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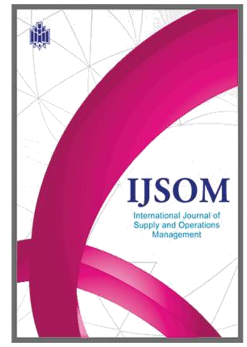

Sustainable Tire Closed-Loop Supply Chain Design under Uncertain Return and Demand

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Abstract

Each year, millions of tires that have reached their end of life are either buried or burned, both of which harm the environment through polluting the air and groundwater. Companies need to consider their social responsibility, including employment and regional development, and the environmental impact of their activities when making strategic and operational decisions. This study addresses the closed-loop supply chain (CLSC) design problem with regard to the dimensions of sustainability. The options of retreading, recycling, and energy recovery, along with the use of green technologies are considered to minimize environmental impacts. The proposed decision approach uses Life cycle assessment (LCA)-based social indicators to model its social impacts, along with the use of eco-indicator 99 as a method of assessing environmental impacts. The developed mathematical model turns out to be a multi-objective, mixed-integer linear programming (MOMILP) model that considers population density and unemployment rate in the social dimension. The model is solved using the Lp-metric method and CPLEX solver. A scenario-based approach is used to address the uncertainty in demand and the return of worn-out tires. The results show to which extent considering social sustainability, along with uncertainties in demand and return, impacts location and technology selection decisions in the tire CLSC design problem. Besides, the economic and environmental dimensions are also affected when considering social indicators, because of relocation and changes in the distances between the various supply chain centers, which in turn results in changes in costs and pollutant emissions.

Keywords: Tire Closed-Loop Supply Chain; Sustainability; Life Cycle Assessment; Stochastic Programming; Lp-Metric.

1. Introduction

By increasing the awareness in the society about environmental and social challenges, many companies encounter increasing pressure from customers, policymakers, and environmentalist groups to pay more attention to the environmental and social impacts of their activities (Rao et al., 2015; Khot & Thiagarajan, 2024). Sustainable supply chain management is a complex task that entails various activities, such as managing the forward flow of materials and finished products from suppliers to consumers, as well as the reverse flow of used products from the consumers to renovation centers, such as repair, recycling, remanufacturing, and energy recovery. This task addresses the three pillars of sustainability, namely economic, environmental, and social factors as sustainable development goals (SDGs) (Barbosa-Póvoa et al., 2018). The World Commission on the Environment and Development (WCED) defines sustainable development as "the use of resources with the aim of meeting current needs without compromising the

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ability of future generations to meet their needs". Sustainable development has become a primary objective for many countries around the world and is only achievable through a balance between human activities and their environment. Companies strive to ensure that their industrial activities have minimum negative social and environmental impacts while maximizing profits (Eskandarpour et al., 2015; Kannan, 2018). Designing a sustainable CLSC is a way for businesses to fulfill their commitment to the SDGs (Zhang et al., 2018; Fathollahi-Fard et al., 2018).

In the tire supply chain, a significant amount of energy is consumed, and significant amounts of greenhouse gases are emitted, which can pollute the environment. Each year, millions of worn-out tires are disposed of, causing serious problems and severe damage to the environment. For example, the amount of worn-out or end-of-life (EOL) tires in Iran was estimated to be between 198,346 and 339,678 tons from 2003 to 2015, which equals 2.95 to 4.52 kg per capita per year. This rate has increased over the years, potentially causing serious damages to both environment and human health (Zarei et al., 2018). The chemicals in worn-out tires pollute the air and are harmful for human health. To address these issues, renovation methods have been developed over the past decades. Designing an efficient renovation network can significantly reduce the negative environmental and social impacts of products such as tires at the EOL. As a result of the growth in recycling technologies and environmental regulations, recyclable used products are transformed into raw materials that can be used for manufacturing new products. Hence, using green technologies plays a key role in realizing the SDGs (Amin et al., 2017; Khot & Thiagarajan, 2024).

The majority of existing studies on tire supply chain modeling have either focused on economic aspects while ignoring social and environmental aspects or have only considered the environmental aspect. Therefore, considering the social aspect in the tire CLSC network design is a major research gap. Industries in Iran are mainly located in large cities, which has led to unbalanced development and unregulated immigration to these regions. It is therefore preferable to establish industries in regions with higher unemployment rates and lower population densities. In this study, all three pillars of sustainability are considered, and the LCA approach is utilized to estimate the environmental and social impacts in the tire supply chain network. Assessing environmental and social impacts along with economic benefits is among the important challenges in designing supply chains. LCA approach is useful in identifying social and environmental measures, analyzing different phases of the product life cycle, and estimating the overall environmental impact of products (Amin et al., 2017).

The main objective of this study is to determine the optimal design of a tire CLSC network, which includes the optimal location of facilities, optimal green technology selection, optimal operations planning (such as the assignment of returned tires to renovation centers), and the optimal inventory levels for products and raw materials while considering the three dimensions of sustainability. To achieve this aim, a multi-objective, scenario-based mathematical programming model is designed and solved. The findings of this study could provide useful insights for supply chain managers in the tire manufacturing industry.

With the integrated location-inventory model featured with uncertain demand and return considering sustainability in the tire CLSC, the following research questions are addressed in our work:

1) What is the optimal design of sustainable tire CLSC network?

2) What indicators should be considered in the social dimension?

3) How should uncertain parameters, such as demand for new products and the return rate of used products, be dealt with in designing sustainable tire CLSC network?

4) To what extent does each sustainability dimension affect the others?

5) What is the optimal operational planning considering the three dimensions of sustainability?

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature to identify the research gaps. In Section 3, the problem under study is described, and the sustainable CLSC mathematical model, including assumptions, variables, and parameters, is presented in Section 3. A detailed description of the case study, solution method, sensitivity analysis, and managerial implications is presented in Sections 4-7, respectively. In Section 8, the conclusions and suggestions for future research are presented.

2. Literature Review

2.1. Environmental dimension

Different indicators have been proposed in the literature for measuring environmental impacts. The most widely used indicators are carbon dioxide (CO2) emissions (e.g., Zhalechian et al., 2016; Allaoui et al., 2018; Taleizadeh et al., 2019; Alizadeh et al., 2019; Yun et al., 2020), greenhouse gas emissions (Chen & Andresen, 2014; Yue et al., 2014; Osmani & Zhang, 2017; Van Nguyen et al., 2016), Recipe Index (Ghaderi et al., 2018; Mota et al., 2018; Sahebjamnia et al., 2018), eco-indicator 99 (Subulan et al., 2015; Pishvaee et al., 2014; Feitó-Cespón et al., 2017), fuel consumption and energy loss (Zhalechian et al., 2016), resource constraints (Azadeh & Arani, 2016), climate change, use of water resources, use of land, and the reduction of fossil fuels (Rohmer et al., 2019), and carbon cost (Kumar et al., 2020). A review of the literature shows that most of the related studies have limited environmental indicators to greenhouse gas and CO2 emissions. However, each product has a different environmental impact during its life cycle, and there is a need for a broader life cycle perspective. LCA, with a cradle-to-grave perspective, provides a suitable framework for measuring the environmental impacts of a product by focusing on the entire life cycle of that product. LCA is a comprehensive method that can assess environmental impacts based on both midpoints and endpoints and can provide a single final environmental score. As a modeling technique, LCA has been applied extensively in the literature (Pishvaee et al., 2014). Eco-indicator is an LCA tool that assesses the environmental impact of a product by calculating eco-indicator scores for the used materials and processes. Its main advantage is that it provides a unique final score that is easily interpretable (Lees, 2012).

2.2. Social indicators

Over the past 20 years, a large number of research papers have been published to develop social indicators (Martínez-Blanco et al., 2014; Traverso et al., 2012). Major social indicators considered in the literature are job opportunities (Yue et al., 2014; Osmani & Zhang, 2017; Zhalechian et al., 2016; Allaoui et al., 2018; Van Nguyen et al., 2016; Mota et al., 2018), employee health damage (Chen & Andresen, 2014; Rohmer et al., 2019), employment, risk, and health indicators (Pishvaee et al., 2014), customer service level (Feitó-Cespón et al., 2017), days lost due to work injuries (Sahebjamnia et al., 2018; Taleizadeh et al., 2019; Yun et al., 2020), employment and regional economic development index (Ghaderi et al., 2018), job satisfaction (Moghaddam et al., 2019), and social benefits (Kumar et al., 2020). Because social effects are qualitative in nature, they are difficult to quantify, especially when social and environmental impacts interact widely (Santibañez-Aguilar et al., 2014; Mota et al., 2015). Due to their complexity and breadth, it can be extremely difficult to measure and control all the social impacts of processes. Several methods and guidelines have been developed by researchers to simplify the measurement and implementation of social responsibilities. The ‘‘Guidelines for Social Life Cycle Assessment of Products’’ (GSLCAP) has been selected as a method for assessing the social impacts because it covers all social issues, and since it has been developed based on LCA, it is compatible with measuring environmental issues based on LCA (Fontes et al., 2018). Social sustainability has been studied less frequently compared with environmental sustainability, probably because of the more complex nature of social sustainability (Fareeduddin et al., 2015). The most important social indicator that has been studied in the literature on designing supply chains with different approaches is employment. Recently published research increasingly recommends taking social considerations into account in supply chain network design as a future research direction (Yawar & Seuring, 2019).

2.3. Green technology

Green technology plays an essential role in achieving the objectives of sustainable development. While in the traditional view the objective of technology is to maximize the use of natural resources without considering its negative impacts on the natural world, green technologies consider the needs of humans and nature simultaneously and attempts to achieve an equilibrium between them (Lee et al., 2015; Farrokh et al., 2023). In addition to the positive environmental impacts, the use of green technologies in supply chains affects social objectives such as employment (Hansen et al., 2016). Green technologies utilize automated tire assembly equipment, which improves productivity and decreases waste and energy consumption. Conventional technologies for tire recycling and recovery consume significant amounts of energy and also have very complex processes; thus, they are not sustainable. In comparison, green technologies for tire renovation can decrease energy consumption and environmental pollution (Dobrotă et al., 2020). Researchs show that compliance with sustainability standards increases market share because customers, in general, are more willing to buy the products and services of companies that comply with these standards (Fathollahi-Fard et al., 2018).

2.4. Sustainable CLSC design and solution approaches

A useful approach to dealing with the sustainable CLSC design problem regarding the trade-off between conflicting aspects of sustainability is a multi-objective model, which normally leads to Pareto-optimal solutions. Many studies have applied multi-objective programming models to address the sustainable CLSC design problem. There are different solution methods for MOMILP problems, including interactive goal programming, ε-constraint, augmented ε-constraint, Lp-metric, weighted-sum, compromise methods, and metaheuristic algorithms. In this paper, the Lp-metric solution method is utilized. Lp-metric is a widely used, non-interactive optimization method for solving multi-objective models (Pasandideh et al., 2015).

In real world, supply chain design problems have an uncertain nature, especially because of uncertain demand for new products. In this study, in addition to product demand, the return rate of used tires is also uncertain. Subulan et al. (2015) proposed a MOMILP model for tire CLSC design problem in Turkey. They considered different renovation options, including recycling, remanufacturing, and energy recovery. Ghaderi et al. (2018) designed a multi-objective, robust, possibilistic programming model to address sustainable CLSC design for the switchgrass-based bioethanol industry under the uncertainty. The results showed that the desired environmental and social objectives are achievable only by increasing costs. Rohmer et al. (2019) investigated the sustainable food supply chain design problem, considering sourcing, processing, and transformation decisions. They developed a bi-objective linear programming model in which the objectives were to minimize costs and environmental impacts. Social sustainability was incorporated into their model as a health constraint. The social and environmental impacts were measured using GRI (Global Reporting Initiative). Renovation options for used products included remanufacturing, recycling, and disposing, depending on their quality. The results showed that using advanced technologies, despite entailing higher costs, can create job satisfaction and bring safety to employees in the fluorescent CFL light bulb supply chain. Yadollahinia et al. (2018) considered the tire forward and reverse supply chain design problem under uncertainty. They proposed a scenario-based MOMILP model and used robust optimization and revised multi-choice goal programming approaches to solve the problem. The objective functions included maximizing profit, maximizing customer satisfaction, and minimizing the distance between collection centers and customers. Shen et al. (2021) evaluated the impact of adopting clean technology and carbon emission taxes on textile and apparel supply chains, finding that increasing the environmental tax rates encourages manufacturers to invest in green technologies. Alinezhad et al. (2022) developed a sustainable CLSC network under fuzzy demand and returns. In this work, the carbon footprint is included in the profit function in terms of carbon tax. The fuzzy linear programming and Lp-metric method were then applied to address the uncertainties and bi-objectiveness of the model, respectively. Akbari-Kasgari et al. (2022) used backup suppliers as a resilience strategy to reduce the effects of earthquakes on mining operations in the copper network design problem. In each model, the environmental objective was to minimize water consumption and air pollutants, while the social objective was to maximize social desirability by considering security and unemployment rates. Additionally, the model is capable of improving the economic and social performances of the supply chain. Seydanlou et al. (2022) considered the sustainable CLSC design problem in the olive industry. They proposed a multi-objective optimization framework to make location, allocation, and inventory decisions for the problem. Based on the triple bottom line approach, the objectives of the optimization model were to minimize the total costs and carbon dioxide (CO2) emissions, and to maximize job opportunities. Deliktaş et al. (2023) proposed a two-stage stochastic model to optimize the supply chain network of EOL buildings and manage the debris resulting from their destruction. They offered a sustainable management strategy to control economic, pollution, land-use stress and population health factors. Goodarzian et al. (2023) considered the citrus supply chain design problem by integrating the production, distribution, inventory, recycling and location decisions, in which the triple bottom lines of sustainability, and circularity strategies are addressed. Accordingly, they proposed a novel MOMILP model to formulate a multi-period, multi-echelon sustainable citrus CLSC network design problem and then employed a ε-constraint approach to solve the developed model for small-sized problems. Mavi et al. (2023) developed a novel MOMILP model to design a sustainable closed-loop supply chain network in the tire industry. The objective of the model is to optimize the overall cost of the network while taking into account the environmental consequences associated with to the establishment of facilities, tire processing, and transportation. A potential strategy for mitigating sustainability issues involves the utilization of discarded tires through the recycling process. Manupati et al. (2024) developed a mixed-integer linear programming model to minimize the total cost of the proposed sustainable EOL tire remanufacturing supply chain network. They used a prediction model that evaluates the operational feasibility of vehicle allocation, and an evolutionary algorithm-based technique is employed to identify optimal facility locations, material flows among facilities, and demand distribution to individual automobiles for near-optimal solutions.

Table 1. Comparing the literature with regard to sustainable CLSC design problem

Study	Environmental aspects	Social aspects	Solution method	Industry	Approach
Pishvaee et al. (2014)	Eco-indicator 99	Job creation and health risk	Benders decomposition	Syringe recycling	Stochastic programing
Subulan et al. (2015)	Eco-indicator 99	-	An fuzzy goal programming	Tire manufacturing	Fuzzy programming
Azadeh & Arani (2016)	Resource limitations	Social Effect of Air Pollution	Weighted sum	Biodiesel supply chain	Robust-Stochastic programming
Feitó-Cespón et al. (2017)	Eco-indicator 99	Customer service level	ε-constraint	Plastic recycling	Stochastic programing
Sahebjamnia et al. (2018)	Recipe	Job opportunities, loss of days caused work's damages	Hybrid metaheuristic algorithms	Tire	-
Ghaderi et al. (2018)	Recipe	Job opportunities, Economic development of the region	Compromise methods	Switch grass-based bioethanol	Fuzzy programming
Taleizadeh et al. (2019)	Carbon emission	Job creation, lost days due to sickness and accidents, self-sufficiency	Compromise methods	Fluorescent CFL light bulbs	Fuzzy programming
Rohmer et al. (2019)	Climate change, Water use, Land use, Fossil fuel depletion	Dietary Health	ε-constraint	Food supply chain	-
Alizadeh et al. (2019)	Carbon tax	Social cost of carbon	Sample average approximation method	Petrochemical	Stochastic robust optimization
Yun et al. (2020)	CO2 emissions	Job opportunities, lost days due to damage to health, unemployed workers	Genetic algorithm	---	-
Akbari-Kasgari et al. (2022)	Water consumption and air pollutants	Security and unemployment rates	ε-constraint and weighted sum methods	Copper	-
Deliktaş et al. (2023)	Pollution	Land-use stress and population health factors	Fermatean fuzzy-based weighting approach	EOL buildings	Stochastic programming
Mavi et al. (2023)	CO2 emissions	-	Metaheuristic algorithms	Tire	-
Manupati et al. (2024)	CO2 emissions	Job opportunities,	Genetic algorithm	Tire	-
The study	Eco-indicator 99	Job opportunities, regional development	Lp-metric	Tire manufacturing	Stochastic programming

2.5. Research gaps

Table 1 indicates the position of this paper in the literature and compares the present study with relevant studies in terms of indicators considered in the social and environmental dimensions, solution approaches, the industry under study, and the approach to dealing with uncertainty. In the following, key research gaps identified in the literature are discussed. Most studies on tire CLSC design have considered the economic or environmental aspect only or combination of them, and very few studies have addressed these three aspects simultaneously. While the integration of the social sustainability into supply chains is still in its early stages, researchers have used mathematical modeling approaches in recent years to design supply chains according to sustainable development principles, mainly focusing on job opportunities, health indicators, customer satisfaction, customer service levels, employment, the days lost due to work injuries, the regional economic development index, job satisfaction, and social benefit waste. However, the literature still lacks a deep examination of other social dimensions in CLSCs. Regional factors can be defined based on the unemployment rate and population density in each region, while the vast majority of the existing studies on supply chain design have considered the job creation only in the social dimension. On the other hand, studies have not considered the influence of the LCA methods (e.g., Eco-Indicator 99) and other social dimensions in the optimized CLSC network structure and in the corresponding economic results obtained for the final supply chain network structure.

The literature extensively identifies the uncertainties related to the quantity, composition, quality, timing, and location of product returns in CLSCs and considers these uncertainties, for example, in capacity planning for recycling activities. However, the research literature has not investigated the impact of these uncertainties on the sustainability dimensions, location and green technology selection decisions in CLSC design problem as well as the use of scenario-based programming approaches to deal with them. These uncertainties regarding used product returns can reduce the potential for economies of scale in investments in sustainability initiatives, such as establishing green renovation centers. The contribution in the literature that provides answers to the research questions mentioned above can be summarized in the following way:

- Designing a tire CLSC network considering the economic, environmental and social aspects of sustainability.
- Eco-indicator 99 and LCA-based social indicators according to the GSLCAP standard have been applied to measure the social and environmental impacts, respectively.
- Evaluating the effect of green technology on the economic and social dimensions in the tire CLSC problem.
- Taking into account the regional factor, such as unemployment rate and population density in each region, along with the job creation with regard to the social dimension in addition to the economic and environmental aspects to move toward balanced development.
- Considering different renovation options in tire CLSC. These options are remanufacturing, recycling and energy recovery. In the reverse path, different quality levels of used tires are considered and they are assigned to different processes based on their quality.

3. Problem statement and mathematical formulation

3.1. Problem statement

During the production and usage of tires, a considerable amount of pollution is generated, and a large number of tires are disposed of each year. The disposal of used tires still has major environmental impacts. An important issue is how to deal with tires at their EOL. If this issue is handled efficiently, it can create valuable resources. Chemicals emitted from worn-out tires that are spread through air and water are harmful to human health and other living creatures. Traditional methods that are extensively applied to dispose of used tires around the world are not environmentally friendly. Therefore, the development of recovery methods has become a vital issue over the last decade (Govindan et al., 2014). Using green technologies can also be a very effective solution to decrease environmental impacts. Another major concern in a developing country like Iran is unemployment, and a large population has emigrated from less-developed, rural areas to cities in search of jobs (Roudi et al., 2017). It is better to establish industries in places with higher unemployment rates and lower population density. Creating job opportunities and decentralization should be considered in supply chain strategic decisions. Considering the above-mentioned environmental and social concerns, this paper tries to determine the optimal design of a tire CLSC network.

In the forward path of the tire CLSC under study, different types of new tires are produced and transported to distribution centers to meet demand. In the reverse or backward route, a portion of worn-out tires are collected from end-consumers. The collection method is as follows: Consumers sell used tires at the price approved by the municipality to collection centers. Finally, these tires are transported to the central collection department. The returned tires are placed in different categories. Tires suitable for reuse are transported directly to remanufacturing centers. The remaining tires are allocated to different sectors, such as energy recovery, recycling centers to produce raw materials, landfilling, and burning, depending on their condition. Raw materials are supplied from two sources: (1) external suppliers and (2) recycling centers. Materials such as granules and plastic powders, recycled metal, and polymer bitumen as the byproducts of recycling are sold. The schematic diagram of the tire CLSC network is illustrated in Fig. 1.

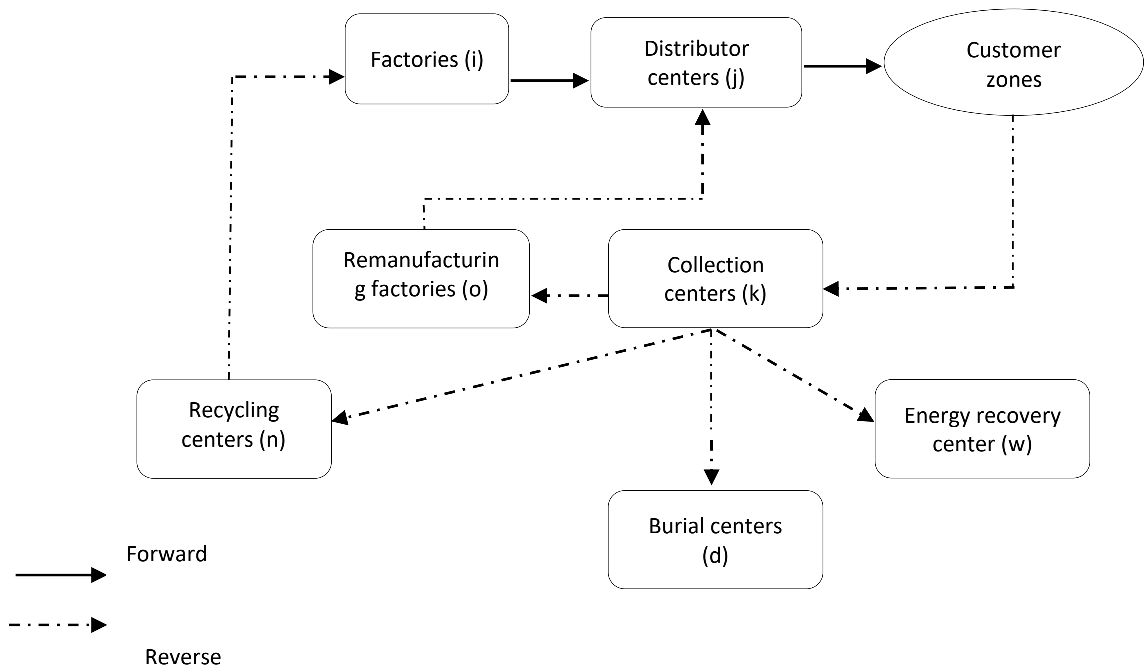


Figure 1. The tire CLSC map

Various recovery options are described in more detail below:

Retreading: By retreading, used tires are given renewed tread and sidewall rubber.

Recycling: During the recycling process, different materials such as rubber powders, steel wires, fibers, and tire granules are separated, which can be used for various purposes including construction, automotive, marine, additives to plastics, bituminous waterproofing, flooring, and artificial grass.

Energy Recovery: Another option is using scrap tires directly as fuel, which has several advantages such as reduced electricity generation costs, maximum heat recovery, and being environmentally friendly (Lebreton & Tuma, 2006).

Landfilling: This is the last option, and many countries have banned unrestricted landfills. In the supply chain under study, the number of tires transferred to landfills is severely limited.

4.1. The assumptions

The model is developed based on the following assumptions:

- Backorder and shortage are not allowed.
- Cost parameters remain constant over the planning horizon.
- Customer demand for new and retreaded tires and the return rate of tires are not exactly known.
- Only one green technology can be used in each plant.
- The capacity of warehouses is known in all sectors.
- The number of vehicles available for transporting the manufactured products is constant.
- The total initial inventory in different facilities is assumed to be zero.
- The amount of used tires sent to landfills is limited according to legal regulations.
- Planning periods are quarterly, and the problem is modeled for four periods (one year).
- To encourage consumers to return used tires, the factory offers discounts.

3.2. Notations

Indices, parameters, and variables needed to develop a mathematical model for the problem under study are presented in Appendix A.

3.3. The objectives and constraints

The objective function and the constraints of the proposed model for the sustainable tire CLSC design problem are presented in this subsection.

3.3.1. Maximizing the total profit

The objective function (1) in the proposed model is to maximize total profit in the sustainable tire CLSC design problem, which includes the revenue from selling finished products minus total costs:

$$Max\ f_1 = \sum_t \sum_s \left(TR^{t,s} - PRC^{t,s} - TC^{t,s} - CCP^{t,s} + HC^{t,s} - LPC^{t,s} \right) - FC \tag{1}$$

Where

$$TR^{t,s} = \Bigg[\sum_p pr^p.(1-\alpha^{p,t}).Dc^{p,t,s} + \sum_p pr'^p.(1-\alpha^{p,t}).Dc'^{p,t,s} + \sum_p (1-\beta).pr^p.\alpha^{p,t}.Dc^{p,t,s} + \sum_p (1-\beta).pr'^p.\alpha^{p,t}.Dc'^{p,t,s} + \sum_p pr''^p.Dw^{p,t,s} + \sum_c pn^c.Dn^{c,t,s} \Bigg] \tag{1.1}$$

$$FC = \left(\sum_i fm_i.M_i + \sum_o fl_o.L_o + \sum_j fd_j.D_j + \sum_k fc_k.C_k + \sum_n fr_n.R_n \right) + \left(\sum_e fcf_e.yf_e + \sum_{e'} fcl_{e'}.yr_{e'} + \sum_{e''} fcn_{e''}.ys_{e''} \right) \tag{1.2}$$

$$PRC^{t,s} = \left(\sum_i \sum_e \sum_p cm_e^p .X_i^{p,t,s} \right) + \left(\sum_k \sum_o \sum_p \sum_{e'} \sum_v cf_{e'}^p .Yf_{k,o,v}^{p,t,s} \right) + \left(\sum_k \sum_n \sum_p \sum_{e''} \sum_v cr_{e''}^p .Yr_{k,n,v}^{p,t,s} \right) \tag{1.3}$$

$$\begin{aligned} TC^{t,s} = \Bigg(& \sum_i \sum_j \sum_p \sum_v pt_v^p .dmd_{i,j} .Xm_{i,j,v}^{p,t,s} + \sum_o \sum_j \sum_p \sum_v pt_v^p .d\,fd_{o,j} .Xf_{o,j,v}^{p,t,s} + \\ & \sum_k \sum_w \sum_p \sum_v pt_v^p .dcw_{k,w} .Dw^{p,t,s} + \sum_k \sum_n \sum_p \sum_v pt_v^p .dcr_{k,n} .Yr_{k,n,v}^{p,t,s} + \\ & \sum_k \sum_o \sum_p \sum_v pt_v^p .dcf_{k,o} .Yf_{k,o,v}^{p,t,s} + \sum_n \sum_i \sum_c \sum_v ct_v^c .drf_{n,i} .Zt_{n,i,v}^{c,t,s} + \\ & \sum_i \sum_k \sum_p \sum_v pt_v^p .dmc_{i,k} .\varepsilon .X_i^{p,t,s} + \sum_k \sum_d \sum_p \sum_v pt_v^p .dcd_{k,d} Yd^{p,t,s} \Bigg) \end{aligned} \tag{1.4}$$

$$CCP^{t,s} = \sum_k \sum_p cc^p .Y_k^{p,t,s} + \sum_p cc^p .q^{t,s} + \left(\sum_c cp^c .Z^{c,t,s} \right) \tag{1.5}$$

$$\begin{aligned} HC^{t,s} = & \sum_i \sum_p h^p .ILI_i^{p,t,s} + \sum_j \sum_p h^p \times (ILJ_j^{p,t,s} + ILJ'^{p,t,s}_j) + \sum_o \sum_p h^p .IL_o^{p,t,s} + \\ & \sum_p h^p \times (ailf^p + aild^p + aild'^p + aill^p) + \sum_k \sum_p h'^p .IK_k^{p,t,s} + \sum_p h'^p .ailc^p + \\ & \sum_i \sum_c hm^c .ICI_i^{c,t,s} + \sum_n \sum_c hm^c .ICN_n^{c,t,s} + \sum_c hm^c (ails^c + ailf'^c) \end{aligned} \tag{1.6}$$

$$\begin{aligned} LPC^{t,s} = & \left(\sum_p dis^p .Yd^{p,t,s} \right) + \sum_i \sum_p ch.X_i^{p,t,s} + \sum_k \sum_n \sum_p \sum_v ch.Yr_{k,n,v}^{p,t,s} + \\ & \sum_k \sum_0 \sum_p \sum_v ch.Yf_{k,o,v}^{p,t,s} + \sum_k \sum_p ch.Y_k^{p,t,s} \end{aligned} \tag{1.7}$$

The objective function (1) is composed of multiple items such as revenue from selling new tires and remanufactured tires to customers, selling used tires to energy recovery centers, and selling raw material (Eq. 1.1), fixed costs of establishing centers and implementing green technology in various centers (Eq. 1.2), costs of producing new tires and remanufactured tires, and recycling costs (Eq. 1.3), transportation costs between different facilities (Eq. 1.4), costs of collecting worn-out tires and raw materials purchasing costs (Eq. 1.5), holding costs of new tires, holding costs of used tires at collection centers, and raw material holding costs (Eq. 1.6), landfilling cost for burying worn-out tires and costs paid for the health and insurance of employees in each period (Eq. 1.7).

3.3.2. Minimizing the environmental impacts

The objective function (2) minimizes environmental impacts, such as damage to the ecosystem, human health, and the excessive use of resources in different parts of the supply chain network:

$$Min\ f_2 = \sum_t \sum_s \left(EI1^{t,s} + EI3^{t,s} + EI3^{t,s} \right) \tag{2}$$

Where

$$\begin{aligned} EI1^{t,s} = & \left(\sum_c EIP^c . Z^{c,t,s} \right) + \left(\sum_i \sum_e \sum_p EIA_e^p . X_i^{p,t,s} \right) + \\ & \left(\sum_i \sum_j \sum_p \sum_v EItr_v^p .dmd_{i,j} .Xm_{i,j,v}^{p,t,s} + \sum_o \sum_j \sum_p \sum_v EItr_v^p .dfd_{o,j} .Xf_{o,j,v}^{p,t,s} + \right. \\ & \sum_k \sum_w \sum_p \sum_v EItr_v^p .dcw_{k,w} .Dw^{p,t,s} + \sum_k \sum_n \sum_p \sum_v EItr_v^p .dcr_{k,n} .Yr_{k,n,v}^{p,t,s} + \\ & \sum_k \sum_o \sum_p \sum_v EItr_v^p .dcf_{k,o} Yf_{k,o,v}^{p,t,s} + \sum_i \sum_n \sum_c \sum_v EItr_v'^c .drf_{n,i} .Zt_{n,i,v}^{c,t,s} + \\ & \left. \sum_i \sum_k \sum_p \sum_v EItr_v^p .dmc_{i,k} .\varepsilon .X_i^{p,t,s} + \sum_k \sum_d \sum_p \sum_v EItr_v^p .dcd_{k.d} Yd^{p,t,s} \right) \end{aligned} \tag{2.1}$$

$$\begin{aligned} EI2^{t,s} = & \left(\sum_k \sum_p EIco^p .Y_k^{p,t,s} \right) + \left(\sum_k \sum_p EIpro^p .Y_k^{p,t,s} + \sum_i \sum_p EIpro^p \varepsilon .X_i^{p,t,s} \right) + \left(\sum_p EIb^p .Dw^{p,t,s} \right) \\ & + \left(\sum_k \sum_o \sum_p \sum_v \sum_{e'} EIre_{e'}^p .Yf_{k,o,v}^{p,t,s} \right) + \left(\sum_k \sum_n \sum_p \sum_v \sum_{e''} EIn_{e''}^p .Yr_{k,n,v}^{p,t,s} \right) + \left(\sum_p EIdis^p .Yd^{p,t,s} \right) \end{aligned} \tag{2.2}$$

$$\begin{aligned} EI3^{t,s} = & \sum_i \sum_p EIht^p .ILI_i^{p,t,s} + \sum_j \sum_p EIht^p .(ILJ_j^{p,t,s} + ILJ_j'^{p,t,s}) + \sum_o \sum_p EIht^p .IL_o^{p,t,s} + \\ & \sum_k \sum_p EIhr^p .IK_k^{p,t,s} + \sum_n \sum_c EIhm^c .ICN_n^{c,t,s} + \sum_i \sum_c EIhm^c .ICI_i^{c,t,s} \end{aligned} \tag{2.3}$$

The objective function is composed of multiple items, such as environmental impacts associated with the purchase of raw materials and new tire production as well as tire and raw material transportation (Eq. 2.1). It also includes the environmental impacts of collecting worn out tires, processing the collected tires at the collection center, using scrap tires as furnace fuel, retreading used tires, recycling scrap tires, and burying worn-out tires (Eq. 2.2). Additionally, it considers the environmental impacts of holding healthy tires, worn-out tires, and raw materials in the warehouse (Eq. 2.3).

3.3.3. Maximizing the social impacts

The objective function (3) in the proposed model is to maximize social impacts in the sustainable tire CLSC design problem:

$$Max\ f_3 = \omega_1 UR + \omega_2 ER - \omega_3 PD \tag{3}$$

Where

$$\mathrm{UR} = \left(\sum_i \mu f_i\ .M_i + \sum_j \mu d_j .D_j + \sum_o \mu r_o .L_o + \sum_k \mu c_k .C_k + \sum_n \mu s_n .R_n \right) \tag{3.1}$$

$$PD = \left(\sum_i \delta f_i .M_i + \sum_j \delta d_j .D_j + \sum_o \delta r_o .L_o + \sum_k \delta c_k .C_k + \sum_n \delta s_n .R_n \right) \tag{3.2}$$

$$\mathrm{ER} = \left(\sum_e jo_e .yf_e + \sum_{e'} jo'_{e'} .yr_{e'} + \sum_{e''} jo''_{e''} .ys_{e''} \right) \tag{3.3}$$

Since the nature of the three above value (*YR*, *PD*, *ER*) are not the same, we use three weights ($\omega_1, \omega_2, \omega_3$) to merge these into a single function (Eq. 3). The objective function is composed of multiple items, such as social impacts by taking into account the unemployment rate and the population density (Eq. 3.1 and 3.2), respectively. Equation (3.1) encourages the model to select locations in regions with higher unemployment rate, while Equation (3.2) seeks to establishing facilities in regions with lower population density and a higher need for development. Equation (3.3) is the employment rate created by the establishment of green technology in the tire manufacturing plant, the tire regeneration plant, and the recycling center, aligning with environmental and social objectives.

3.3.4. Constraints

The objective function is subject to the constraints formulated as follows:

$$X_i^{p,t,s} \le Cam^P \qquad \forall i, p, t, s \tag{4}$$

$$\sum_k \sum_v Yf_{k,o,v}^{p,t,s} \le Caf^{\,p} \qquad \forall o, p, t, s \tag{5}$$

$$\sum_k \sum_v Yr_{k,n,v}^{p,t,s} \le Car^{\,p} \qquad \forall n, p, t, s \tag{6}$$

$$\sum_i ILI_i^{p,t-1,s} + \sum_i X_i^{p,t,s} = \sum_i ILI_i^{p,t,s} + \varepsilon . \sum_i X_i^{p,t,s} + \sum_i \sum_j \sum_v Xm_{i,j,v}^{p,t,s} + ailf^{\,p} \quad \forall p,t,s \tag{7}$$

$$\sum_j ILJ_j^{p,t-1,s} + \sum_i \sum_j \sum_v Xm_{i,j,v}^{p,t,s} = \sum_j ILJ_j^{p,t,s} + Dc^{p,t,s} + aild^{\,p} \qquad \forall p,t,s \tag{8}$$

$$\sum_j ILJ'^{\,p,t-1,s}_j + \sum_o \sum_j \sum_v Xf_{o,j,v}^{p,t,s} = \sum_j ILJ'^{\,p,t,s}_j + Dc'^{\,p,t,s} + aild'^{\,p} \qquad \forall p,t,s \tag{9}$$

$$\sum_k IK_k^{p,t-1,s} + \varepsilon . \sum_i X_i^{p,t,s} + \sum_k Y_k^{p,t,s} = \sum_k IK_k^{p,t,s} + Dw^{p,t,s} + \sum_k \sum_n \sum_v Yr_{k,n,v}^{p,t,s} + \sum_k \sum_o \sum_v Yf_{k,o,v}^{p,t,s} + Yd^{\,p,t,s} + ailc^{\,p} \qquad \forall p,t,s \tag{10}$$

$$\sum_o IL_o^{p,t-1,s} + \sum_k \sum_o \sum_v Yf_{k,o,v}^{p,t,s} = \sum_o IL_o^{p,t,s} + \sum_o \sum_j \sum_v Xf_{o,j,v}^{p,t,s} + aill^{\,p} \quad \forall p,t,s \tag{11}$$

$$\sum_{n} ICN_{n}^{c,t-1,s} + \sum_{n}\sum_{e''} Zr_{n,e''}^{c,t,s} = \sum_{n} ICN_{n}^{c,t,s} + \sum_{n}\sum_{i}\sum_{v} Zt_{n,i,v}^{c,t,s} + Dn^{c,t,s} + ails^{c} \quad \forall c,t,s \tag{12}$$

$$\sum_{i} ICI_{i}^{c,t-1,s} + Z^{c,t,s} + \sum_{i}\sum_{n}\sum_{v} Zt_{n,i,v}^{c,t,s} = \sum_{i} ICI_{i}^{c,t,s} + \sum_{i}\sum_{p} We^{p}.\omega^{c,p}.X_{i}^{p,t,s} + ailf'^{c} \quad \forall c,t,s \tag{13}$$

$$\sum_{k}\sum_{n}\sum_{v}\sum_{p} We^{p}.\omega^{c,p}.Yr_{k,n,v}^{p,t,s} = \sum_{n}\sum_{e''} Zr_{n,e''}^{c,t,s} \quad \forall c,t,s \tag{14}$$

$$\sum_{i}\sum_{p} St^{p}.ILI_{i}^{p,t,s} \le CI \quad \forall t,s \tag{15}$$

$$\sum_{j}\sum_{p} St^{p}.(ILJ_{j}^{p,t,s} + ILJ'^{p,t,s}_{j}) \le CJ \quad \forall t,s \tag{16}$$

$$\sum_{k}\sum_{p} St^{p}.IK_{k}^{p,t,s} \le CK \quad \forall t,s \tag{17}$$

$$\sum_{o}\sum_{p} St^{p}.IL_{o}^{p,t,s} \le CO \quad \forall t,s \tag{18}$$

$$\sum_{i}\sum_{c} Sm^{c}.ICI_{i}^{c,t,s} \le CI' \quad \forall t,s \tag{19}$$

$$\sum_{n}\sum_{c} Sm^{c}.ICN_{n}^{c,t,s} \le CN \quad \forall t,s \tag{20}$$

$$\alpha^{p,t,s}.\left(Dc^{p,t,s} + Dc'^{p,t,s}\right) + q^{t,s} = \sum_{k} Y_{k}^{p,t,s} \quad \forall p,t,s \tag{21}$$

$$\sum_{p} EIdis^{p}\, Yd^{p,t,s} \le ro \quad \forall t,s \tag{22}$$

$$\sum_{i} M_{i} = 1 \tag{23}$$

$$\sum_{j} D_{j} = 1 \tag{24}$$

$$\sum_{k} C_{k} = 1 \tag{25}$$

$$\sum_{n} R_{n} = 1 \tag{26}$$

$$\sum_{o} L_{o} = 1 \tag{27}$$

$$\sum_{e} yf_{e} = 1 \tag{28}$$

$$\sum_{e'} yr_{e'} = 1 \tag{29}$$

$$\sum_{e''} ys_{e''} = 1 \tag{30}$$

$$X_i^{p,t,s}, Xm_{i,j,v}^{p,t,s}, Xf_{o,j,v}^{p,t,s}, Yr_{k,n,v}^{p,t,s}, IK_k^{p,t,s}, Yd^{p,t,s}, Y_k^{p,t,s}, Zr_{n,e''}^{c,t,s}, Z^{c,t,s}, Zt_{n,i,v}^{c,t,s}, ILI_i^{p,t,s}, ILJ_j^{p,t,s}, Yf_{k,o,v}^{p,t,s}, ICI_i^{c,t,s}, IL_o^{p,t,s}, ICN_n^{c,t,s}, ILJ'^{p,t,s}_j, q^{t,s} \geq 0 \tag{31}$$

$$M_i, L_o, D_j, C_k, R_n, yf_e, yr_{e'}, ys_{e''} \in \{0,1\} \tag{32}$$

Constraints (4)-(6) represent the total production capacity of manufacturing, remanufacturing, and recycling centers, respectively. Constraints (7)-(11) ensure the inventory balance for different types of new tires in manufacturing sites, new tires and remanufactured tires in distribution centers, used tires in collection centers, and remanufactured tires in remanufacturing centers in each period, respectively. Constraints (12) and (13) ensure the inventory balance for raw materials in recycling and manufacturing centers in each period, respectively. Constraint (14) computes the amount of recycled material produced from each type of tire. Constraints (15)-(18) are inventory capacity constraints in each center. Constraints (19) and (20) ensure that the inventory level of raw materials in each center does not exceed the capacity of the center's active warehouses. Constraint (21) indicates the amount of collected worn-out tires. Constraint (22) prevents the environmental impact of tire landfilling from exceeding the permissible limit. Constraints (23)-(27) prevent allocating more than one location to each center. Constraints (28)-(30) ensure that at most one technology is allocated to the related centers. Constraints (31) and (32) assure that corresponding variables are non-negativity and binary, respectively.

4. Case study

Barez industrial group is Iran's first tire manufacturing company, with plants located in the western region of Iran. Recently, the company has become more vulnerable to specific risks in sourcing critical raw materials. On the other hand, customers are reluctant to deliver their used tires to the company's collection centers for sustainability goals and instead usually deliver them to unauthorized centers. The company is committed to limiting its carbon emissions and improving social sustainability indices. To address these issues, the company's managers have decided to review their structure of its CLSC to achieve SDGs. The company plans to implement new recycling technologies to develop green recycling, remanufacturing, and recovery centers over a planning horizon of five periods. Based on the managers' assessments, its tire CLSC network includes two potential sites for new tire production plants, four potential sites for distribution centers, four potential sites for used tire collection centers, three potential remanufacturing sites for used tires, three potential sites for used tire recycling centers, three sites for cement kilns as energy recovery centers, and four centers for scrap landfills. These sites are located in different regions, each with varying fixed costs of establishing facilities and regional factors. The main plant produces four types of tires: those tires for automobiles, passenger buses, trucks, and agricultural and industrial trucks, as well as three types of raw materials: steel wires, polyamide yarns, and granules. The production planning periods are seasonal. There are two types of vehicles used for transportation, each with different capacities, costs, and environmental impacts. Additionally, there are three types of environmental protection technology available for the tire factory, two technologies at the tire remanufacturing factory, and two types of technology for the recycling center. Advanced environmental protection technology performs retreading and recycling efficiently and is environmentally friendly but entails higher costs. There is a trade-off between the investment cost of this technology and its environmental protection efficiency. Furthermore, advanced technologies reduce the number of low-skilled jobs due to higher automation levels, while simultaneously creating more jobs for highly skilled workers. Thus, they have a twofold impact on the job creation.

At the material purchasing stage, using recycled materials in production has less environmental impact than purchasing materials from external suppliers. During the transportation phase, although the cost of renting larger trucks is higher, these vehicles are more environmentally friendly. At the end of the collection phase, gathering tires from end-consumers incurs high expenses but helps protect the environment. The energy recovery phase in furnaces, including the retreading and recycling process, has a positive impact on the environment.

5. The model solutions

The data used to solve the mathematical model are provided in Appendix C. The environmental parameter data were collected based on the results of Corti and Lombardi (2004), and Subulan et al. (2015). Additionally, real operational data from 2017 to 2019 were collected from the supply chain under study. The LP-metric method, described in Appendix B, is applied to deal with the multi-objectivity of the model. The Lp-metric is a common method for solving multi-objective problems where there is trade-off between objectives. This means that improving one objective may result in the deterioration of other objectives. In the developed model, the parameters for customer demand and the rate of return of worn-out tires are uncertain. The scenario-based stochastic programming approach is used to deal with the uncertainty, considering different scenarios for various conditions. The scenarios for demand and return rates for worn-out tires are as follows:

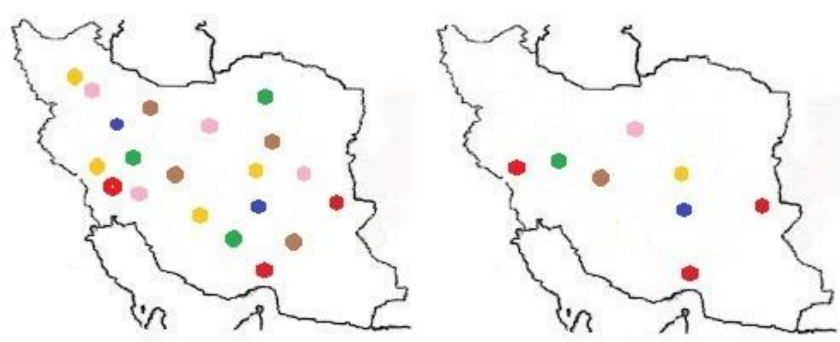
Scenario 1: Low demand and a low rate of return of worn-out tires (approximately 30% of worn-out tires are returned).

Scenario 2: Average demand and an average rate of return of worn-out tires (approximately 50% of worn-out tires are returned).

Scenario 3: High demand and a high rate of return of worn-out tires (approximately 70% of worn-out tires are returned).

The developed model is coded in GAMS 24.1.2 optimization software and solved using the CPLEX solver. All computations are performed on an Intel Core i5-2630 QM 2.00 GHz processor with 4 GB RAM.

Fig. 2 shows the candidate locations (Map A) and the optimal locations obtained (Map B).



(A) **(B)**

Distribution center O **Collection center O** **Remanufacturing centers O**

Recycling center O **Manufacturing centers O** **Energy recovery centers O**

Figure 2. Candidate locations (Map A) and the optimal locations (Map B) in the sustainable tire CLSC

The optimal values of the continuous variables under different scenarios for the planning horizon are obtained and presented in Figs 3-8. The solutions for these variables determine the optimal values of new tire production and the number of collected used tires. In addition, the optimal allocation of used tires to remanufacturing factories, recycling centers, energy recovery facilities, and landfills is determined. Inventory levels for new and used tires are computed to minimize inventory holding costs and environmental impacts. The model also determines the amount of purchased raw materials at the tire factory and the products and raw materials transported by each vehicle between established facilities in the supply chain.

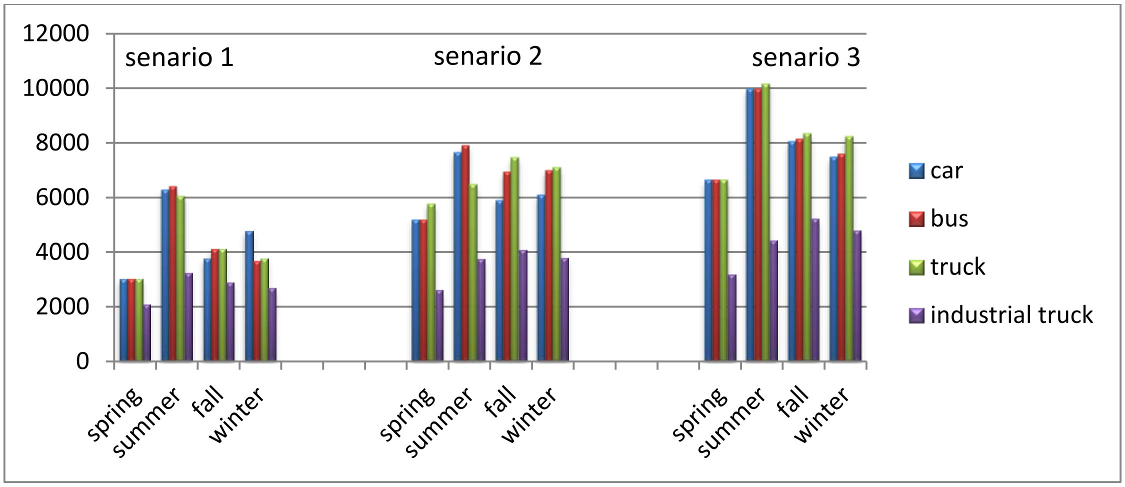


Figure 3. Number of new produced tire type *p* in tire factories in time period t under scenario *s* (unit)

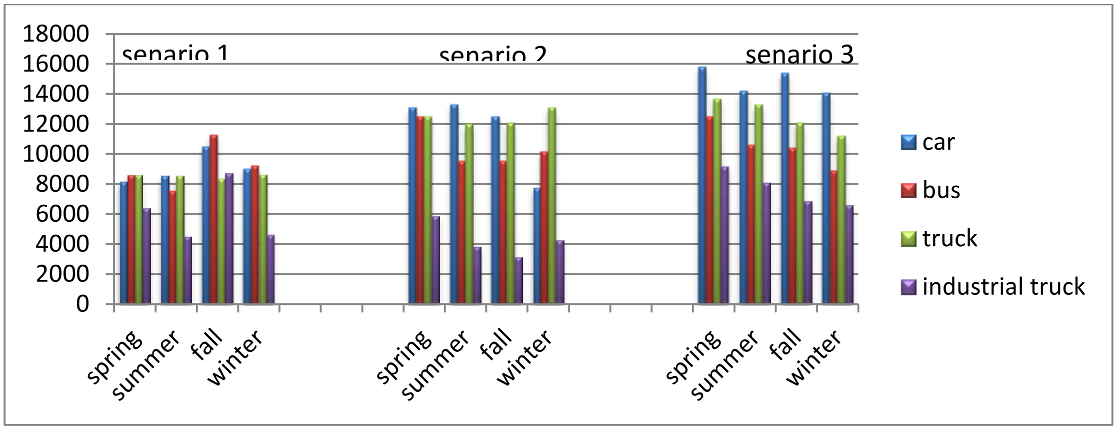


Figure 4. Number of used tire type *p* transported to remanufacturing factory in time period t under scenario *s*

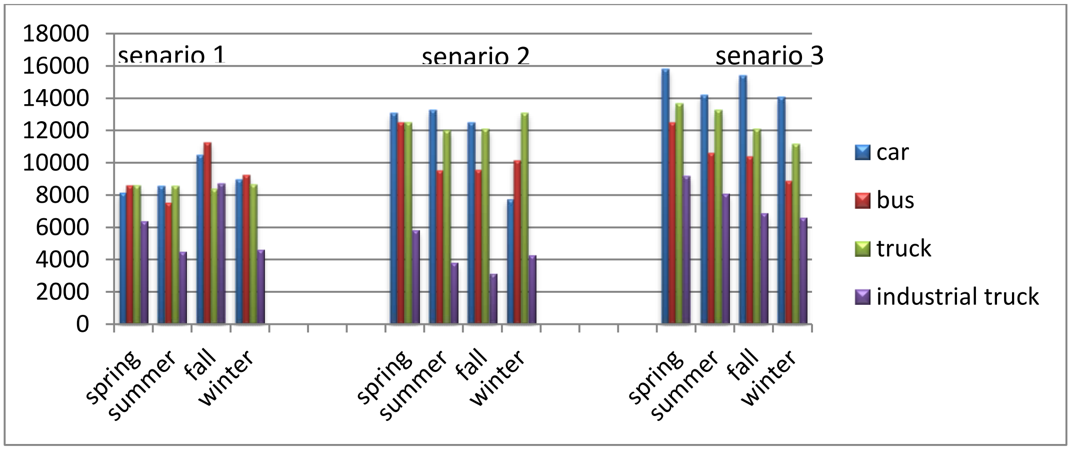


Figure 5. Number of used tire type *p* transported to recycling center in time period *t* under scenario s

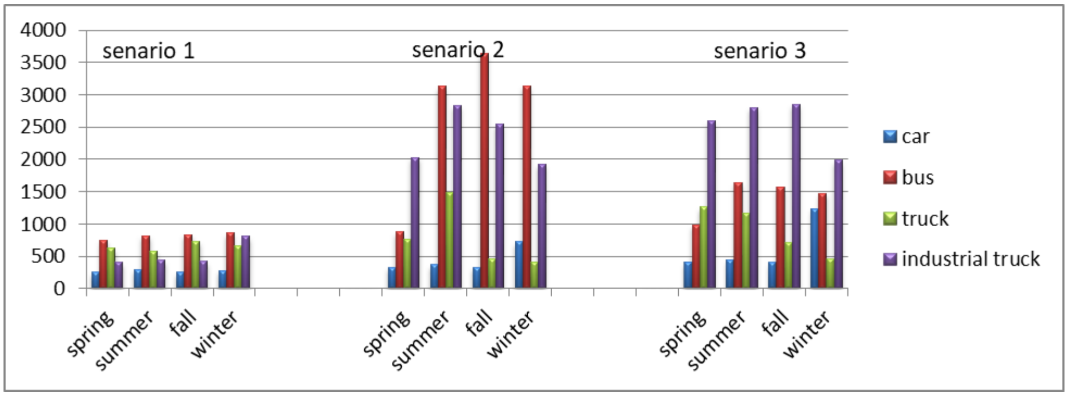


Figure 6. Number of tires assigned to the tire energy recovery center in time period *t* under scenario s

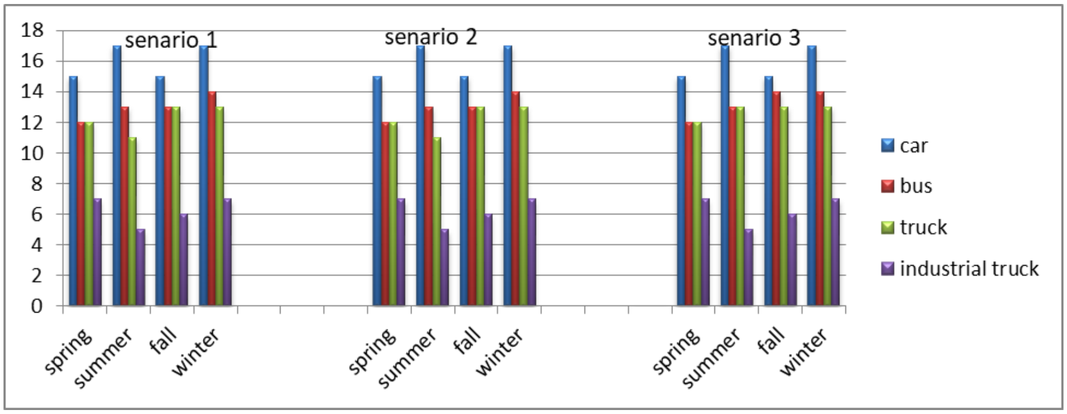


Figure 7. Number of tires assigned to the tire landfilling center in time period *t* under scenario s

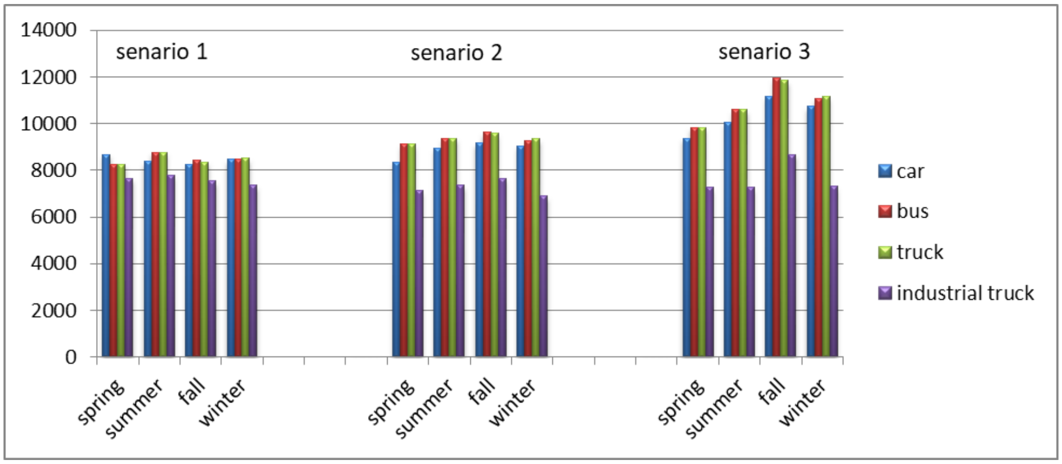


Figure 8. Number of collected tires from different sources in time period t under scenario s

6. Sensitivity analysis

After obtaining the optimal solutions of the proposed model for the problem under study, a sensitivity analysis is performed to examine the effects of possible changes in the input parameters on the current solutions of the model. In other words, sensitivity analysis seeks to determine how changes in the input parameters affect the model solution. To analyze the effects of changing parameters on the final results of the mathematical model, we considered four cases:

- Change in the parameters of demand and return rate of used tires under different scenarios and observe the impact on economic and environmental dimensions.
- Evaluation of the economic and environmental objective functions according to different weight percentages.
- The impact of implementing green technology in different centers on economic, environmental, and social dimensions
- Evaluation of the social objective functions.

6.1. Impact of uncertain demand and return on economic and environmental dimensions

According to Table 2, under the third scenario (high demand and return rate), despite the increase in the return rate due to higher production volumes, the environmental and economic (profit) objective functions increase by 21% and 28%, respectively, compared to the second scenario. A decline in demand under the first scenario, and consequently a 20% decrease in the rate of return of worn-out tires, results in a 22.8% decrease in the environmental objective function and a 32.5% decrease in the economic objective function. However, the demand for different products in various centers has risen from 20% to 35% under different scenarios. It can be seen that the rate of change in the objective functions according to each scenario is proportional to the percentage change in demand. Generally speaking, high demand conditions causes the profit of the whole supply chain to increase, but they also result in more environmental damage.

Table 2. The economic and environmental objective function values under different demand scenarios

	Economic objective function (profit)	Environmental objective function
Scenario 1	1.51E+10	21.56E+06
Scenario 2	2.1E+10	27.3E+06
Scenario 3	2.78.E+10	33.54E+06

6.2. Evaluating the economic and environmental objective functions with respect to different weight percentages

Considering the second scenario, different weights are assigned to the economic and environmental objective functions, disregarding the social objectives. The weights for these objective functions are denoted by w_1 and w_2, respectively, and are determined by the decision makers. The sum of the weights must equal 1, and the objective function values are obtained based on different combinations of these weights. These values reperesent a set of Pareto-optimal solutions, which are presented in Table 3. Negative values for the profit objective function indicate a loss.

Fig. 9 also shows the Pareto-optimal solutions. There is a conflict between the economic and environmental objectives, such that a improvement in one leads to the deterioration of the other.

Table 3. The Pareto-optimal solutions

Weight percentages		objective function values	
w_1 (Economic)	w_2 (Environmental)	Economic	Environmental
0	1	-0.2E+10	5.40E+06
0.1	0.9	-0.09E+10	8.96E+06
0.2	0.8	-0.001E+10	14.6E+06
0.3	0.7	0.57E+10	19.1E+06
0.4	0.6	1.17E+10	23.2E+06
0.5	0.5	2.1E+10	27.3E+06
0.6	0.4	2.67E+10	35.9E+06
0.7	0.3	3.1E+10	43.1E+06
0.8	0.2	3.66E+10	51.76E+06
0.9	0.1	3.91E+10	56.66E+06
1	0	4.36E+10	62.5E+6

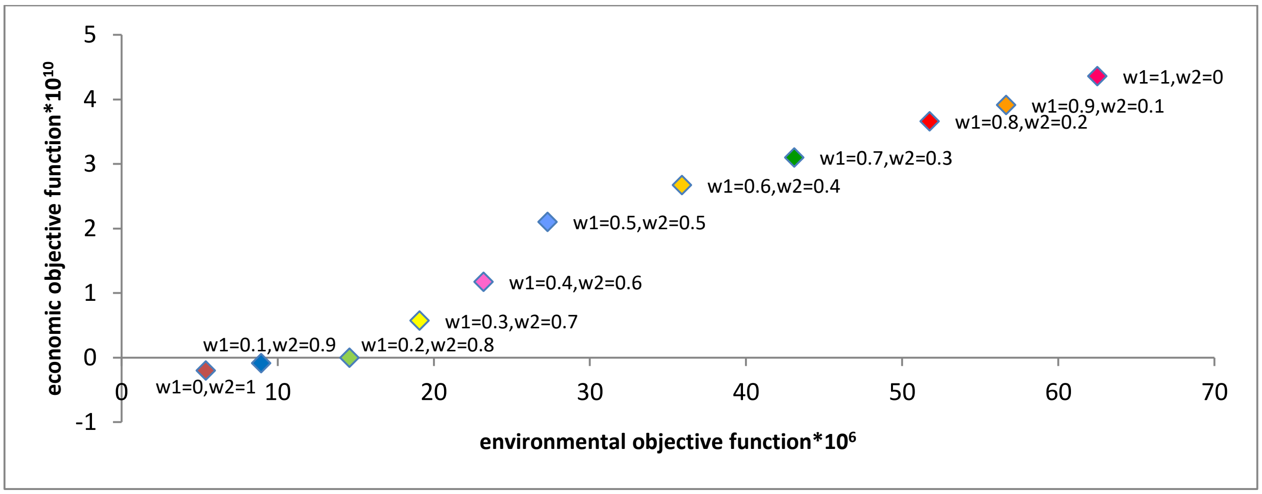


Figure 9. The Pareto-optimal solutions

At one extreme ($w_1 = 1$, $w_2 = 0$), the model only considers the economic objective function and ignores the environmental objective function. In this condition, the model achieves the highest profit, but environmental impacts also reach their maximum level. On the other hand, when ($w_1 = 1$, $w_2 = 0$), the model focuses solely on minimizing the environmental objective function and disregards the economic objectives. To minimize the environmental function, the model recommends closing all sites and plants.

Furthermore, by plotting the trend line of different points in Fig. 9, it can be seen that there is an approximately linear relationship between the values of the economic and environmental objective functions. Fig. 10 illustrates this relationship with regard to the applied weight combinations. The economic and environmental objective functions are positively correlated ($R^2 = 0.9707$), meaning that a increase in the economic objective function leades to greater environmental impacts.

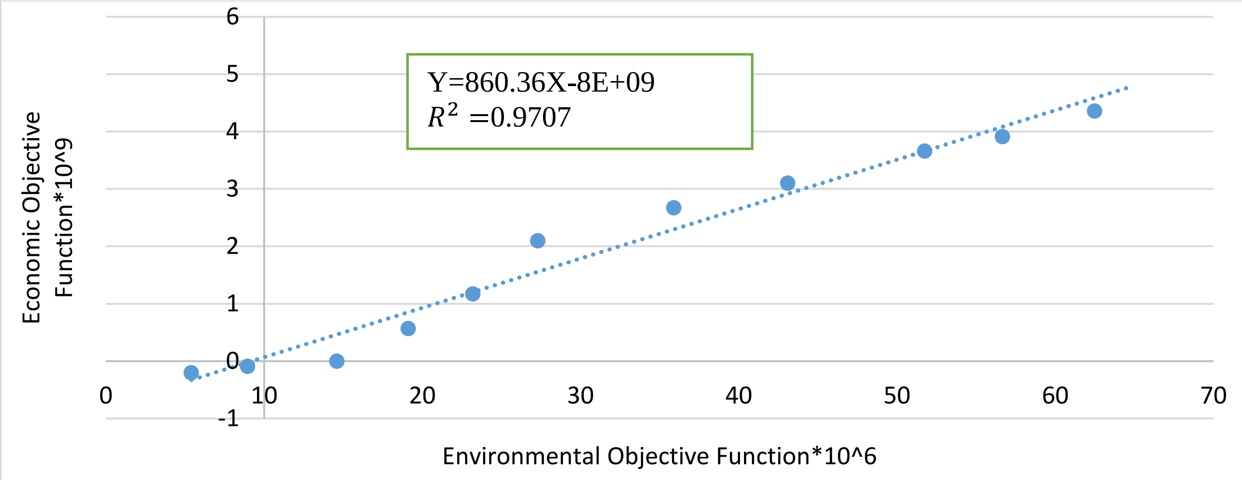


Figure 10. The trend line for the economic and environmental objective function values

6.3. The impact of green technology on sustainability

As mentioned before, implementing more advanced environment protection technologies requires higher investments, where automating processes reduces environmental impacts. However, its impact on the social dimension is complex. Advanced environmental protection technology eliminates more low-skilled jobs while simultaneously creating more jobs for high-skilled jobs. Overall, more advanced technology tends to reduce the number of jobs. Table 4 shows the best environmental technologies for different facilities. The first column lists the optimal green technology if only the economic objective is considered, and the second column indicates the optimal solution if only the social objective only. The fourth column shows the optimal green technologies considering all three dimensions together. Technology number 3 in each facility is the most advanced one.

Table 4. Optimal green technologies considering sustainability dimensions

Facilities	Economic	Social	Environmental	Sustainability
E	1	2		2
E’	1	2	-	2
E”	1	2	-	2

6.4. Evaluating the social objective functions

The optimal locations of facilities are shown in Table 5. In Table 5, the numbers indicate the location numbers. For instance, number 3 in the ‘‘Distribution center’’ row refers to distribution center 3. The second column shows the optimal locations if only the economic objective is considered, while the third column indicates the optimal locations if only the social objective is considered. Based on Table 5, it can be concluded that taking into account the unemployment rate and regional development indicators affects the choice of facility locations. Hence, the social index plays an important role in selecting the optimal location. The fifth column shows the optimal locations of facilities considering all three objectives together, as shown in Fig. 2. According to the results presented in Table 5, social indicators affect the choice of location in 80% of cases. This is due to considering the unemployment rate and population density of different locations, in addition to the fixed costs of establishing the facilities at these regions.

Table 5. Optimal location of the facilities considering sustainability dimensions

Facilities	Economic	Social	Environmental	Sustainability
Factory	1	1	-	1
Distribution center	3	2	-	1
Collection center	1	1	-	1
Remanufacturing center	1	2	-	1
Recycling center	3	2	-	1
Energy recovery center	2	1	-	3

The economic and environmental functions are also affected when social indicators are considered due to changes in location and green technology selection. The relocation alters the distances between various supply chain centers, resulting in changes in costs and pollutant emissions. The computational results are presented in table 6 and Fig. 11. This section considers the second scenario. Overall, taking the social indicators into account causes a slight increase in costs and environmental impacts, which does not justify disregarding social considerations in the CLSC design problem.

Table 6. The effect of social indicators on economic and environmental objective functions

	Economic objective function	Environmental objective function
Considering social indicators	2.001E+10	28.5E+06
Ignoring social indicators	2.1E+10	27.3E+06

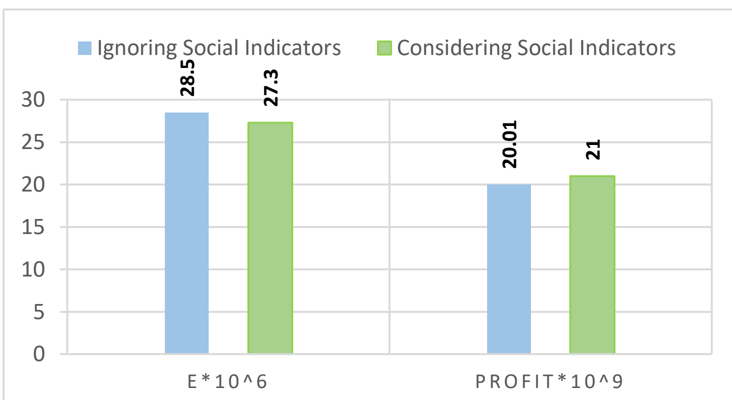


Figure 11. The economic and environmental objective function values

7. Managerial implications

In this subsection, the managerial implications for decision makers are discussed. Sustainable development requirements urge supply chain managers and decision-makers to consider social and environmental aspects alongside the economic dimension in strategic and tactical decision-making. Supply chains should minimize the environmental impacts of their activities and manage their products at their EOL to protect the environment. At the same time, in line with their commitment to the social responsibility, they should consider the employment and balanced development of different regions during the CLSC design phase to prevent uncontrolled immigration to large cities and associated issues. Paying attention to these factors can also increase sales and ensure the long-term profitability of supply chains.

The model determined the optimal location of facilities by considering regional factors such as unemployment rate and population density in addition to cost factors, to prevent the concentration of industries in large cities.

Since the chemicals in tire easily penetrate the soil and groundwater, harming the environment and human health, managers should pay more attention to tires at their EOL. By designing a CLSC and establishing renovation centers, they can minimize the harmful impacts of this product at the EOL. Closing the chain loop and considering various options, such as remanufacturing, recycling and energy recovery in reverse logistics, would significantly reduce the amount of landfilling or burning of tires.

Another solution to reduce the environmental impact of the tire CLSC is utilizing green technologies. Although more advanced environment protection technology can be expensive, it has minimal environmental impact and improves product quality and customer satisfaction, which can offset the investment costs. Establishing these technologies has a twofold impact on job creation; it may reduce the number of low-skilled jobs while simultaneously creating opportunities for highly skilled workers. Given the need for skilled workforces to operate green technologies, managers must make ensure that the necessary workforce is available before choosing the type of technology. Managers need to appreciate the importance of each sustainability dimension in a balanced way within the supply chain. However, during times of recession, the importance of the economic dimension increases for the survival of the industry and should be weighed more heavily.

8. Conclusions and future research

Pressure from society and the government has motivated the companies toward incorporating sustainability requirements into their operations. To advance research in this area, this study presented a MOMILP model for a real-world problem of designing sustainable tire CLSC network under uncertainty. Scenario approach was utilized to deal with the uncertainty in demand and return. The developed model used LCA approach to assess environmental and social impacts in the entire tire supply chain. From a theoretical point of view, this paper evaluates LCA-based social indicators according to the GSLCAP standard to model its social impacts along with the use of eco-indicator 99 as a method of assessing valid environmental impacts. Lp-metric method were applied to solve the mathematical model with multiple objectives. The proposed model was validated using data from a case in the tire supply chain.

The model developed in this research aids the decision makers to configure the sustainable supply chain network considering economic, environmental and social dimensions simultaneously and decentralize the industries by recommending them to establish the industries in less-developed areas as well. The results showed that taking into account the social aspects such as unemployment and job creation in less-developed regions very slightly increases the costs and does not have a meaningful environmental impact. In addition, the model helps determine optimal operational plan and green technology selection in different sites. Different recovery options considered in the CLSC of this study minimizes the landfilling and burning of worn-out tires.

Because social impact assessment is still under-researched, there is a need for developing methods and frameworks in this area. Assessing and measuring environmental damage would also be valuable where some information on environmental parameters may be incomplete or unavailable. In addition, modeling the CLSC network design problems in other manufacturing industries, considering other social impacts such as traffic and water use in strategic and tactical decisions of sustainable supply chains, routing problems, and supplier selection is worth studying by future research. Other Multi-objective solution approaches especially those based on efficient heuristics and metaheuristics can be developed for large scale problems. Finally, future researches can consider creating job opportunities based on dividing the workforce into low-skilled and skilled workers.

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Appendix A

Indices:

I	Factory	$i=1,\dots,I$
J	Distribution center	$j=1,\dots,J$
K	Collection center	$k=1,\dots,K$
O	Remanufacturing factory	$o=1,\dots,O$
N	Recycling center	$n=1,\dots,N$
W	Energy recovery center (Furnace)	$w=1,\dots,W$
P	Product	$p=1,\dots,P$
C	Raw material	$c=1,\dots,C$
V	Vehicle	$v=1,\dots,V$
E	The type of technology used in the production factory	$e=1,\dots,E$
E'	The type of technology used in the remanufacturing factory	$e'=1,\dots,E'$
E”	The type of technology used in the recycling center	$e''=1,\dots,E''$
D	Burial center	$d=1,\dots,D$
T	Time Period	$t=1,\dots,T$
S	Scenario	$s=1,\dots,S$

Parameters:

fm_i	Fixed cost of establishing tire factory *i*	$ailf'^{c}$	Safety stock level of raw material type *c* in tire factory
fd_j	Fixed cost of establishing distribution center *j*	Pr^{p}	Selling price per unit of new tire type *p*
fc_k	Fixed cost of establishing collection center *k*	Pr'^{p}	Selling price per unit of remanufactured tire type *p*
fr_n	Fixed cost of establishing recycling center *n*	Pr''^{p}	Selling price per unit of used tire type *p*
fl_o	Fixed cost of establishing remanufacturing factory *o*	Pn^{c}	Selling price per unit of raw material tire type *c*
fcf_e	Fixed cost of implementing technology *e* in the tire factory	jo_e	Number of jobs created with the implementation of green technology *e* in tire factory

$fcl_{e'}$	Fixed cost of implementing technology *e'* in the tire remanufacturing factory	$jo'_{e'}$	Number of jobs created with the implementation of the green technology *e'* in tire remanufacturing factory
$fcn_{e''}$	Fixed cost of implementing technology *e''* in recycling center	$jo''_{e''}$	Number of jobs created with the implementation of the green technology *e''* in recycling center
cm_e^p	Producing cost per unit of new tire type *p* in the tire factory with green technology *e*	We^p	Weight of Tire type *p*
$cf_{e'}^p$	Remanufacturing cost per unit of used tire type *p* in the remanufacturing factory with environmental protection technology *e'*	$\omega^{c,p}$	Percentage composition of raw material type *c* in tire type *p*
$cr_{e''}^p$	Recycling cost per unit of used tire type *p* with green technology *e''*	ε	Percentage of defective tires in tire factory
pt_v^p	Transportation cost per unit of tire type *p* in one kilometer with vehicle *v*	$\alpha^{p,t,s}$	Percentage of tire type *p* sold to those who deliver used tires to the collection center in period t under scenario s
ct_v^c	Transporting cost per unit of raw material type *c* in one kilometer with vehicle *v*	β	Discount percentage for those who deliver worn-out tires to collection centers
cc^p	Collection cost per unit of used tire type *p*	ro	The legal limit of landfilling used tires
cp^c	Purchase cost per unit of raw material type *c*	EIP^c	Eco-indicator value per unit of raw material type *c*
h^p	Holding cost per unit of new tire type *p*	EIA_e^p	Eco-indicator value per unit of new tire type *p* in the tire factory with technology *e*
h'^p	Holding cost per unit of used tire type *p*	$EItr_v^p$	Eco-indicator value per unit of new tire type *p* in one kilometer by vehicle *v*
hm^c	Holding cost per unit of raw material type *c*	$EItr_v'^c$	Eco-indicator value per unit of raw material type *c* in one kilometer by vehicle *v*
$Dc^{p,t,s}$	Demand for new tire type *p* in period t under scenario *s*	$EIco^p$	Eco-indicator value per unit for collecting tire type *p*
$Dc'^{p,t,s}$	Demand for remanufactured tire type *p* in period t under scenario *s*	$EIpro^p$	Eco-indicator value per unit for processing used tire type *p*
$Dn^{c,t,s}$	Customer demand for raw material type *c* in period t under scenario *s*	EIb^p	Eco-indicator value per unit of used tire type *p* in the energy recovery center(furnace)
$Dw^{p,t,s}$	Demand of used tire type *p* for energy recovery in period t under scenario *s*	$EIre_{e'}^p$	Eco-indicator value per unit for remanufacturing of tire type *p* with green technology *e'*
ch	Pay as damage to employees per unit in the tire factory, collection center, recycling center and remanufacturing factory	$EIn_{e''}^p$	Eco-indicator value per unit for recycling of used tire type *p* in the recycling center with green technology *e''*

δf_i	Population density in region *i* (People per hectare)	$EIdis^p$	Eco-indicator value per unit for landfilling of used tire type *p* at disposal centers
δd_j	Population density in region *j* (People per hectare)	$EIht^p$	Eco-indicator value per unit for holding new tire type p
δr_o	Population density in region *o* (People per hectare)	$EIhr^p$	Eco-indicator value per unit for holding used tire type *p*
δc_k	Population density in region *k* (People per hectare)	$EIhm^c$	Eco-indicator value per unit for holding raw material type *c*
δs_n	Population density in region *n* (People per hectare)	$EIhm^c$	Eco-indicator value per unit for holding raw material type *c*
Cv_v	Vehicle type *v* capacity (Kg)	Cam^p	Total production capacity of new tire type *p* in each tire factory
dis^p	Landfilling cost per unit of used tire type *p*	Caf^p	Total production capacity of tire type *p* in each tire remanufacturing factory (unit)
$dmd_{i,j}$	Distance between factory *i* and distribution center *j*	Car^p	Total recycling capacity of used tire type *p* in each recycling center
$dcw_{k,w}$	Distance between collection center *k* and energy recovery center *w*	St^p	Storage space per unit of tire type *p* (m^3/unit)
$dcd_{k,d}$	Distance between collection center *k* and landfilling center *d*	Sm^c	Storage space per unit of raw material type *c* (m^3/Kg)
$dcr_{k,n}$	Distance between collection center *k* and recycling center *n*	CI'	Total storage capacity of warehouse in the tire factory for raw material (m^3)
$dcf_{k,o}$	Distance between collection center k and remanufacturing factory o	CN	Total storage capacity of the warehouse in recycling center for finished products (m^3)
$drf_{n,i}$	Distance between recycling center *n* and tire factory *i*	CI	Total storage capacity of the warehouse in the tire factory for finished products (m^3)
$dfd_{o,j}$	Distance between remanufacturing factory *o* and distribution center *j*	CJ	Total storage capacity of warehouse in the distribution center for new tires and remanufactured tires (m^3)
$dmc_{i,k}$	Distance between tire factory *i* and collection center *k*	CK	Total storage capacity of warehouse in the collection center for collected tires (m^3)
$ailf^p$	Safety stock level of new tire type *p* in the tire factory	CO	Total storage capacity of the warehouse in the remanufacturing factory for remanufactured tires (m^3)
$aild^p$	Safety stock level of new tire type p in the distribution center	μf_i	Unemployment rate in region *i*
$aild'^p$	Safety stock level of remanufactured tire type *p* in distribution center	μd_j	Unemployment rate in region *j*

$ailc^{p}$	Safety stock level of used tire type *p* in the collection centers	μr_o	Unemployment rate in region *o*
$aill^{p}$	Safety stock level of remanufactured tire type *p* in remanufacturing center	μc_k	Unemployment rate in region *k*
$ails^{c}$	Safety stock level of raw material type *c* in recycling center	μs_n	Unemployment rate in region *n*

Variables:

Continuous variables:

$X_i^{p,t,s}$	Number of new tire of type *p* produced in tire factory *i* in period t under scenario *s*	$Zt_{n,i,v}^{c,t,s}$	Amount of recycled raw material type *c* transported from recycling center *n* to tire factory *i* by vehicle *v* in period t under scenario *s*
$Xm_{i,j,v}^{p,t,s}$	Number of new tire of type *p* transported from tire factory *i* to distribution center *j* by vehicle *v* in time period *t* under scenario *s*	$ILI_i^{p,t,s}$	Inventory level of new tire of type *p* in tire factory *i,* in period *t* under scenario *s*
$Xf_{o,j,v}^{p,t,s}$	Number of remanufactured tire of type *p* transported from remanufacturing factory *o* to distribution center *j* by vehicle v in period *t* under scenario *s*	$ILJ_j^{p,t,s}$	Inventory level of tires of type *p* in distribution center *j* in period *t* in scenario *s*
$Yr_{k,n,v}^{p,t,s}$	Number of used tire of type *p* transported from collection center *k* to recycling center *n* by vehicle *v* in period *t* under scenario s	$Yf_{k,o,v}^{p,t,s}$	Number of used tire of type *p* transported from collection center *k* to remanufacturing factory *o* by vehicle *v* in period t under scenario *s*
$IK_k^{p,t,s}$	Inventory level of used tire type *p* in collection center *k* in time period *t* under scenario *s* (unit)	$ICI_i^{c,t,s}$	Raw material inventory level of type *c* in tire factory *i* in time period *t* under scenario *s*
$Yd^{p,t,s}$	Number of used tire for landfilling in of period *t* under scenario *s*	$IL_o^{p,t,s}$	Remanufactured tire inventory level of type *p* in tire remanufacturing factory *o* in period *t* under scenario *s*
$Y_k^{p,t,s}$	Number of collected tire of type *p* in collection center *k* in period *t* under scenario *s*	$ICN_n^{c,t,s}$	Raw material inventory level of type *c* in recycling center *n* in period *t* under scenario *s*
$Zr_{n,e''}^{c,t,s}$	Amount of raw material type *c* produced in recycling center *n* with green technology *e''* in period *t* under scenario *s*	$ILJ'^{p,t,s}_j$	Inventory level of remanufactured tire of type *p* in distribution center *j* in period *t* under scenario *s*
$Z^{c,t,s}$	Amount of raw material of type *c* purchasing in period *t* under scenario *s*	$q^{t,s}$	Number of worn tires that must be sourced from external suppliers

Binary variables:

M_i	If tire factory is located in location *i*, 1; otherwise 0	R_n	If recycling center is located in location *n*, 1; otherwise 0
L_o	If tire remanufacturing factory is located in location *o*, 1; otherwise 0	yf_e	If green technology e is established in tire factory, 1; otherwise 0

D_j	If distribution center is located in location *j*, 1; otherwise 0	$yr_{e'}$	If green technology *e'* is established in tire remanufacturing factory, 1; otherwise 0
C_k	If collection center is located in location *k*: 1, otherwise zero	$ys_{e''}$	If green technology *e''* is established in recycling center: 1, otherwise zero

Appendix B

Lp-metric method seeks to minimize the deviation of each objective functions from its ideal solution. In other words, the best answer is the one with the shortest distance from the ideal point. The ideal point is a solution that simultaneously includes the optimal value of all the objective functions (Pasandideh et al., 2015). This point is showed by(36-A) Where $f(x^*)$ is an optimal value for all objectives, so that x^* can optimize any value of $f_i(x^*)$

$$f(x^*)=\{f_1(x^*),\dots,f_k(x^*)\} \tag{1-A}$$

In practice, there is no such answer as x^* because of the conflict between objectives. Therefore, in the Lp-metric method, the metric distance is used to measure the proximity of the real solution to the ideal solution. This case is considered in Equation (37-A).

$$lp=\left\{\sum_{j=1}^{k} w_j.\left[f_j(x^{*j})-f_j(x)\right]^p\right\}^{1/p} \tag{2-A}$$

In the above equation, w_j indicates the weight of the j_{th} objective. Also, to minimize the deviation from the ideal solution, the L-p function (37-A) must be minimized. In addition, the p indicates the degree of emphasis on the existing deviation. Therefore, the larger the p, the greater the emphasis on the deviation. The amount of p depends on the decision maker. In order to use the Lp function for different objective functions with different scales, Equation (38-A) is used.

$$lp=\left\{\sum_{j=1}^{k} w_j.\left[\frac{f_j(x^{*j})-f_j(x)}{f_j(x^{*j})}\right]^p\right\}^{1/p} \tag{3-A}$$

Appendix C

Table 1-C. Variable costs

Tire Type	Tire production cost (Rial)			Tire remanufactured cost (Rial)		Tire recycling cost (Rial)	
Green technology	B_1	B_2	B_3	B_1	B_2	B_1	B_2
Car	15000	17000	22000	7000	12000	10000	20000

Bus	50000	65000	75000	19000	21000	20000	30000
Truck	75000	90000	100000	20000	24000	30000	40000
Industrial machine	125000	140000	150000	25000	32000	45000	55000

Table 2-C. fixed costs (In terms of billions of Rial)

Facilities	Tire remanufacturing factory			Distribution Center				Collection center				Recycling center			Tire factory	
Potential locations	O_1	O_2	O_3	D_1	D_2	D_3	D_4	K_1	K_2	K_3	K_4	N_1	N_2	N_3	I_1	I_2
Fixed costs	0.5	0.52	0.45	1.3	1.6	1.8	2	0.8	1	1.1	1.3	0.55	0.5	0.45	6.8	7

Table 3-C. Price unit in Rial

Fixed cost of establishing technology *e* in a tire factory	100000000-120000000
Fixed cost of implementing technology *e'* in tire remanufacturing factory	80000000-120000000
Fixed cost of implementing technology *e''* in recycling center	90000000-150000000
Purchase cost per unit of raw material type *c*	8000-25000
Collection cost per unit of used tire type *p*	500-1500
Holding cost per unit of new tire type *p*	6000-12000
Holding cost per unit of raw material type *c*	1000-5000
Landfilling cost per unit of used tire type *p*	2000-4000
Percentage composition of raw material type *c* in tire type *p*	0.05-0.7
Storage space per unit of tire type *p* (m^3)	0.05-0.2
Storage space per unit of raw material type *c* (m^3)	0.00011-0.0008
Distance between facilities' centers (km)	40-550
Demand of new tire of type *p* in period *t* in scenario *s*	1000-8000
Demand of remanufactured tire of type *p* in period t under scenario *s*	100-1200
Customer demand of raw material of type *c* in period *t* under scenario *s* (kg)	1000-3500
Demand of used tire of type p for energy recovery in period t under scenario *s*	500-1500
Total production capacity of new tire of type *p* in tire factory	45000-75000
Total production capacity of tire of type *p* in tire remanufacturing factory	45000-75000
Total recycling capacity of used tire of type *p* in recycling center	45000-75000
Total Storage capacity of warehouse in tire factory for productions (m^3)	60000
Total Storage capacity of warehouse in distribution center for new tires and remanufactured tires (m^3)	40000-60000
Total Storage capacity of warehouse in collection center for collecting tires (m^3)	40000-60000
Total Storage capacity of warehouse in remanufacturing factory for remanufactured tires (m^3)	40000-60000
Total Storage capacity of warehouse in recycling center for productions (m^3)	40000-60000

Vehicle capacity type v (kg)	16000 & 28000
Selling price per unit of new tire of type *p*	900000-5000000
Selling price per unit of remanufactured tire of type *p*	500000-2500000
Selling price per unit of used tire of type *p*	5000-25000
Selling price per unit of raw material tire of type *c*	20000-60000-280000
Transportation cost per unit of tire of type *p* in one kilometer with vehicle *v*	1200-2500
Transporting cost per unit of raw material of type *c* in one kilometer with vehicle *v*	400-700
Weight of tire type *p*	7-30-25-50
Total Storage capacity of warehouse in tire factory for raw material (m^3)	60000
Percentage of defective tires in tire factory	0.02
Pay as damage to employees per unit in tire factory, collection center, recycling center and remanufactured factory	15000000-30000000
The legal limit of landfilling used tires	300-350
Discount percentage for customers who deliver worn-out tires to collection centers	0.1
Percentage of tire selling of type *p* to customers who deliver used tires to collection center in time period *t* under scenario *s*	0.3-0.7
Number of jobs created with implementing of green technology e, in tire factory	25-45
Number of jobs created with implementing of green technology *e'* in tire remanufacturing factory	30-35
Number of jobs created with implementing of green technology *e''* in recycling center	35-40
Unemployment rate	0.07-0.11
Population density (People per hectare)	35-100

Table 4-C. Raw material phase

	Purchased raw materials			Recycled raw materials		
Type of raw material	1	2	3	1	2	3
Eco-indicator 99	3.5	3	3	0.25	0.18	0.14

Table 5-C. Production phase

	Technology 1				Technology 2				Technology 3			
Tire type	Car	bus	truck	Industrial machines	car	bus	truck	Industrial machines	Car	bus	Truck	Industrial machines
Eco-indicator 99	6	9	11	13	5.5	8.5	10.4	12.2	5	8	10	11.8

Table 6-C. Transportation phase

Vehicle	16 tons				28 tons			
Tire type	car	bus	truck	Industrial machines	car	bus	Truck	Industrial machines
Eco-indicator 99	0.1	0.18	0.2	0.23	0.08	0.15	0.15	0.18

Table 7-C. Return phase

Eco-indicator 99	Car	Bus	Truck	Industrial machines
Collection phase	0.01	1.1	1.25	1.6
Processing phase	0.29	0.4	0.54	0.65
Landfilling phase	1.3	2.2	2.5	2.9
Energy recovery phase	-0.012	-0.018	-0.02	-0.025

Table 8-C. Storage phase

Warehouses	Holding new tires	Holding used tires
Eco-indicator 99	0.3	0.5

Table 9-C. Remanufacturing phase

	Technology 1				Technology 2			
Tire type	Car	Bus	Truck	Industrial machines	Car	Bus	Truck	Industrial machines
Eco-indicator 99	-1.5	-2	-2.4	-2.9	-2.2	-2.6	-3.4	-4.1

Table 10-C. Recycling phase

	Technology 1				Technology 2			
Tire type	Car	Bus	Truck	Industrial machines	Car	Bus	Truck	Industrial machines
Eco-indicator 99	-0.5	-2.4	-2.6	-3.1	-1	-2.8	-3.4	-4.1