \cdot (Y1_{lt} - Y1_{lt-1}) + \sum_{d}\sum_{t} F2_{dt} \cdot (Y2_{dt} - Y2_{dt-1}) + \\ & \sum_{k}\sum_{t} F3_{kt} \cdot \left(Y3_{kt} - Y3_{kt-1}\right) + \sum_{n}\sum_{t} F4_{nt} \cdot \left(Y4_{nt} - Y4_{nt-1}\right) \end{aligned} \tag{4}$$

Equations (5) to (13) show total production costs, total remanufacturing costs, total transport costs between different stages, total recycling costs, total collection costs, material purchasing costs, total inventory carrying costs, total disposal costs, and the cost of final product shortages against the retailers' demands, respectively.

$$\mathrm{TRMC} = \sum_{p}\sum_{l}\sum_{t}\sum_{s} p_s \cdot \mathrm{RTC}_{pl} \cdot \mathrm{RTR}_{plts} \tag{5}$$

$$\mathrm{TPRC} = \sum_{p}\sum_{i}\sum_{t}\sum_{s} p_s \cdot PC_{pi} \cdot Q_{pits} \tag{6}$$

$$\begin{aligned}
\mathrm{TTC} = {} & \sum_{c}\sum_{m}\sum_{i}\sum_{z}\sum_{v}\sum_{t}\sum_{s} p_s \cdot h_z \cdot TC2_{czv} \cdot D11_{miz} \cdot Qp_{cmivts} \\
& + \sum_{p}\sum_{i}\sum_{d}\sum_{v}\sum_{t}\sum_{s} p_s . X1_{pidvts} . TC_{pv} . D1_{id} \\
& + \sum_{p}\sum_{d}\sum_{r}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X2_{pdrvts} \cdot TC_{pv} \cdot D2_{dr} \\
& + \sum_{a}\sum_{d}\sum_{r}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X3_{adrvts} \cdot C1_{av} \cdot D2_{dr} \\
& + \sum_{p}\sum_{k}\sum_{w}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X5_{pkwvts} \cdot TC_{pv} \cdot D5_{kw} \\
& + \sum_{p}\sum_{k}\sum_{n}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X6_{pknvts} \cdot TC_{pv} \cdot D6_{kn} \\
& + \sum_{p}\sum_{k}\sum_{l}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X7_{pklvts} \cdot TC_{pv} \cdot D7_{kl} \\
& + \sum_{a}\sum_{l}\sum_{d}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X8_{aldvts} \cdot TC1_{av} \cdot D8_{ld} \\
& + \sum_{p}\sum_{l}\sum_{n}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X9_{p\,\mathrm{ln}\,vts} \cdot TC_{pv} \cdot D9_{\mathrm{ln}} \\
& + \sum_{c}\sum_{n}\sum_{i}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X10_{cnivts} \cdot TC3_{cv} \cdot D10_{ni}
\end{aligned} \tag{7}$$

$$\mathrm{TRC} = \sum_{p}\sum_{n}\sum_{t}\sum_{s} p_s \cdot \mathrm{RC}_{pn} \cdot \mathrm{REC}_{pnts} \tag{8}$$

$$\mathrm{TCC} = \sum_{p}\sum_{j}\sum_{k}\sum_{v}\sum_{t} Y5_{jkvt} \cdot RE_{pjt} \cdot (TC_{pv} + CC_{p}) \cdot D4_{jk} + \sum_{p}\sum_{r}\sum_{k}\sum_{v}\sum_{t}\sum_{s} p_s \cdot X4_{prkvts} \cdot TC_{pv} \cdot D3_{rk} \tag{9}$$

$$\mathrm{TMPC} = \sum_{c}\sum_{m}\sum_{i}\sum_{z}\sum_{v}\sum_{t}\sum_{s} p_s \cdot h_z \cdot \left(1 + b_{cmz}\right) \cdot \mathrm{PUC}_{cmz} \cdot Qp_{cmivts} \tag{10}$$

$$\begin{aligned}\mathrm{TIC} = {} & \sum_{p}\sum_{i}\sum_{t}\sum_{s} p_s \cdot I1_{pits} \cdot IC1_{pi} + \sum_{p}\sum_{d}\sum_{t}\sum_{s} p_s \cdot I2_{pdts} \cdot IC2_{pd} \\ & + \sum_{a}\sum_{d}\sum_{t}\sum_{s} p_s \cdot I3_{adts} \cdot IC3_{ad} + \sum_{p}\sum_{k}\sum_{t}\sum_{s} p_s \cdot I4_{pkts} \cdot IC4_{pk} \\ & + \sum_{c}\sum_{i}\sum_{t}\sum_{s} p_s \cdot I5_{cits} \cdot IC5_{ci}\end{aligned} \tag{11}$$

$$\begin{aligned}\mathrm{TDC} = {} & \sum_{p}\sum_{k}\sum_{l}\sum_{n}\sum_{v}\sum_{t}\sum_{s} p_s \cdot \left(X6_{pknvts} + X9_{p\ln vts}\right) \cdot \left(1-\beta_p\right) \cdot e \cdot INC_p \\ & + \sum_{p}\sum_{k}\sum_{l}\sum_{n}\sum_{v}\sum_{t}\sum_{s} p_s \cdot \left(X6_{pknvts} + X9_{p\ln vts}\right) \cdot \left(1-\beta_p\right)(1-e) \cdot LNFC_p + (1-e) \cdot LNFC_p \\ & + \sum_{p}\sum_{r}\sum_{j}\sum_{k}\sum_{v}\sum_{t}\sum_{s} \left(p_s \cdot X4_{prkvts} + RE_{pjt} \cdot Y5_{jkvt}\right) \cdot d_p \cdot e \cdot INC_p \\ & + \sum_{p}\sum_{r}\sum_{j}\sum_{k}\sum_{v}\sum_{t}\sum_{s} \left(p_s \cdot X4_{prkvts} + RE_{pjt} \cdot Y5_{jkvt}\right) \cdot d_p \cdot (1-e) \cdot LNFC_P\end{aligned} \tag{12}$$

$$\mathrm{TSC} = \sum_{p}\sum_{r}\sum_{t}\sum_{s} p_s \cdot UD_{prts} \cdot Cd_{prt} \sum_{a}\sum_{r}\sum_{t}\sum_{s} p_s \cdot UD1_{arts} \cdot Cd1_{art} \tag{13}$$

Equation (14) minimizes the total Eco-indicator 99 value through the CLSC. This is obtained by multiplying the standard index amounts for each life cycle phase and their respective predefined values.

$$\mathrm{Min}Z2 = \mathrm{EIMP} + \mathrm{EIPR} + \mathrm{EITR} + \mathrm{EIWH} + \mathrm{EICL} + \mathrm{EIEOP} - \mathrm{EIER} - \mathrm{EIRTR} - \mathrm{EIREC} + \mathrm{EIDS} \tag{14}$$

Equations (15)–(23) represent the total environmental impact of the following phases, respectively: material purchasing, production, distribution/transport, end-of-life collection, end-of-life processing, energy recovery, tire remanufacturing, warehousing, tire recycling, and tire disposal.

$$\mathrm{EIMP} = \sum_{c}\sum_{m}\sum_{i}\sum_{z}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EI1_{cz} \cdot Qp_{cmivts} + \sum_{c}\sum_{n}\sum_{i}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EI2_{c} \cdot X10_{cnivts} \tag{15}$$

$$\mathrm{EIPR} = \sum_{p}\sum_{i}\sum_{t}\sum_{s} p_s \cdot \mathrm{EIP}_{pi} \cdot Q_{pits} \tag{16}$$

$$\begin{aligned}\mathrm{EITR} = {} & \sum_{p}\sum_{i}\sum_{d}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT1_{pv} \cdot X1_{pidvts} \cdot D1_{id} \\ & + \sum_{p}\sum_{d}\sum_{r}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT1_{pv} \cdot X2_{pdrvts} \cdot D2_{dr} + \sum_{a}\sum_{d}\sum_{r}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT2_{av} \cdot X3_{adrvts} \cdot D2_{dr} + \\ & \sum_{p}\sum_{k}\sum_{w}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT1_{pv} \cdot X5_{pkwvts} \\ & D5_{kw} + \sum_{p}\sum_{k}\sum_{n}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT1_{pv} \cdot X6_{pknvts} \cdot D6_{kn} + \sum_{p}\sum_{k}\sum_{l}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT1_{pv} \cdot X7_{pklvts} \cdot \\ & D7_{kl} + \sum_{a}\sum_{l}\sum_{d}\sum_{v}\sum_{t}\sum_{s} p_s EIT2_{av}.X8_{aldvts} \cdot D8_{ld} + \sum_{p}\sum_{l}\sum_{n}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT1_{pv} \cdot X9_{p\ln vts} \cdot \\ & D9_{\ln} + \sum_{c}\sum_{n}\sum_{i}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT3_{cv} \cdot X10_{cnivts} \cdot D10_{ni} + \sum_{c}\sum_{m}\sum_{i}\sum_{z}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIT3_{cv} \cdot Qp_{cmivts} \cdot D11_{miz}\end{aligned} \tag{17}$$

$$\mathrm{EICL} = \sum_{p}\sum_{r}\sum_{k}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EIC1_{pv} \cdot X4_{prkvts} \cdot D3_{rk} + \sum_{p}\sum_{j}\sum_{k}\sum_{v}\sum_{t} EIC2_{pv} \cdot Y5_{jkvt} \cdot RE_{pjt} \cdot D4_{jk} \tag{18}$$

$$\mathrm{EIEOP} = \sum_{p}\sum_{r}\sum_{k}\sum_{v}\sum_{t}\sum_{s} p_s \cdot \mathrm{EIE}_{pk} \cdot X4_{prkvts} + \sum_{p}\sum_{j}\sum_{k}\sum_{v}\sum_{t} \mathrm{EIE}_{pk} \cdot \mathrm{RE}_{pjt} \cdot Y5_{jkvt} \tag{19}$$

$$\mathrm{EIER} = \sum_{p}\sum_{k}\sum_{w}\sum_{v}\sum_{t}\sum_{s} p_s \cdot \mathrm{EIR}_{pw} \cdot X5_{pkwvts} \tag{20}$$

$$\mathrm{EIRTR} = \sum_{p}\sum_{l}\sum_{t}\sum_{s} p_s \cdot \mathrm{EIRM}_{\mathrm{pl}} \cdot \mathrm{RTR}_{\mathrm{plts}} \tag{21}$$

$$\mathrm{EIREC} = \sum_{p}\sum_{n}\sum_{t}\sum_{s} p_s \cdot \mathrm{EIRC}_{\mathrm{pn}} \cdot \mathrm{REC}_{\mathrm{pnts}} \tag{22}$$

$$\begin{aligned}\mathrm{EIDS} = {} & \sum_{p}\sum_{k}\sum_{l}\sum_{n}\sum_{v}\sum_{t}\sum_{s} p_s \cdot EII_p \cdot \left(X6_{pknvts} + X9_{plnvts}\right) \\ & .\left(1 - B_p\right) \cdot e + \sum_{p}\sum_{k}\sum_{l}\sum_{n}\sum_{v}\sum_{t}\sum_{s} p_s EIL_p \left(X6_{pknvts} + X9_{plnvts}\right) \cdot \left(1 - B_p\right) \cdot (1 - e) + \\ & \sum_{p}\sum_{r}\sum_{j}\sum_{k}\sum_{v}\sum_{t}\sum_{s} EII_p \cdot \left(p_s \cdot X4_{prkvts} + RE_{pjt} \cdot Y5_{jkvt}\right) \cdot d_p \cdot e + \\ & \sum_{p}\sum_{r}\sum_{j}\sum_{k}\sum_{v}\sum_{t}\sum_{s} EIL_p \cdot \left(p_s \cdot X4_{prkvts} + RE_{pjt} \cdot Y5_{jkvt}\right) \cdot d_p \cdot (1 - e)\end{aligned} \tag{23}$$

s.t.

Constraints (24)–(26) guarantee that the production, remanufacturing, and recycling amounts are not more than the capacities of these facilities.

$$\sum_{p} Q_{pits} \leq Cap_i \quad \forall i, t, s \tag{24}$$

$$\sum_{p} RTR_{plts} \leq Cap1_l \cdot Y1_{lt} \quad \forall l, t, s \tag{25}$$

$$\sum_{p} REC_{pnts} \leq Cap2_n \cdot Y4_{nt} \quad \forall n, t, s \tag{26}$$

Constraints (27)–(31) emphasize that the storage capacity for each type of material and the new brand tires at each new tire factory, each type of retreaded and new brand tires at each distribution point, and each type of used tires at each centralized return site can be calculated in each period.

$$I1_{pits} = I1_{pits-1} + Q_{pits} - \sum_{d}\sum_{v} X1_{pidvts} \quad \forall p, i, t, s \tag{27}$$

$$I2_{pdts} = I2_{pdts-1} + \sum_{i}\sum_{v} X1_{pidvts} - \sum_{r}\sum_{v} X2_{pdrvts} \quad \forall p, d, t, s \tag{28}$$

$$I3_{adts} = I3_{adts-1} + \sum_{l}\sum_{v} X8_{aldvts} - \sum_{r}\sum_{v} X3_{adrvts} \quad \forall a, d, t, s \tag{29}$$

$$\begin{aligned} I4_{pkts} =& I4_{pkts-1} + \sum_{r}\sum_{v} X4_{prkvts} + \sum_{j}\sum_{v} RE_{pjt} \cdot Y5_{jkvt} \\ & - \sum_{w}\sum_{v} X5_{pkwvts} - \sum_{l}\sum_{v} X7_{pklvts} - \sum_{n}\sum_{v} X6_{pknvts} \\ & - d_p\left(\sum_{r}\sum_{v} X4_{prkvts} + \sum_{j}\sum_{v} RE_{pjt} \cdot Y5_{jkvt} \right) \quad \forall p, k, t, s \end{aligned} \tag{30}$$

$$I5_{cits} = I5_{cits-1} + \sum_{m}\sum_{v} Qp_{cmivts} + \sum_{n}\sum_{v} X10_{cnivts} - \sum_{p} Q_{pits} \cdot h_{cp} \quad \forall c, i, t, s \tag{31}$$

Constraint (32) ensures that at least the external supplier supplies λ% of the raw material.

$$\sum_{m}\sum_{v} Qp_{c,m,i,v,t,s} * \lambda \leq \sum_{mp}\sum_{v} Qp_{c,mp,i,v,t,s} \quad \forall c, i, t, s \tag{32}$$

The storage capacity limits for new tire factories, distribution points, and centralized return sites are represented in constraints (33)–(35), respectively. The levels of inventory at each centralized return point and established distribution point cannot exceed their capacity.

$$\sum_{p} Ps1_p \cdot I1_{\mathrm{pits}} + \sum_{c} CS_c \cdot I5_{\mathrm{cits}} \leq Tscap_i \quad \forall i, t, s \tag{33}$$

$$\sum_{p} Ps1_p \cdot I2_{pdts} + \sum_{a} Ps2_a \cdot I3_{adts} \leq MIcap1_d \cdot Y2_{dt} \quad \forall d, t, s \tag{34}$$

$$\sum_{p} Ps1_p \cdot I4_{pkts} \leq MIcap2_k \cdot Y3_{kt} \quad \forall k, t, s \tag{35}$$

Constraints (36) and (37) are the amounts of the inputs to the distribution centers and the centralized return point; they are as large as the storage capacity of these centers.

$$\sum_{p}\sum_{i}\sum_{v} X1_{pidvts} + \sum_{a}\sum_{l}\sum_{v} X8_{aldvts} \leq MIcap1_d \cdot Y2_{dt} \quad \forall d, t, s \tag{36}$$

$$\sum_{p}\sum_{r}\sum_{v} X4_{prkvts} + \sum_{p}\sum_{j}\sum_{v} RE_{pjt} \cdot Y5_{jkvt} \leq MIcap2_k \cdot Y3_{kt} \quad \forall k, t, s \tag{37}$$

Constraints (38) and (39) show that the total amount of the sent goods and lost demands is equal to the amount of each retailer's demand.

$$\sum_{d}\sum_{v} X2_{pdrvts} + UD_{prts} = DE1_{prts} \quad \forall p, r, t, s \tag{38}$$

$$\sum_{d}\sum_{v} X3_{adrvts} + UD1_{arts} = DE2_{arts} \quad \forall a, r, t, s \tag{39}$$

Constraint (40) indicates that the percentage of products returning from the demand market is equal to the number of goods sent to the centralized return sites.

$$\sum_{d}\sum_{v} X2_{pdrvts} \cdot a_{ps} = \sum_{k}\sum_{v} X4_{prkvts} \quad \forall p, r, t, s \tag{40}$$

Constraints (41) and (42) indicate what percentage of the products goes to retreading centers and what percentage to the recycling factory.

$$\mathrm{RTR}_{plts} \cdot y1_{lt} = O_{pl} \cdot \sum_{k}\sum_{v} X7_{pklvts} \quad \forall p, l, t, s \tag{41}$$

$$\sum_{n}\sum_{v} X9_{p\ln vts} = \left(1 - O_{pl}\right) \cdot \sum_{k}\sum_{v} X7_{pklvts} \quad \forall p, l, t, s \tag{42}$$

Constraint (43) states that the number of types of p-type tires recycled in company n is equal to the percentage of tires that came from the retreading point and centralized return sites.

$$\mathrm{REC}_{pnts} \cdot y4_{nt} = \beta_{p} \cdot \left(\sum_{k}\sum_{v} X6_{pknvts} + \sum_{l}\sum_{v} X9_{p\ln vts}\right) \quad \forall p, n, t, s \tag{43}$$

Constraint (44) emphasizes that the total amount of recycled materials sent to manufacturers and secondary markets is as much as the recycled materials produced at recycling factory n.

$$\sum_{i}\sum_{v} X10_{cnivts} + Qs_{cnts} = \sum_{p} REC_{pnts} \cdot h_{cp} \quad \forall c, n, t, s \tag{44}$$

Constraint (45) states that all of tires that are being retreaded are transferred to the distributor's point.

$$\sum_{d}\sum_{v} X8_{aldvts} = \mathrm{RTR}_{plts} \quad \forall p = a, l, t, s \tag{45}$$

Constraint (46) ensures that initial collection centers are connected by only one vehicle to a centralized return point.

$$\sum_{k}\sum_{v} Y5_{jkvt} = 1 \quad \forall j, t \tag{46}$$

Constraints (47)–(50) show the minimum amount of inventory in the centers that they can establish.

$$\sum_{p}\sum_{i}\sum_{v} X1_{pidvts} + \sum_{a}\sum_{l}\sum_{v} X8_{aldvts} \geq MT1_{d} \cdot Y2_{dt} \quad \forall d, t, s \tag{47}$$

$$\sum_p \sum_r \sum_v X4_{prkvts} + \sum_p \sum_j \sum_v RE_{pjt} \cdot Y5_{jkvt} \geq MT2_k \cdot Y3_{kt} \quad \forall k, t, s \tag{48}$$

$$\sum_a \sum_d \sum_v X8_{aldvts} \geq MT3_l \cdot Y1_{lt} \quad \forall l, t, s \tag{49}$$

$$\sum_c \sum_i \sum_v X10_{cnivts} + \sum_c Qs_{cnts} \geq MT4_n \cdot Y4_{nt} \quad \forall n, t, s \tag{50}$$

Constraints (51)–(58) indicate the capacity of machines to transport materials and products among various facilities.

$$\sum_p \sum_d X1_{pidvts} \leq VCap_v \cdot N1_{ivt} \quad \forall i, v, t, s \tag{51}$$

$$\sum_p \sum_r X2_{pdrvts} + \sum_a \sum_r X3_{adrvts} \leq VCap_v \cdot N2_{dvt} \quad \forall d, v, t, s \tag{52}$$

$$\sum_p \sum_k X4_{prkvts} \leq VCap_v \cdot N3_{rvt} \quad \forall r, v, t, s \tag{53}$$

$$\sum_p \sum_k Y5_{jkvt} \cdot RE_{pjt} \leq VCap_v \cdot N4_{jvt} \quad \forall j, v, t \tag{54}$$

$$\sum_p \sum_w X5_{pkwvts} + \sum_p \sum_n X6_{pknvts} + \sum_p \sum_l X7_{pklvts} \leq VCap_v \cdot N5_{kvt} \quad \forall k, v, t, s \tag{55}$$

$$\sum_a \sum_d X8_{aldvts} + \sum_p \sum_n X9_{p\ln vts} \leq VCap_v \cdot N6_{lvt} \quad \forall l, v, t, s \tag{56}$$

$$\sum_c \sum_i X10_{cnivts} \leq VCap_v \cdot N7_{nvt} \quad \forall n, v, t, s \tag{57}$$

$$\sum_c \sum_i Qp_{cmivts} \leq VCap_v \cdot N8_{mvt} \quad \forall m, v, t, s \tag{58}$$

Constraints (59)–(62) indicate that a factory is maintained until the end of the design period.

$$Y1_{lt} \leq Y1_{lt+1} \quad \forall l, t = T - 1 \tag{59}$$

$$Y1_{dt} \leq Y2_{dt+1} \quad \forall d, t = T - 1 \tag{60}$$

$$Y3_{kt} \leq Y3_{kt+1} \quad \forall k, t = T - 1 \tag{61}$$

$$Y4_{nt} \leq Y4_{nt+1} \quad \forall n, t = T - 1 \tag{62}$$

The final constraints represent the type of decision variables.

$$Y1_{lt}, Y2_{dt}, Y3_{kt}, Y4_{nt}, Y5_{jkvt}\varepsilon(0,1) \tag{63}$$

$$X1_{pidvts}, X2_{pdrvts}, X3_{adrvt}, X5_{pkwvts}, X6_{pknvts}, X7_{pklvts}, \dots \geq 0 \tag{64}$$

4 Stochastic programming

According to the practical conditions of the proposed problem, in this study, some parameters, including demand and return rate, are assumed uncertain. Here, uncertainty is in accordance with a two-stage stochastic programming and its uncertainty parameters are considered as possible scenarios. The following formulation is a common approach for two-stage stochastic programming (Brige and louveaux 2011):

$$\begin{aligned}
&\text{Min } z = c^T x + \sum_s p^s b^{s^T} y^s \\
&St. \\
&Ax = d, \\
&B^s x + D^s y^s = h^s, s\varepsilon S \\
&x \geq 0,\ y^s \geq 0
\end{aligned} \tag{65}$$

The nature of this type of problem indicates that the decisions of the first stage (x) are made, while all the scenarios (S), the probability of their occurrence (p), and the values of the corresponding random parameters are known. However, the decisions of the second stage (y^s) are taken, while one of the possible scenarios (S) has happened.

In the current study, the two-stage stochastic programming is planned such that in the first stage, it is decided for the establishment and non-establishment of facilities. Then, in the second stage, it determines the amount of production, the amount of retreading, and the amount of recycling.

5 The improved augmented ε-constraint (AUGMECON2)

The ε-constraint is one of the precise methods for solving multi-objective problems that have been very efficient and have been used in many problems, such as scheduling issues, operation sequences, and maintenance and repairs (Mavrotas 2009).

Here, the augmented ε-constraint method version 2 (AUGMECON2) is used. AUGMECON improves the typical ε-constraint to generate Pareto optimal solutions. In general, AUGMECON tries to address most of the weak points of the typical ε-constraint. In the conventional AUGMECON, the problem is formulated as the following mathematical model (Mavrotas and Florios 2013):

$$
\begin{aligned}
& Max\left(f_1(x) + eps * \left(S_2/r_2 + \ldots + S_p/r_p\right)\right) \\
& St. \\
& f_2(x) + S_2 = \varepsilon_2, \\
& . \\
& . \\
& f_p(x) + S_p = \varepsilon_p, \\
& x \varepsilon S
\end{aligned}
\tag{66}
$$

where ε_2; ε_3;...; ε_p are the parameters of the RHS for the predetermined iteration drawn from the grid points of objectives 2, 3,..., p. Parameters r_2, r_3,..., r_p are the ranges of the respective objectives. Scenarios S_2, S_3,..., S_p are distributed uniformly in $eps \in [10^{-6},10^{-3}]$ and the surplus variables of the respective constraints. In the improved version of AUGMECON, named AUGMECON2, the objective is somewhat modified as follows:

$$Max(f1(x) + eps \times (S_2/r_2 + 10^{(-1)} \times n + 10^{-p-2})) \times S_2/r_2)) \tag{67}$$

This modification should be done to perform a type of lexicographic optimization on the rest of the objectives if there are any optimum alternatives. For further studies, Mavrotas (2009) and Brige and Louveaux (2011) are suggested.

6 Case study

In order to represent the efficiency of the proposed MILP formulation for real-life applications, an Iranian tire industry is explained. Iran Tire is an automobile tire manufacturer in Tehran, Iran. It produces several types of tire with particular specifications such as quality and size. A percentage of their raw materials is imported. Accordingly, the supply chain consists of two suppliers (internal and external), a manufacturing company, two distribution points, two dealer centers, a temporary warehouse, a collection center, two retreading centers, two recycling centers, and a cement plant for fuel consumption. There are also two kinds of retreaded and new tires, i.e., bus and truck tires, as well as two kinds of material, i.e., steel and rubber. The planning time period is divided into two six-month periods. In this network, there are two types of transportation vehicles with several capacities, costs and environmental impacts. According to the decision maker, the costs are considered in a specific currency or monetary unit (e.g., $, €, etc.). Other parameters of the problem are given in Table 2.

To consider the uncertainty of the model's parameters, 18 (3×3×2) scenarios are defined. Thus, for new and retreaded tires, there are three modes; and two modes for the return rate of the products are considered. Data related to the demand for retreading and new tires are uncertain with an increase of 10% and a reduction of 20% from the previous data. The probability of the occurrence of each scenario is given in Table 3.

After running the model, on a personal computer with 2.8 GHz CPU and 8 GB main memory, the model was run through optimization software GAMS 24.0.1, including CPLEX 9.0, and the relationship between the first and second objectives in ten Pareto points is given in Table 4. Also, their performances are shown in Fig. 2. As can be concluded, the first and second objectives have a direct relationship, such that when the first objective is increased, the second objective increases also.

Table 2 Parameters of case study and their ranges

Parameters	Range
Operation cost of retreading companies	3500–5000 currency
Operation cost of distribution points	1000–2000 currency
Operation cost of centralized return sites	600–1300 currency
Operation cost of tire recycling plants	4000–7000 currency
Material purchase costs from the internal suppliers	1–2 currency
Material purchase costs from the external suppliers	3–4 currency
Costs of collection of the initial collection points	0.005–0.012 currency
Costs of inventory of new brand tires in tire factories	0.5–1.25 currency
Costs of inventory of new brand tires in distribution points	0.5–1.25 currency
Costs of inventory of retreaded tires in distribution points	0.5–1.2 currency
Costs of inventory of waste tires in centralized return sites	0.4–1 currency
Costs of inventory of materials in tire factories	0.002–0.006 currency
Costs of burning at the disposal centers	0.4–0.9 currency
Costs of landfill at the disposal centers	0.1–0.5 currency
Contribution of several types of materials (rubber, steel, etc.) in tire production (%)	2–47%
Unit storing capacity utilization factor for retreaded and new brand tire	0.04–0.3
Unit storing capacity utilization factor for materials	0.0007–0.0021
Recovery rate fraction for retreading process	65–95%
Distances between all stages	15–350 km
Demand range for new brand bus and truck tires	600–900 units
Demand range for retreaded bus and truck tires	400–600 units
Lost demand cost for new tires	20–40 currency
Lost demand cost for retreaded tires	60–80 currency
Returned amounts range via the initial collection points	180–300 units
Storing capacities of distribution points	800–1000 units
Storing capacities of centralized return sites	1500 units
Maximum production capacities of new tire factories	75,000 units
Maximum remanufacturing capacities of retreading companies	50,000–60,000 units
Maximum recycling capacities of recycling factories	60,000–70,000 units
Maximum storing capacities of new tire factories	20,000 units
Minimum requested demand to establish distribution points	50–100 units
Minimum requested demand to establish centralized return sites	15–20 units
Minimum requested demand to establish retreading companies	8–15 units
Minimum requested demand to establish tire recycling facilities	10–15 units
The value of Eco-indicator for purchasing per *kg* of material type *c* from suppliers in country *z*	2.5–8
The value of Eco-indicator of attainment per *kg* of material type *c* through recycling	0.1–0.2
The value of Eco-indicator for producing one unit of new brand tire type *p* in new tire factory *i*	8–11
The value of Eco-indicator for remanufacturing one unit of used tire type *p* in the *l*	1.9–2.5
The value of Eco-indicator for recycling one unit of used tire type *p* in tire recycling factory *n*	2–2.5
The value of Eco-indicator for shipping one unit of tire type *p* per kilometer by the *v*	0.18–0.2
The value of Eco-indicator for shipping one unit of retreaded tire type *a* per kilometer by the *v*	0.13–0.24

Table 2 (continued)

Parameters	Range
The value of Eco-indicator for shipping per *kg* of material type c per kilometer by the *v*	0.14–0.19
The value of Eco-indicator for collecting one unit of used tire type *p* by dealers directly from the end users and transshipping it by the *v*	0.86–1
The value of Eco-indicator for collecting one unit of used tire type *p* by initial collection centers and transshipping it by the *v*	1–1.3
The value of Eco-indicator for end-of-life processing for one unit of waste tire type *p* at the *k*	0.35–0.5
The value of Eco-indicator for incinerating one unit of used tire type *p* in cement kiln or thermoelectric factory *w*	0.016–0.02
The value of Eco-indicator for incinerating one unit of waste tire type *p* at disposal centers	0.56–1
The value of Eco-indicator for landfilling one unit of waste tire type *p* at disposal centers	2.3–2.5
The value of Eco-indicator for storing/warehousing operations of distribution points *d*	0.1–0.2
The value of Eco-indicator for storing/warehousing operations of centralized return sites *k*	0.2
Raw materials (%) received from external suppliers	20%

Table 3 Probability of different scenarios

Scenario	1	2	3	4	5	6	7	8	9
Value	0.264	0.066	0.088	0.022	0.048	0.088	0.022	0.012	0.016
Scenario	10	11	12	13	14	15	16	17	18
Value	0.004	0.016	0.004	0.168	0.042	0.056	0.014	0.056	0.014

Table 4 Ten Pareto points derived from the objective functions

	Z_1	Z_2	Y_1	Y_2	Y_3	Y_4	Y_5
1	433,351.814	389,418.25	$l_1=1,l_2=0$	$d_1,d_2=1$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_1=1$
2	431,950.45	358,715.18	$l_1=1,l_2=0$	$d_1,d_2=1$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_2=1$
3	422,829.073	328,012.11	$l_1=1,l_2=0$	$d_1,d_2=1$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_2=1$
4	377,810.77	297,309.04	$l_1=1,l_2=0$	$d_1,d_2=1$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_2=1$
5	273,029.86	266,605.976	$l_1=1,l_2=0$	$d_1,d_2=1$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_2=1$
6	154,256.257	235,902.907	$l_1=1,l_2=0$	$d_1,d_2=1$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_2=1$
7	20,860.521	205,199.837	$l_1=1,l_2=0$	$d_1,d_2=1$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_2=1$
8	− 111,935.624	174,496.767	$l_1=1,l_2=0$	$d_1=1,d_2=0$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_2=1$
9	− 240,102.413	143,793.698	$l_1=1,l_2=0$	$d_1=1,d_2=0$	$k_1=1$	$n_1=1,n_2=0$	$j_1.k_1.v_2=1$
10	− 508,487.198	113,090.628	$l_1,l_2=0$	$d_1,d_2=0$	$k_1=1$	$n_1,n_2=0$	$j_1.k_1.v_2=1$

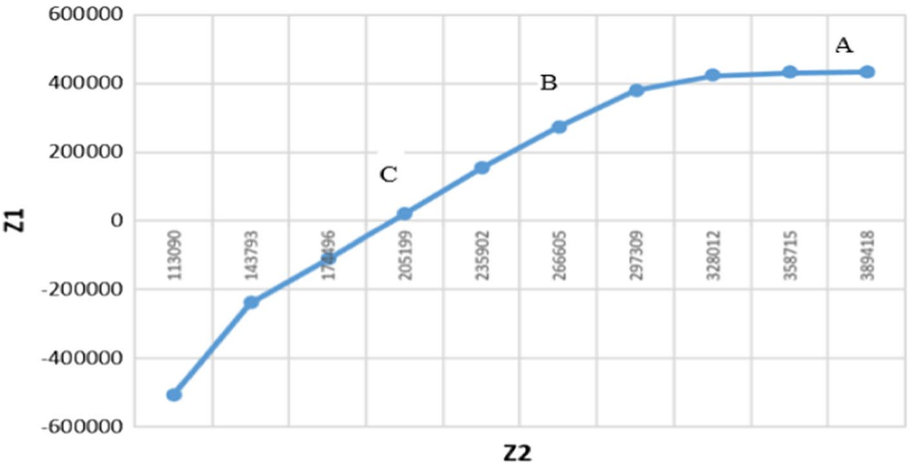


Fig. 2 Changes of the first objective to change the second objective in uncertainty conditions

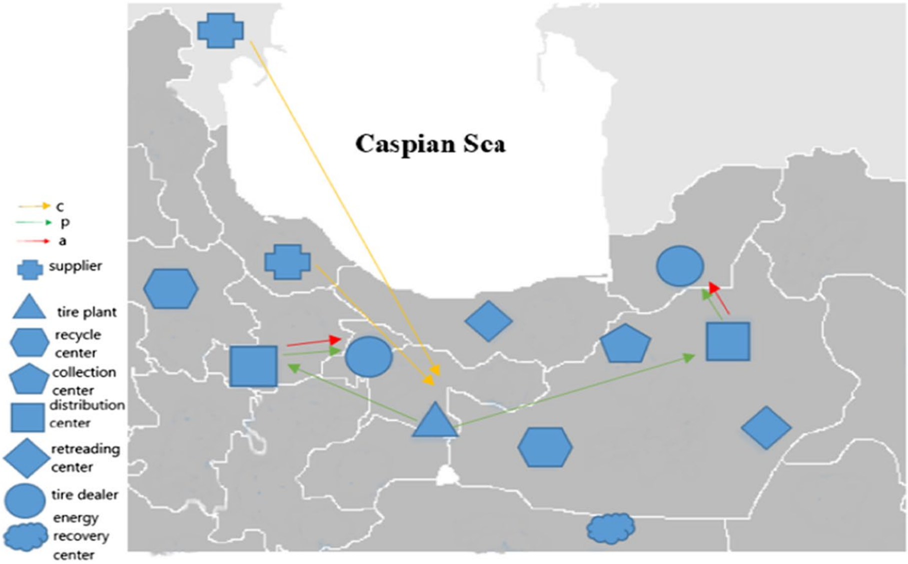


Fig. 3 Forward logistic network for product type 1

To consider the uncertainty of the model's parameters, 18 (3×3×2) scenarios are defined. Thus, for new and retreaded tires there are three modes; two modes for the return rate of the products are considered. Data related to the demand for retreading and new tires are uncertain with an increase of 10% and a reduction of 20% from the previous data. The probability of the occurrence of each scenario is given in Table 3.

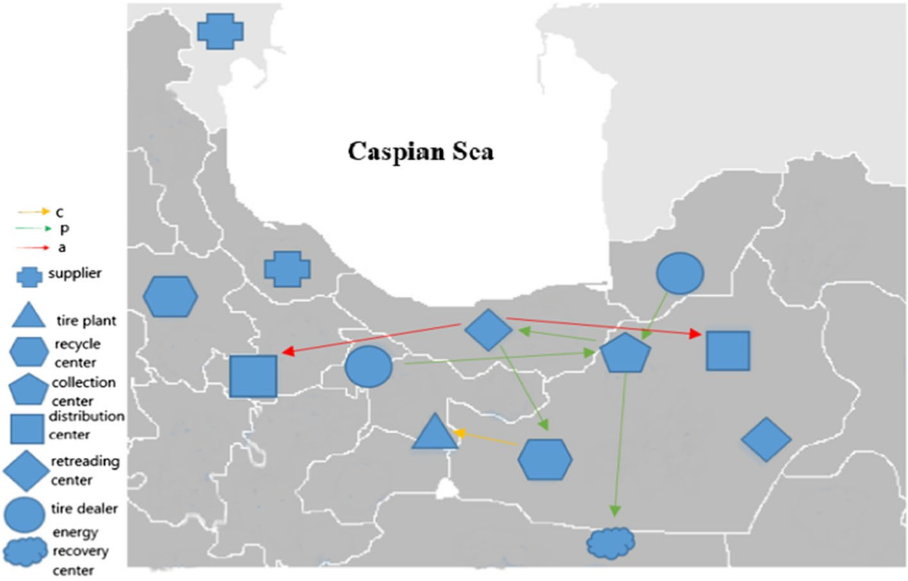
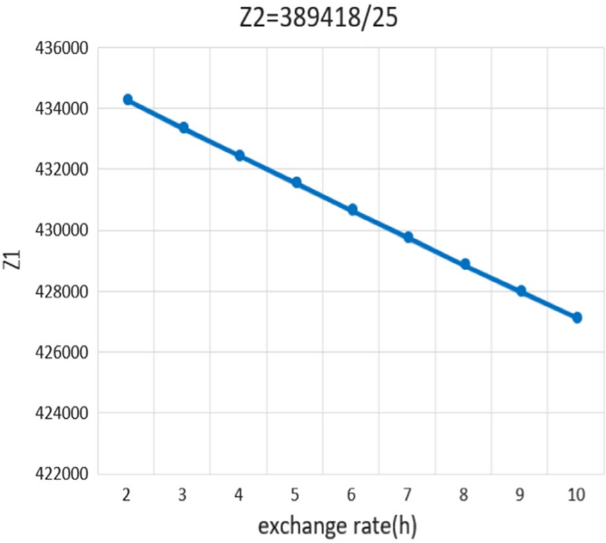


Fig. 4 Reverse logistic network for product type 1

Fig. 5 Changes in the first objective relative to the exchange rate (point A in Fig. 2)



7 Sensitivity analysis

This section examines the effects of essential parameters such as the exchange rate and customs duty rates on the proposed mathematical model. Based on the decision maker's view, the importance of the objective functions may differ. The sensitivity analysis was performed based on three points (points A, B, and C), as indicated in Fig. 2. In this study,

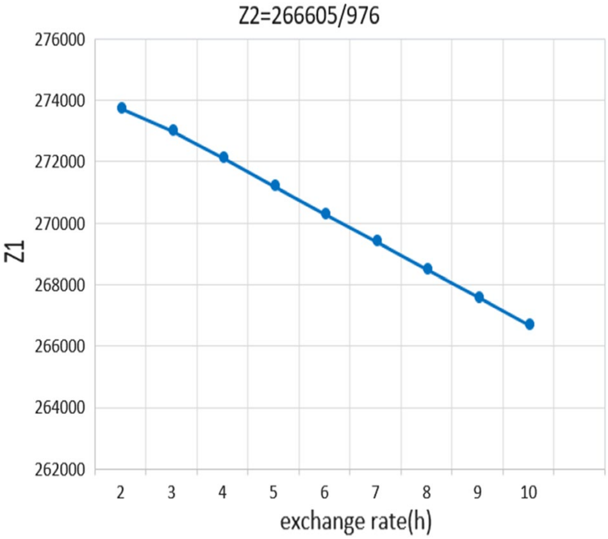


Fig. 6 Changes in the first objective relative to the exchange rate (see point B in Fig. 2)

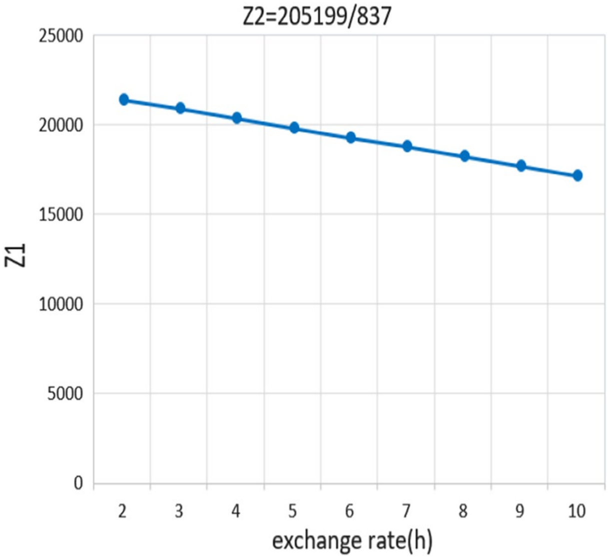


Fig. 7 Changes in the first objective relative to the exchange rate of money (point C in Fig. 2)

with an increase and decrease in the customs duty and exchange rates, the formulation is resolved (Figs. 3, 4). After each run, the values obtained from the first objective function are represented in Figs. 5, 6, 7 related to the exchange rate. It is clear that as the rate rises, the profit decreases. Therefore, the existence of an unsustainable economy in the country will be a risk to the global supply chain. Similarly, by analyzing sensitivity to customs duties, presented in Figs. 8, 9, 10, similar results are obtained. From a management perspective, national decisions about customs duties can affect organizational profit and decision making.

Fig. 8 Changes to the first objective relative to the rate of customs duties (point A in Fig. 2)

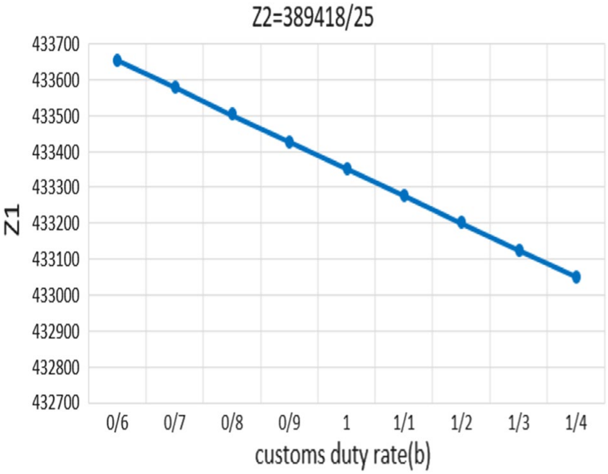


Fig. 9 Changes to the primary objective relative to the rate of customs duties (point B in Fig. 2)

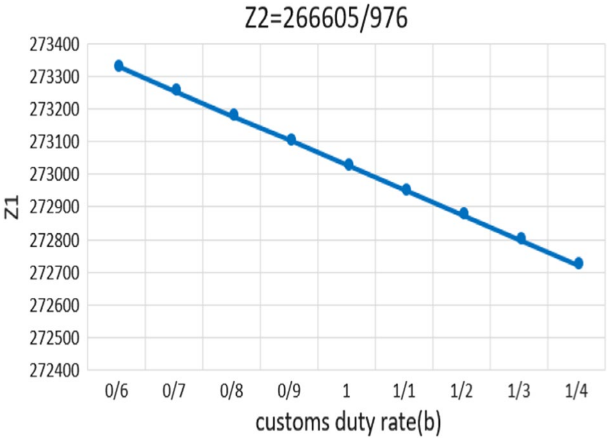
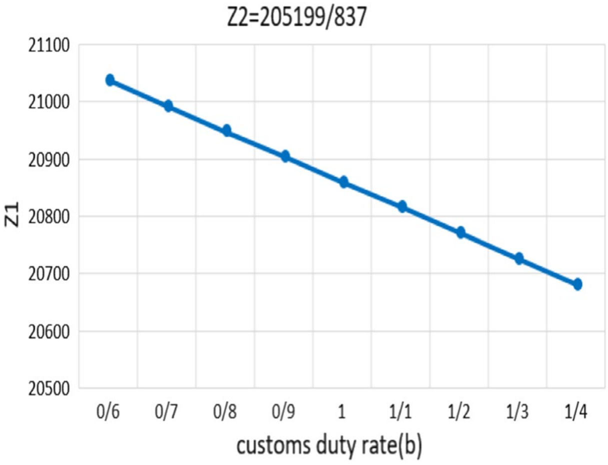


Fig. 10 Changes to the first objective relative to the rate of customs duties (point C in Fig. 2)



8 Conclusions and future guides

In the current study, a MILP formulation has been used in order to study a closed-loop SCND with a two-objective function, i.e., maximizing profit and minimizing Eco-indicator 99 in a multi-product, multi-period, and multi-echelon formulation for tires. In this mathematical formulation, the constraints of supplying raw materials by external suppliers, shortage, and uncertainty are included. This proposed formulation was tested using a case study inspired by a tire industry in Tehran, Iran. In this research, it is observed that an optimal network with global factors can be very different, because the formulation is sensitive to customs duty and exchange rates. Both factors are related to economic, political, and other important national issues, and without considering the limitations of supplying raw materials by external suppliers, profits would increase by about 12%. On the other hand, by comparing the output of the model in the deterministic and stochastic modes, it can be concluded that not only the final profit rate in those two modes is different, but also the facilities that open and even the CPU solution time are different.

The following suggestions are given for future studies: Considering uncertainty in most of the parameters of the problem, the model is closer to reality and can be more reliable than the model output. If the size of the problem increases, GAMS 24.0.1 software cannot be solved and the solution time will increase; thus, there is an undeniable need to use metaheuristic and heuristic methods. Considering factors such as disturbances and failures in the components of the chain, as well as considering the lead time, is a significant element that can be aimed. The model can also be developed with consideration of external customers and tire imports, along with other important international factors such as income tax.

Appendix

The nomenclature can be defined as follows.

Sets:

a	Retreaded tire types, $a = 1,\ldots,A$	p	A new brand of tire types, $p = 1,\ldots,P$
i	New tire factories, $i = 1,\ldots, I$	c	Raw material or component type, $c = 1,\ldots,C$
r	Tire dealers, $r = 1,\ldots,R$	j	Initial collection centers, $j = 1,\ldots, J$
n	Potential locations for tire recycling factories, $n = 1,\ldots,N$	d	Potential locations for distribution points, $d = 1,\ldots,D$
k	Potential locations for centralized return sites, $k = 1,\ldots,K$	l	Potential locations for retreading factories, $l = 1,\ldots,L$
t	Periods in the planning horizon, $t = 1,\ldots,T$	w	Paper mills, thermoelectric factories, or cement kilns, $w = 1,\ldots,W$
m	External and internal suppliers	v	Vehicle types, $v = 1,\ldots,V$
s	Scenarios, $s = 1, \ldots, S$	mp	External suppliers
Z	Countries where suppliers are located		

Parameters

$F1_{lt}$	Cost of initial setup for l at the start of t
$F2_{dt}$	Cost of initial setup for d at the start of t
$F3_{kt}$	Cost of initial setup for k at the start of t
$F4_{nt}$	Cost of initial setup for n at the start of t
$Sl1_p$	Discount on the unit sale price of new tire type p for the tire dealer in case of tire return
$Sl2_p$	Sale price of unit for new tire type p for the tire dealer without any tire return
$Sl3_a$	Sale price of unit for retreaded tire type a for the tire dealer for secondary markets
$Sl4_p$	Sale price of unit for waste tire type p to cement/thermoelectric factories
$SL5c$	Sale price of unit for recycled material type c to external factories for third-party usages
$OC1_l$	Seasonal, operational, and rental cost of l
$OC2_d$	Seasonal, operational, and rental cost of d
$OC3_k$	Seasonal, operational, and rental cost of k
$OC4_n$	Seasonal, operational, and rental cost of n
PC_{pi}	Cost of production per unit of tire type p in i
RTC_{plb}	Cost of remanufacture per unit of used tire type p in l
RC_{pnb}	Cost of recycling per unit of used tire type p in n
PUC_{cmz}	Cost of purchasing per kilogram of material type c from m in z
h_z	Exchange rate of z
b_{cmz}	Customs duty rate of material type c from m in z
$ƛ$	Factor supply of raw materials by external suppliers
$TC1_{av}$	Transport cost of unit for a per kilometer by vehicle type v
$TC2_{czv}$	Transport cost of unit for c between suppliers and manufacturers per kilometer in z by vehicle type v
$TC3_{cv}$	Transport cost of unit for tire type c between recycling factory and new tire factories per kilometer by vehicle type v
$LNFC_p$	Cost of landfill per unit of used tire type p
INC_p	Cost of burning per unit of used tire type p
TC_{pv}	Transport cost of unit of tire type p per kilometer by vehicle type v
CCp	Cost of collection per unit of used tire type p through the initial collection points
$IC1_{pi}$	Cost of inventory per unit of new brand tire type p in i
$IC2_{pd}$	Cost of inventory per unit of new brand tire type p in d
$IC3_{ad}$	Cost of inventory per unit of retreaded tire type a in d
$IC4_{pk}$	Cost of inventory per unit of waste tire type p in k
$IC5_{ci}$	Cost of inventory per kilogram of material c in i
Cd_{rpt}	Cost of lost demand of r for new brand tire type p in t
$Cd1_{rat}$	Cost of lost demand of r for retreaded tire type a in t
$DE1_{prts}$	Demand of r for new brand tire type p in t for s
$DE2_{arts}$	Demand of r for retreaded tire type a in t for s
RE_{pjt}	Returned amount of used tire type p to j in t
α_{ps}	Return fraction of the demand for tire type p from tire dealers for s
p_s	Probability of s
β_p	Minimum requested fraction of used tire type p which satisfies the quality characteristics for the recycling process
d_p	Minimum disposal rates of used tire type p transported from k to disposal centers

$F1_{lt}$	Cost of initial setup for l at the start of t
O_{pl}	Recovery rate fraction at l for used tire type p
e	Fraction of disposed tires through burning
h_{cp}	Contribution of type c for type p (%)
$Ps1_{p}$	Unit storing capacity-consuming factor for type p
$Ps2_{a}$	Unit storing capacity-consuming factor for type a
Cs_{c}	Unit storing capacity-consuming factor for type c
Cap_{i}	Maximum production capacity of i
$Cap1_{l}$	Maximum remanufacturing capacity of l
$Cap2_{n}$	Maximum recycling capacity of n
$Tscap_{i}$	Maximum storage capacity of i at the start of each t
$MIcap1_{d}$	Storage capacity for d
$MIcap2_{k}$	Storage capacity for k
$Vcap_{v}$	Maximum transport capacity of type v
$MT1_{d}$	Minimum requested demand to establish d
$MT2_{k}$	Minimum requested demand to establish k
$MT3_{l}$	Minimum requested volume to establish l
$MT4_{n}$	Minimum requested volume to establish n
$N1_{ivt}$	Maximum number of vehicle type v for transportation from i in t
$N2_{dvt}$	Maximum number of vehicle type v for transportation from d in t
$N3_{rvt}$	Maximum number of vehicle type v for transportation from r in t
$N4_{jvt}$	Maximum number of vehicle type v for transportation from j in t
$N5_{kvt}$	Maximum number of vehicle type v for transportation from k in t
$N6_{lvt}$	Maximum number of vehicle type v for transportation from l in t
$N7_{nvt}$	Maximum number of vehicle type v for transportation from the n in t
$D1_{id}$	Distance between i and d
$D2_{dr}$	Distance between d and r
$D3_{rk}$	Distance between r and k
$D4_{jk}$	Distance between j and k
$D5_{kw}$	Distance between k and w
$D6_{kn}$	Distance between k and n
$D7_{kl}$	Distance between k and l
$D8_{ld}$	Distance between l and d
$D9_{ln}$	Distance between l and n
$D10_{ni}$	Distance between n and i
$D11_{miz}$	Distance between i and m in country z
$EI1_{cz}$	The Eco-indicator 99 score for purchasing per kilogram of type c from m in country z
$EI2_{c}$	The Eco-indicator 99 score for attainment per kilogram of type c through recycling
EIP_{pi}	The Eco-indicator 99 score for producing one unit of new brand tire type p in i
$EIRM_{pl}$	The Eco-indicator 99 score for remanufacturing one unit of used tire type p in l
$EIRC_{pn}$	The Eco-indicator 99 score for recycling one unit of used tire type p in n
$EIT1_{pv}$	The Eco-indicator 99 score for shipping one unit of tire type p per kilometer by v
$EIT2_{av}$	The Eco-indicator 99 score for shipping one unit of retreaded tire type a per kilometer by v
$EIT3_{cv}$	The Eco-indicator 99 score for shipping per kilogram of material type c per kilometer by v
$EIC1_{pv}$	The Eco-indicator 99 score for collecting one unit of used tire type p by dealers directly from the end users and transporting it by v

$F1_{lt}$	Cost of initial setup for l at the start of t
$EIC2_{pv}$	The Eco-indicator 99 score for collecting one unit of used tire type p by initial collection centers and transporting it by v
EIE_{pk}	The Eco-indicator 99 score for end-of-life processing for one unit of scrap tire type p at k
EIR_{pw}	The Eco-indicator 99 score for incinerating one unit of used tire type p in cement kiln/thermo-electric factory w
EII_p	The Eco-indicator 99 score for incinerating one unit of waste tire type p at disposal centers
EIL_p	The Eco-indicator 99 score for land filling one unit of waste tire type p at disposal centers
$EIW1_d$	The Eco-indicator 99 score for storing/warehousing operations of d
$EIW2_k$	The Eco-indicator 99 score for storing/warehousing operations of k

Decision variables

$Y1_{lt}$	1 if a retreading factory is established at l in t; 0 otherwise
$Y2_{dt}$	1 if a distribution point is established at d in t; 0 otherwise
$Y3_{kt}$	1 if a centralized return point is established at k in t; 0 otherwise
$Y4_{nt}$	1 if a tire recycling factory is established at n in t; 0 otherwise
$Y5_{jkvt}$	1 if j is allocated to k with vehicle type v; 0 otherwise
Q_{pits}	Amount of new brand tire type p manufactured in new tire factory i during t for scenario s
RTR_{plts}	Amount of used tire type p retreaded in l during t for scenario s
REC_{pnts}	Amount of used tire type p recycled in tire recycling factory n during t for scenario s
Qp_{cmivts}	Quantity of purchased material type c transported to new tire factory i from m by v in t for scenario s
Qs_{cnts}	Quantity of recycled material type c sold by the tire recycling factory n in t for third-party applications for scenario s
Ud_{prts}	Amount of lost demand for tire dealer r on new brand tire type p in t for scenario s
$Ud1_{arts}$	Amount of lost demand for tire dealer r on retreaded tire type a in the t for scenario s
$X1_{pidvts}$	Amount of new brand tire type p transported from new tire factory i to d by v in t for scenario s
$X2_{pdrvts}$	Amount of new brand tire type p transported from d to r by v in t for scenario s
$X3_{adrvts}$	Amount of retreaded tire type a transported from d to r by v in t for scenario s
$X4_{prkvts}$	Amount of used tire type p transported from r to k by v in t for scenario s
$X5_{pkwvts}$	Amount of used tire type p transported from k to cement kiln w by vehicle type v in t for scenario s
$X6_{pknvts}$	Amount of used tire type p transported from k to n by v in t for scenario s
$X7_{pklvts}$	Amount of used tire type p transported from k to l by v in t for scenario s
$X8_{aldvts}$	Amount of retreaded tire type a transported from l to d by v in t for scenario s
$X9_{plnvts}$	Amount of non-remanufactured tire type p transported from l to n by v in t for scenario s
$X10_{cnivts}$	Quantity of recycled material type c transported from n to i by v in t for scenario s
$I1_{pits}$	Inventory level of new brand tire type p at new tire factory i in t for scenario s
$I2_{pdts}$	Inventory level of new brand tire type p at d in t for scenario s
$I3_{adts}$	Inventory level of retreaded tire type a at d in t for scenario s
$I4_{pkts}$	Inventory level of used tire type p at k in t for scenario s
$I5_{cits}$	Inventory level of material type c at new tire factory i in t for scenario s

References

Abdolazimi, O., Esfandarani, M. S., Salehi, M., & Shishebori, D. (2020). Robust design of a multi-objective closed-loop supply chain by integrating on-time delivery, cost, and environmental aspects, case study of a Tire Factory. *Journal of Cleaner Production*, *264*, 1–15.

Akbarimehr, D., Aflaki, E., & Eslami, A. (2019). Experimental investigation of the densification properties of clay soil mixes with tire waste. *Civil Engineering Journal, 5*(2), 363–372.

Boronoos, M., Mousazadeh, M., & Torabi, S. A. (2020). *A robust mixed flexible-possibilistic programming approach for multi-objective closed-loop green supply chain network design* (pp. 1–28). Development and Sustainability: Environment.

Brige, J. R., & Louveaux, F. (2011). Introduction to stochastic programming. Springer, pp. 85–145.

Cabalar, A. F., & Karabash, Z. (2015). California bearing ratio of a sub-base material modified with tire buffings and cement addition. *Journal of Testing and Evaluation, 43*(6), 1279–1287.

Cohen, M. A., & Lee, H. L. (2020). Designing the right global supply chain network. *Manufacturing & Service Operations Management*, https://doi.org/10.1287/msom.2019.0839.

Debo, L. G., & Wassenhove, L. N. (2005). Tire recovery: The retread co case. *Managing Closed-Loop Supply Chain, 4*(2), 119–128.

Dehghanian, F., & Mansouri, S. (2009). Designing sustainable recovery network of end-of-life products using genetic algorithm. *Resources, Conservation and Recycling, 53*(10), 559–570.

Fathollahi-Fard, A. M., Hajiaghaei-Keshteli, M., & Mirjalili, S. (2018). Hybrid optimizers to solve a tri-level programming model for a tire closed-loop supply chain network design problem. *Applied Soft Computing, 62*, 328–346.

Ferrao, P., Ribeiro, P., & Silva, P. (2008). A management system for end-of-life tires: A Portuguese case study. *Waste Management, 28*(3), 604–614.

Gusmerotti, N. M., Corsini, F., Borghini, A., et al. (2019). Assessing the role of preparation for reuse in waste-prevention strategies by analytical hierarchical process: Suggestions for an optimal implementation in waste management supply chain. *Environment, Development and Sustainability, 21*, 2773–2792.

Hassanzadeh Amin, S., & Baki, F. (2017). A facility location model for global closed-loop supply chain network design. *Applied Mathematical Modelling, 41*, 316–330.

Hassanzadeh Amin, S., Zhang, G., & Akhtar, P. (2017). Effects of uncertainty on a tire closed-loop supply chain network. *Expert Systems with Applications, 73*(1), 82–91.

Karabash, Z., & Cabalar, A. F. (2015). Effect of tire crumb and cement addition on triaxial shear behavior of sandy soils. *Geomechanics and Engineering, 8*(1), 1–15.

Koberg, E., & Longoni, A. (2019). A systematic review of sustainable supply chain management in global supply chains. *Journal of Cleaner Production, 207*, 1084–1098.

Lee, S., Park, S. J., & Seshadri, S. (2017). Plant location and inventory level decisions in global supply chains: Evidence from Korean firms. *European Journal of Operational Research, 262*(1), 163–179.

Liu, S., & Papageorgiou, L. G. (2013). Multi-objective optimisation of production, distribution and capacity planning of global supply chains in the process industry. *Omega, 41*(2), 369–382.

Mavrotas, G. (2009). Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. *Applied Mathematics and Computation, 213*(2), 455–465.

Mavrotas, G., & Florios, K. (2013). An improved version of the augmented ε-constraint method (AUGMECON2) for finding the exact Pareto set in multi-objective integer programming problems. *Applied Mathematics and Computation, 219*(18), 9652–9669.

Meixell, M. J., & Gargeya, V. B. (2005). Global supply chain design: A literature review and critique. *Transportation Research Part E: Logistics and Transportation Review, 41*(6), 531–550.

Panagiotidou, S., & Tagaras, G. (2005). End-of-life tire recovery: The Thessaloniki initiative. *Managing Closed-Loop Supply Chain, 6*(1), 183–193.

Pedram, A., Yusoff, N. B., Udoncy, O. E., Mahat, A. B., Pedram, P., & Babalola, A. (2017). Integrated forward and reverse supply chain: A tire case study. *Waste Management, 60*, 460–470.

Pishvaee, M. S., & Razmi, J. (2012). Environmental supply chain network design using multi-objective fuzzy mathematical programming. *Applied Mathematical Modelling, 36*(8), 3433–3446.

Rezaei, S., & Maihami, R. (2019). *Optimizing the sustainable decisions in a multi-echelon closed-loop supply chain of the manufacturing/remanufacturing products with a competitive environment* (pp. 1–27). Development and Sustainability: Environment.

Sahebjamnia, N., Fathollahi Fard, A. M., & Hajiaghaei-Keshteli, M. (2018). Sustainable tire closed-loop supply chain network design: Hybrid metaheuristic algorithms for large-scale networks'. *Journal of Cleaner Production, 196*, 273–296.

Sasikumar, P., Kannan, G., & Haq, A. N. (2010). A multi-echelon reverse logistics network design for product recovery- a case of truck tire remanufacturing. *The International Journal of Advanced Manufacturing Technology, 49*(9), 1223–1234.

Shakhsi-Niaei, M., & Esfandarani, M. S. (2019). Multi-objective deterministic and robust models for selecting optimal pipe materials in water distribution system planning under cost, health, and environmental perspectives. *Journal of Cleaner Production*, *207*, 951–960.

Shi, J., Zhou, J., & Zhu, Q. (2019). Barriers of a closed-loop cartridge remanufacturing supply chain for urban waste recovery governance in China. *Journal of Cleaner Production, 212*, 1544–1553.

Subulan, K., Tasan, A. S., & Baykasoglu, A. (2015). Designing an environmentally conscious tire closed-loop supply chain network with multiple recovery options using interactive fuzzy goal programming. *Applied Mathematical Modelling, 39*(9), 2661–2702.

Tanzadeh, G., & Haghighat, A. (2012). Application of tire waste powder recycling in crude oil recycling. In: *First international conference and sixth national conference on waste management*, Mashhad, Vol. 6 (2), pp. 18–26

Yadav, J. S., & Tiwari, S. K. (2019). The impact of end-of-life tires on the mechanical properties of fine-grained soil: A review. *Environment Development and Sustainability, 21*, 485–568.

Yıldızbaşı, A., Öztürk, C., Efendioğlu, D., & Bulkan, S. (2020). Assessing the social sustainable supply chain indicators using an integrated fuzzy multi-criteria decision-making methods: A case study of Turkey. *Environment, Development and Sustainability*, pp.1–36

Zerang, E. S., Taleizadeh, A. A., & Razmi, J. (2018). Analytical comparisons in a three-echelon closed-loop supply chain with price and marketing effort-dependent demand: Game theory approaches. *Environment, Development and Sustainability, 20*(1), 451–478.