Sustainable tire supply chain network design and operations planning using a multi objective , scenario-based optimization approach

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Abstract

Each year, millions of tires reach their end of life. Worn-out tires are either buried or burned, both of which harm the environment through polluting the air and groundwater. Companies need to consider their social responsibility, such as 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 network design (SCND) and operations planning problem with regard to the three dimensions of sustainability using a mathematical programming approach. The options of retreading, recycling, and energy recovery together with the use of green technologies are considered to minimize the environmental impacts. The proposed decision model can help supply chain managers in tire manufacturing industry make better-informed decisions in order to achieve the three-fold objectives of sustainability.

The developed mathematical model turns out to be a multi-objective, multi-echelon, and multi-product mixed integer linear programming. The model is solved using the Lp-metric method and CPLEX solver. The scenario approach is used to address the uncertainty in demand of new products and the rate of return of worn-out tires. The model solutions are the optimal location of the facilities considering population density and unemployment rate in addition to economic dimension, the optimal amount of allocation, the flow of materials, and the best green technology selection. Sensitivity analysis is also conducted to validate the model and test the robustness of the obtained solutions. Finally, managerial implications are provided.

Keywords

Sustainable tire supply chain network design (SSCND), Life cycle assessment (LCA), Regional development, Job opportunities, Scenario approach, Lp-metric

1. Introduction

By increasing the awareness of the society about the environmental and social challenges, businesses encounter increasing pressures from customers, policy makers and environmentalist groups to pay more attention to the environmental and social impact of their activities (Rao, et al.,2015); Abbasi & Nilsson,2016). Concerns about the environmental and social impacts of industrial activities have led to designing a model called "sustainable development".

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 ability of future generations to meet their needs" (WCED, 1987). Nowadays, sustainable development is a main objective for many countries around the world. They strive to ensure that industrial activities have minimum negative social and environmental impact while profit is maximized (Eskandarpour et.al, 2015; Kannan, 2018).

Sustainable supply chain management is a complex task, which entails different activities such as managing the forward flow of materials and finished products from suppliers to end-consumers and also the reverse flow of the used-products from the end-consumers to recycling centers considering the three pillars of sustainability, i.e., economic, environment and society (Barbosa-Póvoa et al., 2018). Designing an efficient closed-loop SCND is a way for businesses to fulfill their commitment to the sustainable development (Zhang et.al, 2016; Fathollahi-Fard et al., 2019).

In the tire supply chain, excessive amount of energy is consumed, and large amounts of greenhouse gases are emitted which can pollute the environment significantly. Each year, millions of worn-out tires are disposed of, causing serious problems and severe damage to the environment. The chemicals in worn-out tires pollute the air and are harmful for human health (Collins et al., 2002).

To address these issues, recovery methods have been developed over the past decade. Designing an efficient recovery network can significantly reduce the negative environmental and social impacts of products such as tires at the end of life (EOL). Nowadays, 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 global sustainable development (Dehghanian & Mansour, 2009; Amin et al., 2017).

Majority of the existing studies on the tire supply chain modeling have either focused on economic aspects while ignoring the social and environmental aspects or have considered the environmental aspect only. Therefore, considering the social aspect in the tire supply chain network design is a major research gap. In this study, all three pillars of sustainability are considered, and the life cycle assessment approach (LCA) is used to estimate the environmental and social impacts in the closed-loop tire supply chain network. Assessing environmental and social impacts along with economic benefits are among the important challenges in designing supply chains (Marta et al., 2019). LCA approach is useful in identifying social and environmental measures, analyzing different phases of 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 closed-loop tire supply chain network which includes optimal location of facilities and optimal green technologies options, optimal operations planning such as the assignment of returned tires to recovery centers, and the optimal inventory level for the finished products and raw materials considering the three dimensions of sustainability. For this purpose, a multi objective, scenario-based mathematical programming model is designed and solved. The findings of this study could provide useful insights for closed-loop supply chain managers in tire manufacturing industry and logistics service providers.

Thus, the research questions are posed as follows:

RQ1: What is the optimal design of sustainable tire supply chain network?

RQ2: What indicators should be considered in the social dimension?

RQ3: How should the uncertain parameters like demand of new products and return rate of used products be dealt with in designing sustainable tire supply chain network?

RQ4: To what extent does each sustainability dimension affect other dimensions?

RQ5: What is the optimal operational planning considering the three dimensions of sustainability?

The remainder of this paper is organized as follows. In Section 2, the problem under study is described, and an outline of a closed-loop tire supply chain is presented. Section 3 reviews the relevant literature to identify the research gaps. The mathematical model, including assumptions, variables, and parameters, is presented in Section 4. In Section 5, the proposed model is implemented. This section includes the detailed description of solution method, the computational results and managerial implications. In Section 6, the conclusions and suggestions for future research are presented.

2. Problem statement

The amount of worn-out or EOL tires in Iran was estimated to be 198,346–339,678 tons between 2003 and 2015 which equals 2.95–4.52 kg per capita per year. This rate has increased over the years, which can cause serious damages to environment and human health (Zarei et al., 2018).

During the production and usage of tires, considerable amount of pollution is generated, and a large amount 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 (Lin, 2011). Chemicals emitted from worn-out tires that are spread through air and water are harmful for 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 also can be a very effective solution to decrease the 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 job (Roudi et al., 2017). Industries in Iran are mainly located in large cities, which has led to unbalanced development and unregulated immigration to large cities. So it is better to establish industries in places with higher unemployment rate and lower populations places. 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 closed-loop tire supply chain network and optimal operations planning.

In the forward path of closed loop tire supply chain under study, different types of new tires are produced and transported to distribution centers to meet demand. In reverse or backward route, a portion of worn out tires are collected from the end-consumers. The collecting method is as follows: consumers sell used tires at the price approved by the municipality to the collection centers, and 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 center to produce raw materials and 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 tire closed-loop supply chain network is illustrated in Figure 1.

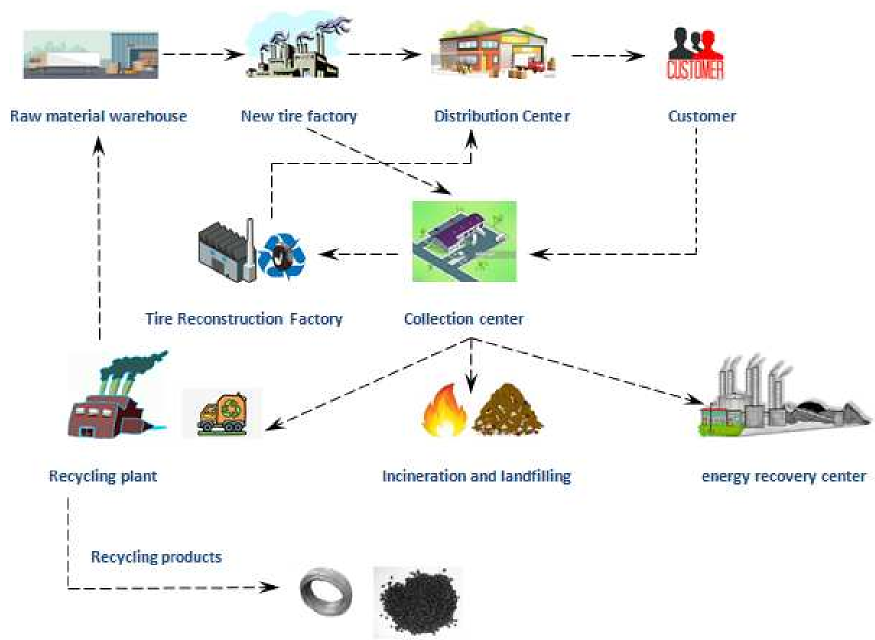

Figure 1- The tire closed-loop supply chain network

Various recovery options are described in more details below:

Retreading: By retreading, the 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 that can be used for various purposes including construction, automotive, marine, additives to plastics, bituminous waterproofing, flooring and artificial grass. (Rutherford, 1992).

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

Landfilling: 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.

3. Literature Review

3.1. Environmental indicators

Different indicators have been proposed in the literature for measuring the environmental impact. The most widely-used indicators are carbon dioxide (CO2) emissions (Ramos et al.,2013; Tseng et al., 2013; Zhalechian et al., 2016; Allaoui et al., 2016; Zhalechian et al. (2016), Taleizadeh et al., 2019; Alizadeh et al., 2019; Yun et al., 2020), greenhouse gas emissions (Chen & Andresen, 2014; Yue et al., 2014; Boukherroub et al., 2015; Osmani & Zhang, 2016; Nguyen et al., 2016; Isaloo & Paydar, 2019), Recipe Index (Ghaderi et al., 2017; Mota et al., 2018; Sahebjamnia et al., 2018), and eco-indicator 99 (Subulan et al.,2014; Pishvaee et al., 2014; Feitó-Cespón et al., 2017; Daghigh et al., 2018), fuel consumption, and energy loss (Zhalechian et al., 2016) resource constraints (Azadeh et al., 2016), climate change, use of water resources, use of lands, and the reduction of fossil fuels (Rohmer et al., 2019), carbon cost (Kumar et al.,2020)

Review of the literature shows that most of the related studies have limited the environmental indicators to greenhouse gas and CO2 emissions. However, each product has different environmental impact during its life cycle, and there is a need to a broader lifecycle perspective. LCA, with a cradle-to-grave perspective, provides a suitable framework to measure the environmental impacts of a product by focusing on the entire life cycle of that product

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 final unique score that is simply interpretable (Lees, 2012).

3.2. Social indicators

Over the past 20 years, a large number of research papers have been published to develop social indicators (Blanco et al., 2014; Traverso et al., 2012).

Major social indicators considered in the literature are: job opportunities (Yue et al., 2014; Boukherroub et al., 2015; Osmani & Zhang, 2017; Zhalechian et al., 2016; Allaoui et al., 2016; Nguyen et al., 2016; Mota et al., 2018), working hours (Rodrigues et al., 2013), employee’s health damage (Chen & Andresen, 2014; Rohmer et al., 2018), employment, risk, and health indicators (Pishvaee et al., 2014), customer satisfaction (Ebrahimi, 2018), customer service level (Feitó-Cespón et al., 2017), employment and the days lost due to work injuries (Sahebjamnia et al., 2018; Taleizadeh et al., 2018; Yun et al., 2020), employment and region economic development index (Ghaderi et al., 2018), job satisfaction (Moghaddam et al., 2018), social benefit (Kumar et al, 2020)

Due to their complexity and breadth, it could be extremely difficult to measure and control all the social impacts of a process (Pishvaee et al., 2012). Social sustainability has been studied less frequently compared with environmental sustainability, probably because of the more complex nature of the social sustainability (Fareeduddin et al., 2015).

The most important social indicator that has been studied in the literature on designing supply chain with different approaches is employment. Recently published research is increasingly recommending taking into account the social considerations in designing supply chain network as a future research direction (Yawar & Seuring, 2019).

3.3. Green technology

Green technology plays an essential role in achieving the objectives of sustainable development (Ismaniza et al., 2017). While in traditional view the objective of technology is to maximize the use of natural resources without considering the negative impacts on the natural world, green technology considers the needs of humans and nature simultaneously and attempts to achieve a balance between them (Lee et al., 2015). In addition to the positive environmental impacts, the use of green technologies in supply chains affects social objectives, including employment (Hansen et al., 2016). Green technologies utilize automated tire assembly equipment which improves the productivity and decreases the waste and energy consumption (Gent & Walter, 2006)

Conventional technologies of tire recycling and recovery consume large amounts of energy and also have very complex processes, thus they are not efficient. In comparison, green technologies of tire recovery can decrease energy consumption and environmental pollution (Dobrotă et al., 2020)

3.4. Literature on sustainable supply chain network design (SSCND) and solution approaches

A useful approach to deal with sustainability decisions regarding the trade-off between conflicting objectives that represent different aspects of sustainability is multi-objective modeling, which normally leads to Pareto-optimal solutions. Many studies have applied multi-objective optimization modeling to address SSCND problem.

There are different solution methods for multi-objective linear programming problems, including interactive goal programming, $\varepsilon -$ constraint, augmented $\epsilon -$ constraint, Lp-metric , weighted-sum, TH (Torabi-Hassini), compromise methods and metaheuristic algorithms. In this paper, 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, SCND problems are of 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.

Pishvaee et al. (2014) proposed a multi-objective possibilistic programming model in order to design a sustainable medical needle and syringe supply chain under uncertainty. The results show that considering the environmental and social concerns comes with cost.

Subulan et al. (2015) proposed a multi-objective, mixed-integer, linear programming model for closed-loop tire SCND problem in Turkey. They considered different recovery options of recycling, remanufacturing and energy recovery

Sahebjamnia et al. (2018) developed a multi-objective, mixed-integer, linear programming model for designing sustainable, tire, closed-loop supply chain network. The only recovery option in their study is recycling

Ghaderi et al. (2018) designed a multi objective, robust, possibilistic programming model to address SSCND for switchgrass-based bioethanol industry under epistemic uncertainty of input parameters. Results showed that desired environmental and social objectives are achievable only by increasing costs.

Ebrahimi (2018) considered the closed loop, tire SCND problem under uncertainty. A multi objective stochastic optimization model was formulated to determine the optimal location allocation and routing decisions. Two of the objectives were to minimize total costs and environmental effects and the third objective was to maximize the responsiveness of the supply chain network (SCN).

Alizadeh et al. (2019) proposed a robust three stage stochastic programming model for olefin supply chain network optimization problem at the state of Mississippi. Carbon tax rate and seasonal supply of biomass feedstock were supposed to be uncertain. .

Rohmer et al. (2019) investigated sustainable food supply chain design problem considering sourcing, processing and transformation decisions. They developed a bi-objective, linear programming model, where the objectives were to minimize the costs and environmental impacts. The social sustainability was incorporated in their model as a health constraint.

Taleizadeh et al. (2019) proposed a mixed-integer, linear programming approach to model the production planning of a multi-objective, multi-period, multi-echelon, sustainable closed-loop supply chain. Social and environmental impacts was measured using GRI (Global Reporting Initiative). In order to encourage the customers to return the used-products, the model offers discount for the returned products according to their quality. Recovery options of returned products were remanufacturing, recycling and disposing of depending on their quality. Results showed that using advanced technologies, despite entailing higher costs, can create job satisfaction and bring safety to the employees in fluorescent CFL light bulbs supply chain.

Abdolazmi et al. (2020) proposed a multi-objective, mixed-integer, linear programming model for closed loop, tire SCND considering the uncertainty present in the model parameters such as production cost, demand and return rates. The objective functions of the model try to maximize the timely delivery of raw materials by suppliers and minimize total costs and environmental impacts. Soyster and Mulvey robust optimization approaches were adopted to capture uncertainties.

Yadollahnia et al. (2020) considered tire forward and reverse supply chain design problem under uncertainty. They proposed a scenario-based, multi-objective, mixed-integer programming model and used robust optimization and revised multi-choice goal programming approaches to solve the problem. The three objective functions were about maximizing profit, maximizing customer satisfaction and minimizing distance between collection centers and customers.

Gao & Cao (2020) developed a scenario-based, multi-objective, mixed-integer, nonlinear model to redesign a sustainable SCN under uncertainty. In their proposed network, the facilities have hybrid processing capabilities. After linearizing the model, weighted-sum and an augmented $\epsilon-$ constraint methods were used to solve the model.

3.5. Research contributions

Table 1 indicates the position of this paper in the literature and compares the present study with the relevant studies in terms of indicators considered in the social and environmental dimensions, solution approaches, the industry under study, and the approach to deal with uncertainty.

In this paper, eco indicator-99 has been applied to measure the environmental impacts, because it is a comprehensive method that can assess environmental impacts based on both middle and end points and can provide a single final environmental score (Pishvaee et al. 2014).

Because social effects are qualitative in nature, they are difficult to quantify, especially when social and environmental impacts interact widely (Santibañez-Aguilar, 2013, Mota et al., 2015). Several methods and guidelines have been developed by researchers to simplify the measurement and implementation of social responsibilities. ‘‘Guidelines for Social Life Cycle Assessment of Products’’(GSLCAP) was selected as the method for assessing the social impacts because it covers all social issues studied in current study, and since it has been developed based on LCA, it is compatible with measuring environmental issues based on LCA.

The main contributions of this research are as follows:

- Designing a closed-loop tire supply chain network considering the economic, environmental and social aspects of sustainability. Most studies on tire SSCND have considered the economic or environmental aspect only or combination of them. Very few studies have addressed these three aspects simultaneously.
- Evaluating the effect of green technology on the economic and social dimensions in the closed-loop tire supply chain.
- Taking into account the regional factor along with the job creation with regard to the social dimension in addition to the economic and environmental aspects to move toward balanced development. Regional factor is defined based on the unemployment rate and population density in each region. The vast majority of the existing studies on tire SCND have considered the job creation only in the social dimension.
- Considering different options in reverse or backward tire supply chain. 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.

- The developed model also determines the optimal value of operational decision variables such as the inventory level of different products, the allocation of products to different centers, and the amount of raw materials to be purchased.

Table 1- Comparing the relevant literature to present study

Study	Environmental aspects	Social aspects	Solution method	Industry	The method used to deal with uncertainty
Pishvaee et al. (2014)	Eco-indicator 99	Job creation, health risk	Benders decomposition, Posteriori fuzzy	Syringe recycling	Stochastic programing
Subulan et al. (2015)	Eco-indicator 99	---	An interactive fuzzy goal programming approach	Tire manufacturing	Fuzzy programming
Yue et al. (2014)	GHG emissions	Job opportunities	ε-constraint	Bioelectricity supply chain	---
Miret (2016)	Eco-cost	Job opportunities, Competition between food and energy	Goal programming	Bioethanol production	---
Osmani & Zhang (2017)	GHG emission	Job opportunities	sample average approximation, ε-constraint ,Benders decomposition	Bioethanol production	Stochastic programming
Nguyen et al. (2016)	GHG emission	Job opportunities	Weighted sum method	Automotive industry	---
Azadeh & Vafa Arani (2016)	Resource limitations	Social Effect of Air Pollution	Weighted sum method	Biodiesel supply chain	Robust-Stochastic programming
Ebrahimi (2018)	---	Customer satisfaction	Genetic algorithm	Plastic industry	---
Cespón, M.F et al. (2017)	Eco-indicator 99	Customer service level	ε-constraint	Plastic recycling	Stochastic programing
Mota et al. (2018)	Recipe	Job opportunities	ε-constraint	Electronic components	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	TH method	Switch grass-based bioethanol	Fuzzy programming
Taleizadeh et al. (2019)	Carbon emission	Job creation, lost days due to sickness and accidents, self-sufficiency	TH method	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	---
Gao &Cao 2020	Expected total carbon emission	Expected total created jobs	Augmented ε-constraint, Weighted sum method	---	Stochastic programing
Alizadeh et al. (2019)	Carbon tax rate	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	Hybrid GA(combine GA with TS)	---	---
The present study	Eco-indicator 99	Job opportunities, regional development	Lp-metric	Tire manufacturing	Stochastic programming

4. The mathematical model development

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 also return rate of the tires is 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 assumed to be zero.
- The amount of burial of scrap tires is limited according to the legal regulations.
- Planning periods are quarterly and the problem is modeled for four periods (one year).
- In order to encourage the consumers to return the used-tires, the factory offers discounts.

4.2. Notations

Indices, parameters, and variables needed to develop a mathematical model for the problem under study are as follows:

4.2.1. 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	$t=1,\ldots,T$
S	Scenario	$s=1,\ldots,S$

4.2.2. Parameters

fm_i	Fixed cost of establishing tire factory i (Toman)	dis^p	Landfilling cost per unit of used tire type p (Toman/unit)	EIP^c	Eco-indicator value per unit of raw material type c (EI/Kg)
fd_j	Fixed cost of establishing distribution center j (Toman)	$dmd_{i,j}$	Distance between factory i and distribution center j (Km)	EIA_e^p	Eco-indicator value per unit of new tire type p in tire factory with technology e (EI/unit)
fc_k	Fixed cost of establishing collection center k (Toman)	$dcw_{k,}$	Distance between collection center k and energy recovery center w (Km)	$EItr_v^p$	Eco-indicator value per unit of new tire type p in one kilometer by vehicle v (EI/unit.Km)
fr_n	Fixed cost of establishing recycling center n (Toman)	$dcd_{k,d}$	Distance between collection center k and landfilling center d (Km)	$EItr_v'^c$	Eco-indicator value per unit of raw material type c in one kilometer by vehicle v (EI/Kg.Km)
fl_o	Fixed cost of establishing remanufacturing factory o (Toman)	$dcr_{k,n}$	Distance between collection center k and recycling center n (Km)	$EIco^p$	Eco-indicator value per unit for collecting tire type p (EI/unit)
fcf_e	Fixed cost of establishing technology e in tire factory (Toman)	$dcf_{k,o}$	Distance between collection center k and remanufacturing factory o (Km)	$EIpro^p$	Eco-indicator value per unit for processing used tire type p (EI/unit)
$fcl_{e'}$	Fixed cost of establishing technology e' in tire remanufacturing factory (Toman)	$drf_{n,i}$	Distance between recycling center n and tire factory i (Km)	EIb^p	Eco-indicator value per unit of used tire type p in the energy recovery center(furnace) (EI/unit)
$fcn_{e''}$	Fixed cost of establishing technology *e''* in recycling center (Toman)	$dfd_{o,j}$	Distance between remanufacturing factory o and distribution center j (Km)	$EIre_{e'}^p$	Eco-indicator value per unit for remanufacturing of tire type p with green technology *e'* (EI/unit)
cm_e^p	Producing cost per unit of new tire type p in tire factory, with green technology e (Toman/unit)	$dmc_{i,k}$	Distance between tire factory i and collection center k (Km)	$EIn_{e''}^p$	Eco-indicator value per unit for recycling of used tire type p in the recycling center with green technology *e''* (EI/unit)
$cf_{e'}^p$	Remanufacturing cost per unit of used tire type p in remanufacturing factory with environmental protection technology *e'* (Toman/unit)	$ailf^p$	Safety stock level of new tire type p in tire factory (unit)	$EIdis^p$	Eco-indicator value per unit for landfilling of used tire type p at disposal centers (EI/unit)
$cr_{e''}^p$	Recycling cost per unit of used tire type p with green technology *e''* (Toman/unit)	$aild^p$	Safety stock level of new tire type p in distribution center (unit)	$EIht^p$	Eco-indicator value per unit for holding new tire type p (EI/unit)
pt_v^p	Transportation cost per unit of tire type p in one kilometer with vehicle v (Toman/unit. Km)	$aild'^p$	Safety stock level of remanufactured tire type p in distribution center (unit)	$EIhr^p$	Eco-indicator value per unit for holding used tire type p (EI/unit)
ct_v^c	Transporting cost per unit of raw material type c in one kilometer with vehicle v (Toman/ Kg. Km)	$ailc^p$	Safety stock level of used tire type p in collection center (unit)	$EIhm^c$	Eco-indicator value per unit for holding raw material type c (EI/Kg)
cc^p	Collection cost per unit of used tire type p (Toman/unit)	$aill^p$	Safety stock level of remanufactured tire type p in remanufacturing center (unit)	Cam^p	Total production capacity of new tire type p in tire factory (unit)
cp^c	Purchase cost per unit of raw material type c (Toman/ Kg)	$ails^c$	Safety stock level of raw material type c in recycling center (Kg)	Caf^p	Total production capacity of tire type p in tire remanufacturing factory (unit)
h^p	Holding cost per unit of new tire type p (Toman/unit)	$ailf'^c$	Safety stock level of raw material type c in tire factory (Kg)	Car^p	Total recycling capacity of used tire type p in recycling center (unit)
h'^p	Holding cost per unit of used tire type p (Toman/unit)	Pr^p	Selling price per unit of new tire type p (Toman/unit)	St^p	Storage space per unit of tire type p (m^3/unit)

hm^c	Holding cost per unit of raw material type *c* (Toman/ Kg)	Pr'^p	Selling price per unit of remanufactured tire type *p* (Toman/unit)	Sm^c	Storage space per unit of raw material type *c* (m3/Kg)
Dc^p	Demand of new tire type *p* in time period t under scenario *s* (unit)	Pr''^p	Selling price per unit of used tire type *p* (Toman/unit)	CI'	Total storage capacity of warehouse in tire factory for raw material (m3)
Dc'^p	Demand of remanufactured tire type *p* in time period t under scenario *s* (unit)	Pn^c	Selling price per unit of raw material tire type *c* (Toman/Kg)	CN	Total storage capacity of warehouse in recycling center for finished products (m3)
Dn^c	Customer demand of raw material type *c* in time period t under scenario *s* (Kg)	jo_e	Number of jobs created with establishment of the green technology *e* in tire factory	CI	Total storage capacity of warehouse in tire factory for finished products (m3)
Dw	Demand of used tire type *p* for energy recovery in time period t under scenario *s* (unit)	$jo'_{e'}$	Number of jobs created with establishment of the green technology *e'* in tire remanufacturing factory	CJ	Total storage capacity of warehouse in distribution center for new tires and remanufactured tires (m3)
ch	Pay as damage to employees per unit in tire factory, collection center, recycling center and remanufacturing factory (Toman/unit)	$jo''_{e''}$	Number of jobs created with establishment of the green technology *e''* in recycling center	CK	Total storage capacity of warehouse in collection center for collected tires (m3)
δf_i	Population density in region *i* (People per hectare)	We^p	Weight of Tire type *p* (Kg/unit)	CO	Total storage capacity of warehouse in remanufacturing factory for remanufactured tires (m3)
δd_j	Population density in region *j* (People per hectare)	$\omega^{c,p}$	Percentage composition of raw material type *c* in tire type *p*	μf_i	Unemployment rate in region *i*
δr_o	Population density in region *o* (People per hectare)	ε	Percentage of defective tires in tire factory	μd_j	Unemployment rate in region *j*
δc_k	Population density in region *k* (People per hectare)	$\alpha^{p,t,s}$	Percentage of tire type *p* sold to those who deliver used tires to collection center in time period t under scenario s	μr_o	Unemployment rate in region *o*
δs_n	Population density in region *n* (People per hectare)	β	Discount percentage for those who deliver worn-out tires to collection centers	μc_k	Unemployment rate in region *k*
Cv_v	Vehicle type *v* capacity (Kg)	ro	The legal limit of landfilling used tires (EI)	μs_n	Unemployment rate in region *n*

4.2.3. Continuous variables

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

4.2.4. 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

4.3. The objectives and constraints

The mathematical modeling of the problem is as follows:

4.3.1. Maximizing the total profit

Objective function (1) maximizes total profit that includes the revenue from selling finished products minus total costs.

$Max\, f_1^{\,t} = total\ \ revenue - total\ \cos t$

Revenue comes from selling new tires and remanufactured tires to customers, selling used tires to energy recovery centers and selling raw material.
The total revenue is computed as follows:

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

The mathematical formulation of the components of total cost are presented below:
fixed costs of establishing centers:

$$\left(\sum_i fm_i.M_i + \sum_o fl_o.L_o + \sum_j fd_j.D_j + \sum_k fc_k.C_k + \sum_n fr_n.R_n\right)+$$

Fixed costs of establishing green technology in various centers:

$$\left(\sum_e fcf_e.yf_e + \sum_{e'} fcl_{e'}.yr_{e'} + \sum_{e''} fcn_{e''}.ys_{e''}\right)+$$

Variable costs of producing new tires and remanufactured tires, and variable cost of recycling:

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

Transportation costs between different facilities:

$$\left(\sum_i \sum_j \sum_p \sum_v pt_v^p.dmd_{i,j}.Xm_{i,j,v}^{p,t,s} + \sum_o \sum_j \sum_p \sum_v pt_v^p.dfd_{o,j}.Xf_{o,j,v}^{p,t,s} + \right.$$

$$\sum_k \sum_w \sum_p \sum_v pt_v^p.dcw_{k,w}.Dw^{p,t,s} + \sum_k \sum_n \sum_p \sum_v pt_v^p.dcr_{k,n}.Yr_{k,n,v}^{p,t,s} +$$

$$\sum_k \sum_o \sum_p \sum_v pt_v^p.dcf_{k,o}.Yf_{k,o,v}^{p,t,s} + \sum_n \sum_i \sum_c \sum_v ct_v^c.drf_{n,i}.Zt_{n,i,v}^{c,t,s} +$$

$$\left.\sum_i \sum_k \sum_p \sum_v pt_v^p.dmc_{i,k}.\varepsilon.X_i^{p,t,s} + \sum_k \sum_d \sum_p \sum_v pt_v^p.dcd_{k,d}.Yd^{p,t,s}\right)+$$

Cost of collecting worn out tires:

$$\sum_k \sum_p cc^p.Y_k^{p,t,s} + \sum_p cc^p q^{t,s}$$

Raw materials purchasing cost:

$$\left(\sum_c cp^c.Z^{c,t,s}\right)+$$

Holding costs of new tires:

$$\sum_i \sum_p h^p.ILI_i^{p,t,s} + \sum_j \sum_p h^p \times (ILJ_j^{p,t,s} + ILJ'^{p,t,s}_j) + \sum_o \sum_p h^p.IL_o^{p,t,s} +$$
$$\sum_p h^p \times (ailf^p + aild^p + aild'^p + aill^p)$$

Holding costs of used tires at collection centers:

$$\sum_k \sum_p h'^p.IK_k^{p,t,s} + \sum_p h'^p ailc^p +$$

Raw material holding costs:

$$\sum_i \sum_c hm^c.ICI_i^{c,t,s} + \sum_n \sum_c hm^c.ICN_n^{c,t,s} + \sum_c hm^c(ails^c + ailf'^c)$$

Landfilling cost for burying worn-out tires:

$$\left(\sum_{p} dis^{p}\, Yd^{p,t,s}\right)+$$

Costs paid for the health and insurance of employees in each period:

$$\sum_{i}\sum_{p} ch.X_{i}^{p,t,s} + \sum_{k}\sum_{n}\sum_{p}\sum_{v} ch.Yr_{k,n,v}^{p,t,s} + \sum_{k}\sum_{0}\sum_{p}\sum_{v} ch.Yf_{k,o,v}^{p,t,s} + \sum_{k}\sum_{p} ch.Y_{k}^{p,t,s}$$

4.3.2. 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. This function considers the environmental impacts associated with the purchase of raw materials, new tire production, tire and raw material transportation throughout the supply chain, the collection of worn-out tires, processing the collected tires at the collection center, the use of scrap tires as furnace fuel, the retreading of used tires, recycling scrap tires, burying worn-out tires and the environmental impacts of holding healthy tires, worn-out tires, and raw materials in warehouses.

$Min\ f_{2}^{t}$ = minimizing environmental impact

The mathematical formulations of the components of the objective function (2) are presented as follows:

Environmental impacts associated with the purchase of raw materials:

$$\left(\sum_{c} EIP^{c}\,.\,Z^{c,t,s}\right)+$$

New tire production:

$$\left(\sum_{i}\sum_{e}\sum_{p} EIA_{e}^{p}.X_{i}^{p,t,s}\right)+$$

Tire and raw material transportation throughout the supply chain:

$$\left(\sum_i\sum_j\sum_p\sum_v EItr_v^p.dmd_{i,j}.Xm_{i,j,v}^{p,t,s}+\sum_o\sum_j\sum_p\sum_v EItr_v^p.dfd_{o,j}.Xf_{o,j,v}^{p,t,s}+\right.$$

$$\sum_k\sum_w\sum_p\sum_v EItr_v^p.dcw_{k,w}.Dw^{p,t,s}+\sum_k\sum_n\sum_p\sum_v EItr_v^p.dcr_{k,n}.Yr_{k,n,v}^{p,t,s}+$$

$$\sum_k\sum_o\sum_p\sum_v EItr_v^p.dcf_{k,o}.Yf_{k,o,v}^{p,t,s}+\sum_i\sum_n\sum_c\sum_v EItr_v'^c.drf_{n,i}.Zt_{n,i,v}^{c,t,s}$$

$$\left.\sum_i\sum_k\sum_p\sum_v EItr_v^p.dmc_{i,k}.\varepsilon.X_i^{p,t,s}+\sum_k\sum_d\sum_p\sum_v EItr_v^p.dcd_{k.d}.Yd^{p,t,s}\right)+$$

Environmental impacts of collecting worn out tires:

$$\left(\sum_k\sum_p EIco^p.Y_k^{p,t,s}\right)+$$

Processing the collected tires at the collection center:

$$\left(\sum_k\sum_p EIpro^p.Y_k^{p,t,s}+\sum_i\sum_p EIpro^p\varepsilon.X_i^{p,t,s}\right)+$$

The use of scrap tires as furnace fuel:

$$\left(\sum_p EIb^p.Dw^{p,t,s}\right)+$$

Retreading of used tires:

$$\left(\sum_k\sum_o\sum_p\sum_v\sum_{e'} EIre_{e'}^p.Yf_{k,o,v}^{p,t,s}\right)+$$

Recycling scrap tires:

$$\left(\sum_k\sum_n\sum_p\sum_v\sum_{e''} EIn_{e''}^p.Yr_{k,n,v}^{p,t,s}\right)+$$

Burying worn-out tires:

$$\left(\sum_p EIdis^p\,Yd^{p,t,s}\right)+$$

And, the environmental impacts of holding healthy tires, worn-out tires, and raw materials in warehouse:

$$\sum_i \sum_p EIht^p . ILI_i^{p,t,s} + \sum_j \sum_p EIht^p . (ILJ_j^{p,t,s} + ILJ'^{p,t,s}_j) + \sum_o \sum_p EIht^p . IL_o^{p,t,s} + \sum_k \sum_p EIhr^p . IK_k^{p,t,s}$$

$$\sum_n \sum_c EIhm^c . ICN_n^{c,t,s} + \sum_i \sum_c EIhm^c . ICI_i^{c,t,s}$$

Objective functions (3)-(5) represent the social dimension.

4.3.3 Establishing facilities in regions with high unemployment rate

$$Maxf_3 = \left(\sum_i \mu f_i . M_i + \sum_j \mu d_j . D_j + \sum_o \mu r_o . L_o + \sum_k \mu c_k . C_k + \sum_n \mu s_n . R_n \right) \tag{3}$$

4.3.4 Establishing facilities in regions with low population density

$$Min\, f_4 = \left(\sum_i \delta f_i . M_i + \sum_j \delta d_j . D_j + \sum_o \delta r_o . L_o + \sum_k \delta c_k . C_k + \sum_n \delta s_n . R_n \right) \tag{4}$$

Objective functions (3) and (4) maximize social impacts by taking into account the unemployment rate and the population density. Objective function (3) forces the model to select locations with higher unemployment rate, while objective function (4) seeks to select regions with lower population density and higher need for development.

4.3.5 The impact of green technology on job creation

$$Max\ f_5 = \left(\sum_e jo_e . yf_e + \sum_{e'} jo'_{e'} . yr_{e'} + \sum_{e''} jo''_{e''} . ys_{e''} \right) \tag{5}$$

The objective function (5) maximizes the rate of employment created by the establishment of green technology in the tire manufacturing plant, the tire regeneration plant, and the recycling center, which is in line with environmental and social objectives.

4.3.6 Constraints

$$\sum_i X_i^{p,t,s} \le Cam^P \qquad \forall p,t,s \tag{6}$$

$$\sum_k \sum_o \sum_v Yf_{k,o,v}^{p,t,s} \le Caf^p \qquad \forall p,t,s \tag{7}$$

$$\sum_k \sum_n \sum_v Yr_{k,n,v}^{p,t,s} \le Car^p \qquad \forall p,t,s \tag{8}$$

Constraints (6) - (8) represent total production capacity of manufacturing, remanufacturing and recycling centers respectively.

$$\sum_i ILI_i^{p,t-1,s} + \sum_i X_i^{p,t,s} = \sum_i ILI_i^{p,t,s} + \varepsilon.\sum_i X_i^{p,t,s} + \sum_i \sum_j \sum_v Xm_{i,j,v}^{p,t,s} + ailf^{\,p} \qquad \forall p,t,s \qquad (9)$$

$$\sum_j ILJ_j^{p,t-1,s} + \sum_i \sum_j \sum_v Xm_{i,j,v}^{p,t,s} = \sum_j ILJ_j^{p,t,s} + Dc^{p,t,s} + aild^{\,p} \qquad \forall p,t,s \qquad (10)$$

$$\sum_j ILJ'^{p,t-1,s}_j + \sum_o \sum_j \sum_v Xf_{o,j,v}^{p,t,s} = \sum_j ILJ'^{p,t,s}_j + Dc'^{p,t,s} + aild'^{\,p} \qquad \forall p,t,s \qquad (11)$$

$$\sum_k IK_k^{p,t-1,s} + \varepsilon.\sum_i X_i^{p,t,s} + \sum_k Y_k^{p,t,s} = \sum_k IK_k^{p,t,s} + Dw^{p,t,s} + \qquad \forall p,t,s \qquad (12)$$

$$\sum_k \sum_n \sum_v Yr_{k,n,v}^{p,t,s} + \sum_k \sum_o \sum_v Yf_{k,o,v}^{p,t,s} + Yd^{p,t,s} + ailc^{\,p}$$

$$\sum_o IL_o^{p,t-1,s} + \sum_k \sum_o \sum_v Yf_{k,o,v}^{p,t,s} = \sum_o IL_o^{p,t,s} + \sum_o \sum_j \sum_v Xf_{o,j,v}^{p,t,s} + aill^{\,p} \qquad \forall p,t,s \qquad (13)$$

Constraints (9) - (13) 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.

$$\sum_n ICN_n^{c,t-1,s} + \sum_n \sum_{e''} Zr_{n,e''}^{c,t,s} = \sum_n ICN_n^{c,t,s} + \sum_n \sum_i \sum_v Zt_{n,i,v}^{c,t,s} + Dn^{c,t,s} + ails^{c} \qquad \forall c,t,s \qquad (14)$$

$$\sum_i ICI_i^{c,t-1,s} + Z^{c,t,s} + \sum_i \sum_n \sum_v Zt_{n,i,v}^{c,t,s} = \sum_i ICI_i^{c,t,s} + \sum_i \sum_p We^{p}.\omega^{c,p}.X_i^{p,t,s} \qquad \forall c,t,s \qquad (15)$$

$$+ailf'^{\,c}$$

Constraints (14) and (15) ensure the inventory balance for raw materials in recycling and manufacturing centers in each period respectively.

$$\sum_k \sum_n \sum_v \sum_p We^{p}.\omega^{c,p}.Yr_{k,n,v}^{p,t,s} = \sum_n \sum_{e''} Zr_{n,e''}^{c,t,s} \qquad \forall c,t,s \qquad (16)$$

The equality constraint (16) computes the amount of the recycled material that is produced from each type of tire.

$$\sum_i \sum_p St^{p}.ILI_i^{p,t,s} \le CI \qquad \forall t,s \qquad (17)$$

$$\sum_j \sum_p St^{p}.(ILJ_j^{p,t,s} + ILJ'^{p,t,s}_j) \le CJ \qquad \forall t,s \qquad (18)$$

$$\sum_k \sum_p St^{p}.IK_k^{p,t,s} \le CK \qquad \forall t,s \qquad (19)$$

$$\sum_{o}\sum_{p} St^{p}.IL_{o}^{p,t,s} \leq CO \qquad \forall t,s \qquad (20)$$

Constraints (17) - (20) are inventory capacity constraints in each center.

$$\sum_{i}\sum_{c} Sm^{c}.ICI_{i}^{c,t,s} \leq CI' \qquad \forall t,s \qquad (21)$$

$$\sum_{n}\sum_{c} Sm^{c}.ICN_{n}^{c,t,s} \leq CN \qquad \forall t,s \qquad (22)$$

Constraints (21) and (22) ensure that the inventory level of raw material in each center does not exceed the capacity of the center's active warehouses.

$$\alpha^{p,t,s}.\left(Dc^{p,t,s} + Dc'^{p,t,s}\right) + q^{t,s} = \sum_{k} Y_{k}^{p,t,s} \qquad \forall p,t,s \qquad (23)$$

Constraint (23) indicates the amount of collected worn-out tires.

$$\sum_{p} EIdis^{p}\,Yd^{p,t,s} \leq ro \qquad \forall t,s \qquad (24)$$

Constraint (24) prevents the environmental impact of tire landfilling from exceeding the permissible limit.

$$\sum_{i} M_{i} = 1 \qquad (25)$$

$$\sum_{j} D_{j} = 1 \qquad (26)$$

$$\sum_{k} C_{k} = 1 \qquad (27)$$

$$\sum_{n} R_{n} = 1 \qquad (28)$$

$$\sum_{o} L_{o} = 1 \qquad (29)$$

Constraints (25) - (29) prevent allocating more than one location to each center.

Technology allocation to centers:

$$\sum_{e} yf_{e} = 1 \qquad (30)$$

$$\sum_{e'} yr_{e'} = 1 \tag{31}$$

$$\sum_{e''} ys_{e''} = 1 \tag{32}$$

Constraints (30) - (32) ensure that at most one technology is allocated to the related centers.

5. The model implementation

5.1. Case study

Barez industrial group is Iran's first tire manufacturing company that has established new plants in the western region of Iran. Its closed-loop tire supply chain network includes two potential sites for new tire production plant, four potential sites for distribution centers, four potential sites for worn out tire collection centers, three potential sites for retreading used tires, three potential sites for scrap tire recycling centers, three sites for cement kilns as energy recovery centers, and four centers for scrap landfills. These sites are in different locations with different fixed costs of establishing the facilities and different regional factors.

The main plant produces four types of tires, including tires for automobiles, passenger buses, trucks, and agricultural and industrial trucks, and three types of raw materials, including steel wires, polyamide yarns, and granules. The production planning periods are seasonal. There are two types of vehicles used for transportation, which have different capacities, costs, and different environmental impacts. 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. The advanced environmental protection technology performs retreading and recycling efficiently and is environmentally friendly but it entails higher costs. However, research shows that compliance with sustainability standards increases the market share, because customers, in general, are more willing to buy the products/services of the companies that comply with sustainability standards (Gong et al., 2019).

There is a trade-off between the investment cost of the environmental protection technology and its environmental protection efficiency. Furthermore, advanced technologies eliminate more low skilled jobs because of higher level of automation while at the same time create more jobs for highly skilled workers. Thus, it has twofold impact on the job creation.

At the material purchasing stage, using recycled materials in production has less environmental impact than purchasing them from external suppliers. During the transportation phase, although the cost of rent is higher for larger trucks, but this type of vehicle is more environmentally friendly. At the end of the phase for collecting used-tires, the collection of worn-out tires from end-consumers entails high expenses but it helps protect the environment. The energy recovery phase in furnaces, including the retreading and recycling process, has a positive impact on the environment.

5.2. The model solutions

The data used to solve the mathematical model is provided in Appendix B. The data on environmental parameters was collected based on the results of Corti and Lombardi (2004), Ferrão et al. (2007), and Subulan et al. (2015). In addition, the real operational data from year 2017 to year 2019 has been collected from the supply chain under study.

The LP-metric method (presented in Appendix A) is applied to deal with the multi-objectivity of the model. Lp-metric is a common method for solving multi-objective problems, where there is trade-off between the objectives. It means that improving one objective would result in the deterioration of other objectives. Lp-metric is a non-interactive optimization method. That is, in the process of solving the model, interaction with the decision-maker is not required.

In the developed model, the parameters of customer demand and the rate of return of worn-out tires are of uncertain nature. The scenario-based random programming approach is applied to deal with the uncertainty, where different scenarios are considered for different conditions.

The scenarios for demand and return rates for worn-out tires are as follows:

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

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

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

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

The optimal values of the continuous variables under different scenarios for the planning horizon are obtained and is presented in figures (5-8), in appendix C. Solution for these variables determines the optimal value of new tire production and the number of collected used-tires considering economic and environmental objectives are. In addition, the optimal allocation of used-tires to remanufacturing factory, recycling center, energy recovery and landfilling is obtained. Inventory level of new tires and used-tires are computed to minimize the inventory holding costs and environmental impacts. The model determines the amount of purchased raw materials at the tire factory and also the transported products and raw materials by each vehicle between established facilities in the supply chain.

5.3 Sensitivity analysis

After obtaining the optimal solutions of the proposed model for the problem under study, the sensitivity analysis is performed, which examines the effects of possible changes in the input parameters of the problem on the current solutions of the model. In other words, sensitivity analysis seeks to determine the percentage of model solution changes by changing the input parameters of the problem. 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.
- Evaluating the economic and environmental objective functions according to different weight percentages.
- The impact of green technology establishment in different centers on economic, environmental, and social dimensions
- Evaluating the social objective functions.

5.3.1 Impact of change in uncertain parameters on economic and environmental objective functions

According to Table 2, under the third scenario (high demand and return rate) despite the increase in return rate due to an increase in production volume, the environmental and economic (profit) objective functions increase by 21% and 28% respectively compared to the second scenario. A decline in the demand under the first scenario and consequently a decrease in the rate of return of worn-out tires by 20% results in a decrease in the environmental objective function by 22.8% and in the economic objective function by 32.5%. However, the demand in different centers for different products has risen from 20% to 35% under different scenarios and for different products. It can be seen that the rate of change in objective functions according to each scenario is proportionate to the percentage of changes in demand. Generally speaking, high demand condition causes the profit of whole supply chain to increase but at the same time it creates 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

5.3.3 Evaluating the economic and environmental objective functions with respect to different weight percentages disregarding the social objectives

Considering the second scenario, diffirent weights are assigned to the economic and environmental objective functions. The weights of these objective functions are denoted by w_1 and w_2 respectively which is determined by the decision makers. The sum of the weights should equal 1 . The objective function values are obtained with regard to different combinations of the weights.

These values are in fact a set of Pareto-optimal solutions, which are presented in Table 3. The negative values for the profit objective function indicate the loss.

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 2 also shows the Pareto-optimal solutions. There is a conflict between the economic and environmental objectives so that the improvement in one of the them leads to the deterioration of the another.

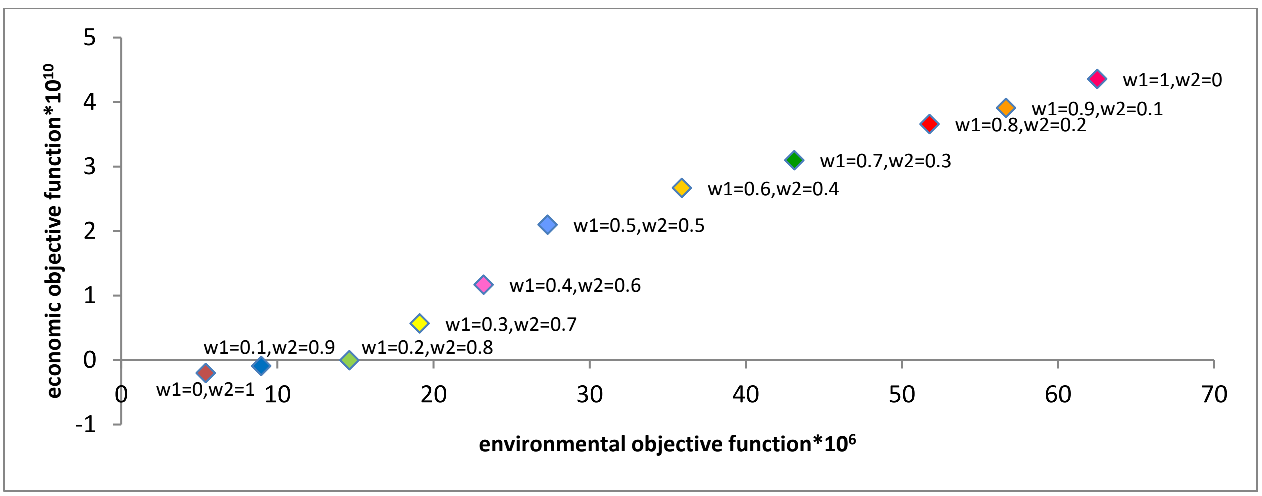

Figure 2- The Pareto-optimal solutions

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 situation the model can reach the highest profit but at the same time environmetntal impacts reach the maximum level. On the other hand, when ($w_1 = 1, w_2 = 0$), model tries to minimize the environmental objective fumction and does not consider the economic objectives. In order to minimize the environmental function, model recommends closing all sites and plants.

Furthermore, by plotting the trend line of different points in Figure 2, it can be seen that there is an approximately linear relationship between the values of economic and environmental objective functions with regard to the applied weight combinations, Figure 3 shows this relationship. These functions are positively correlated to each other ($R^2 = 0.9707$). It means increasing economic objective function creates more environmental impacts.

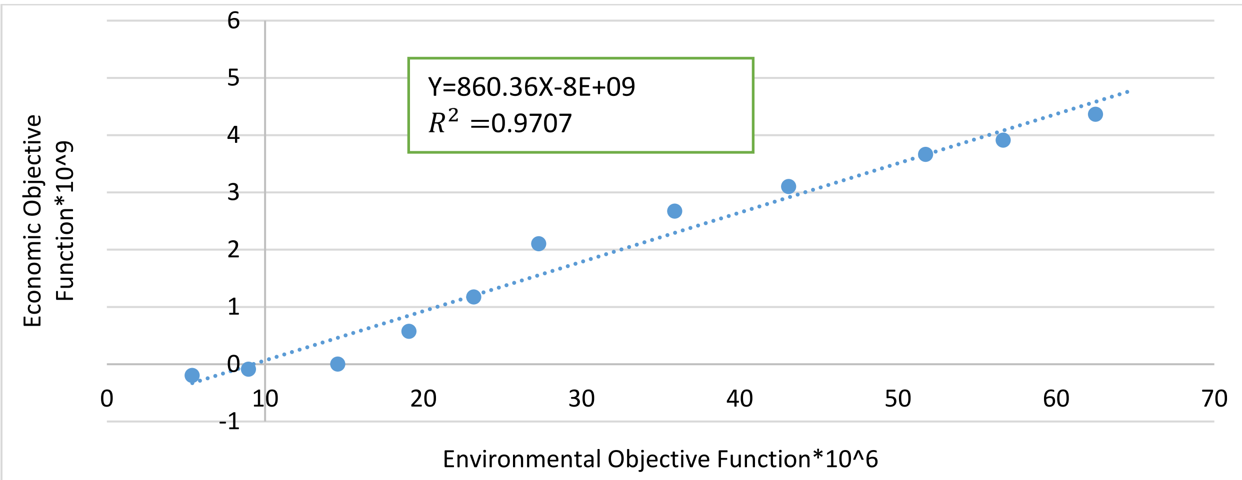

Figure 3- The trend line for the economic and environmental objective function values

5.3.3 The impact of green technology establishment in different centers on economic, environmental, and social dimensions

As it was mentioned before, establishing more advanced environment protection technologies requires higher investments, where automating the processes reduces the environmental impacts. However, its impact on the social dimension is complicated. The advanced environmental protection technology, eliminates more low skilled jobs while at the same time create more jobs for highly skilled workers. On the whole, more advanced technology cuts the jobs. Table 4 shows the best environmental technologies for different facilities. The first column shows the optimal green technology if only the economic objective is considered, and the second column indicates the optimal solution if we consider the social objective only. The fourth column shows the optimal green technologies considering the three dimensions together. Technology number 3 in each facility is the most advanced one.

Table4- Optimal green technologies considering sustainability dimensions

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

5.3.4 Evaluating the social objective functions

The optimal locations of facilities are shown in Table 5. In Table 5, the numbers indicate the location number. For instance, number 3 in ‘‘Distribution center’’ row means distribution center 3. The second column shows the optimal locations if only the economic objective is considered, and the third column indicates the optimal locations if we consider the social objective only. Based on Table 5, it can be concluded that taking into account the indicators of unemployment rate and regional development affects the choice of facility locations. Hence, the social index plays an important role in choosing the optimal location. The fifth column shows the optimal locations of facilities considering the three objectives together. According to the results presented in Table 5, social indicators in 80% of cases affect the choice of location. It is because of 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	-	2
Remanufacturing	1	2	-	2
Recycling	3	2	-	2

The economic and environmental functions are also affected when social indicators are considered, because of the change in location and green technology selection. With relocation, the distances between the various supply chain centers changes, resulting in changes in costs and pollutant emissions. The computational results are presented in table 6 and figure 4. The second scenario is considered in this section. Overall, taking into account the social indicators causes a slight increase in the costs and environmental impacts, which would not justify disregarding the social considerations in closed-loop SCND.

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

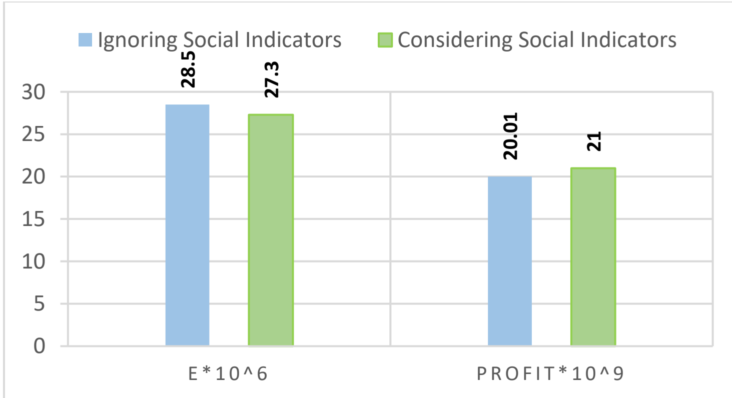

Figure 4- The economic and environmental objective function values

5.4. Managerial implications

The following managerial implications are drawn for decision makers:

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 also 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 SCND phase in order to prevent uncontrolled immigration to large cities and subsequent issues. Paying attention to these factors also can increase the sales and guarantee the long-term profitability of supply chains. The model determined the optimal location of facilities considering regional factors such as unemployment rate and population density in addition to the cost factors to prevent the concentration of industries in large cities.

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

Another solution to reduce the environmental impact of the tire supply chain is utilizing green technologies. Although more advanced environment protection technology can be expensive, but it has minimum environmental impact and it improves the product quality and customer satisfaction which can compensate the investment costs. Establishing these technologies has twofold impact on the job creation: it may retrench excess workers but at the same time it could create opportunities for highly skilled workers. Given the need for skilled workforce to use green technologies, managers must make sure that the required workforce is available before choosing the type of technology.

Managers need to appreciate the importance of each dimension of sustainability in a balanced way in the supply chain. However, in times of recession, the importance of the economic dimension increases for the survival of the industry and it should be weighed more.

In this paper, instead of evaluating the environmental impacts separately based on each green technology, the average impact is considered. Additionally, creating job opportunities is not evaluated based on dividing the workforce into low-skilled and skilled workers. Future researches can consider this issue.

6. 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 multi-objective, mixed-integer, linear programming model for a real-world problem of designing sustainable tire supply chain network under uncertainty. The developed model is capable of examining environmental, social, and economic issues in the entire closed-loop tire supply chain. Scenario approach was utilized to deal with the uncertainty. The LCA approach was also used to assess environmental and social impacts. From a theoretical point of view, this article 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 and the Banders decomposition algorithm were applied to solve the mathematical model with multiple objectives. The proposed model was validated using data from 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 closed-loop supply chain of this study minimizes the landfilling and burning of worn-out tires.

This research can be extended in future. 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, lack of real information and historical data for some parameters of the problem such as costs and social and environmental impacts add to the uncertainty in the problem. Investigating and modeling CLSC 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 in CLSC context 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. In addition, other methods of recovering worn-out tires can be considered in future studies.

Declarations:

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Ethics approval: This manuscript is an original work and has not been published elsewhere in any form or language (partially or full) and that it has not been submitted simultaneously for publication elsewhere. It contains no matter that scandalous, obscene, fraud, plagiarism, libellous, or otherwise contrary to law.

Conflicts of interest/Competing interests: The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Availability of data and material: Real Data were used to solve the problem that are appended.

Code availability: software application or custom code are available that provided upon request

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8. Appendix A - Lp-metric method

This 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 $f_i(x^*)$.

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

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.

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

9. Appendix B

Table 1- Variable costs

Tire Type	Tire production cost (Toman)			Tire remanufactured cost (Toman)		Tire recycling cost (Toman)	
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- fixed costs (In terms of billions of Tomans)

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- Price unit in Tomans

Fixed cost of establishing technology *e* in a tire factory	100000000-120000000
Fixed cost of establishing technology *e'* in tire remanufacturing factory	80000000-120000000
Fixed cost of establishing 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 the centers (km)	40-550
Demand of new tire type *p* in time period *t* in scenario *s*	1000-8000
Demand of remanufactured tire type *p* in time period t under scenario *s*	100-1200
Customer demand of raw material type *c* in time period *t* under scenario *s* (kg)	1000-3500
Demand of used tire type p for energy recovery in time period t under scenario *s*	500-1500
Total production capacity of new tire type *p* in tire factory	45000-75000
Total production capacity of tire type *p* in tire remanufacturing factory	45000-75000
Total recycling capacity of used tire 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 type *p*	900000-5000000
Selling price per unit of remanufactured tire type *p*	500000-2500000
Selling price per unit of used tire type *p*	5000-25000
Selling price per unit of raw material tire type *c*	20000-60000-280000
Transportation cost per unit of tire type *p* in one kilometer, with vehicle *v*	1200-2500
Transporting cost per unit of raw material 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 those who deliver worn-out tires to collection centers	0.1
Percentage of tire selling type *p* to those who deliver used tires to collection center in time period *t* under scenario *s*	0.3-0.7
Number of jobs created with the establishing of green technology e, in tire factory	25-45
Number of jobs created with the establishing of green technology *e'* in tire remanufacturing factory	30-35
Number of jobs created with the establishing of green technology *e''* in recycling center	35-40
Unemployment rate	0.07-0.11
Population density (People per hectare)	35-100

Table 4- 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- Production phase

	Technology 1				Technology 2				Technology 3			
Tire type	Car	bus	truck	Industrial machines	car	bus	truck	Industrial machines	Ca r	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- 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- 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- Storage phase

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

Table 9- 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- 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

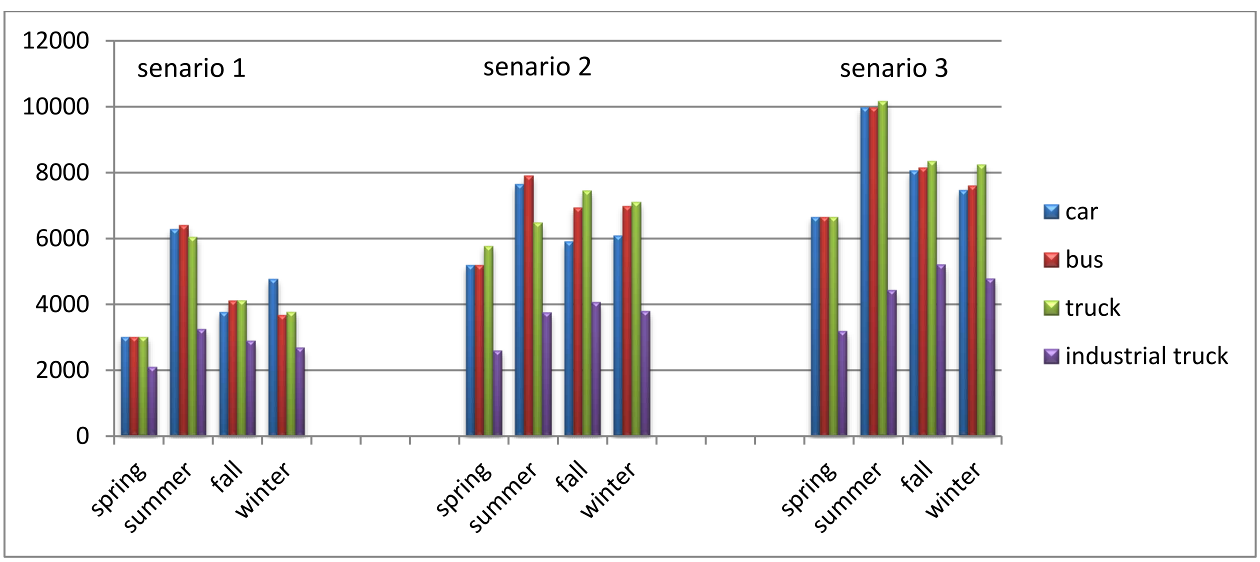

Figure 1- Number of new produced tire type p in tire factories in time period t under scenario s (unit)

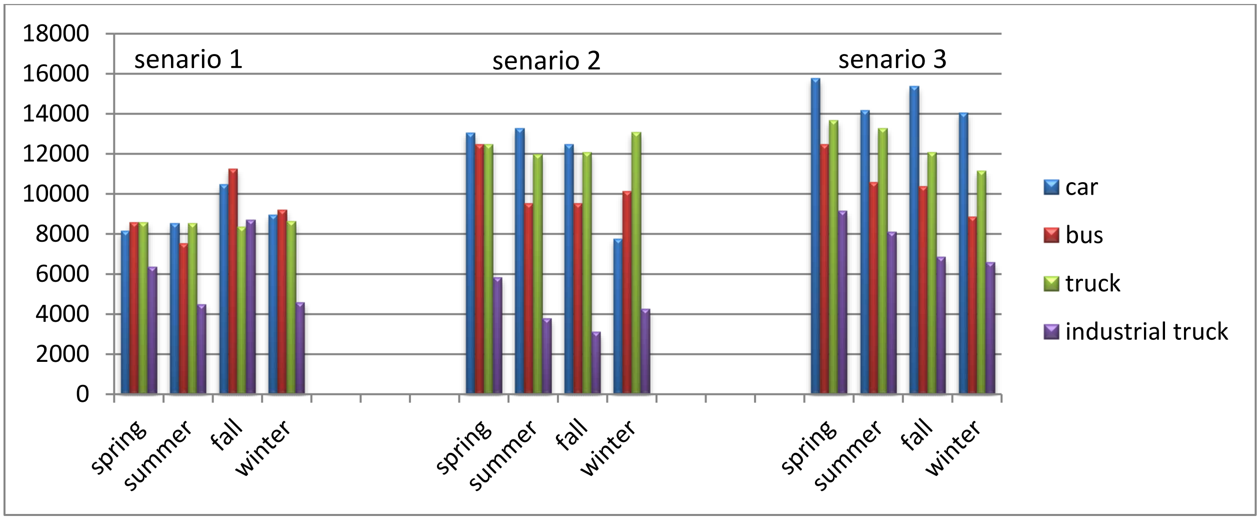

Figure 2- Number of transported used tire type p to remanufacturing factory in time period t under scenario s

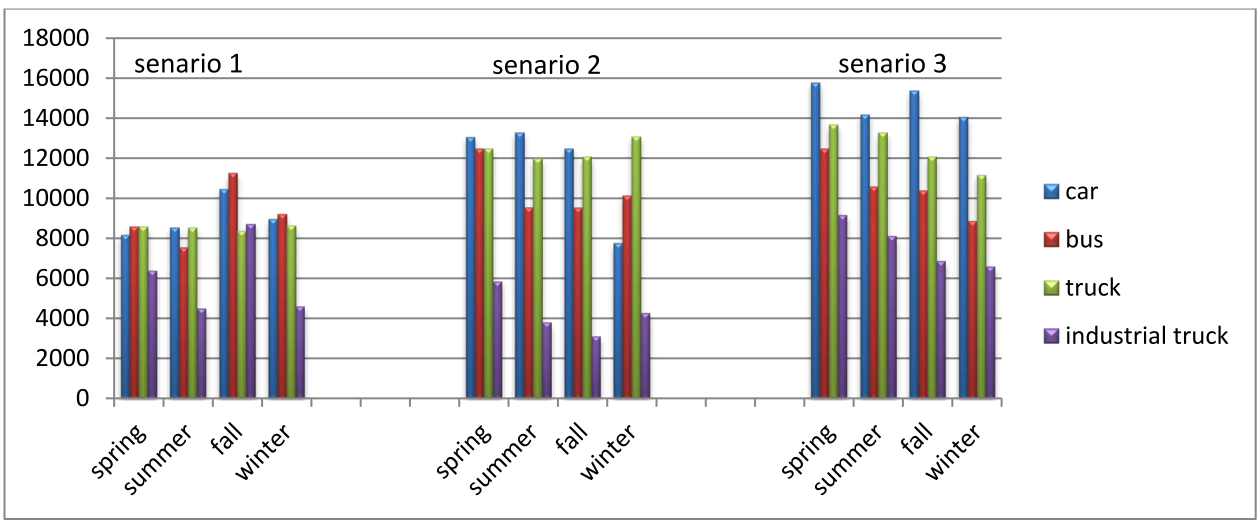

Figure 3- Number of transported used tire type p to recycling center in time period t under scenario s

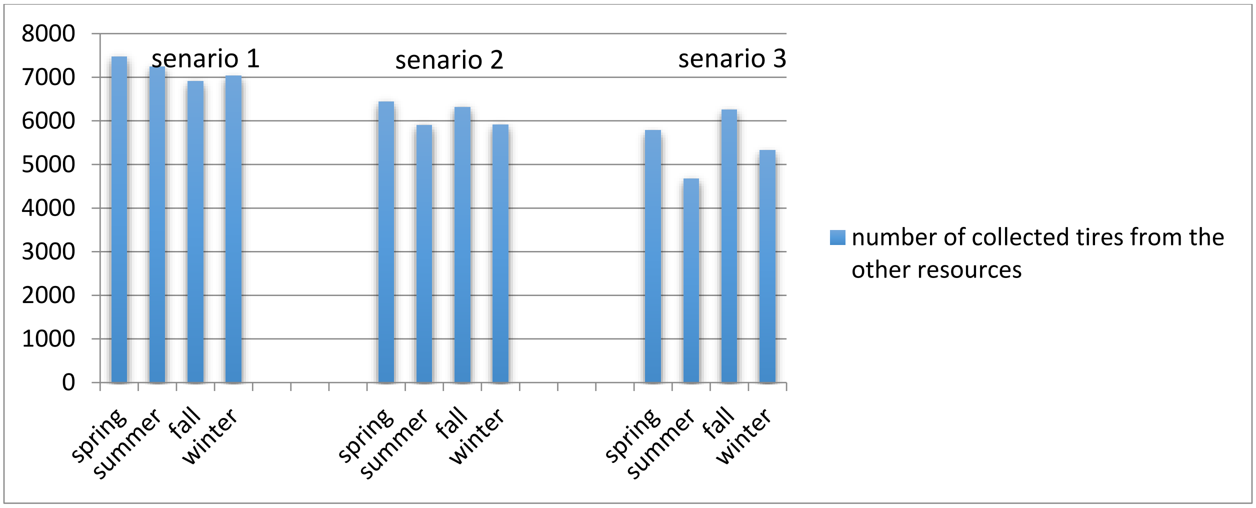

Figure 4- Number of collected tires form other sources in time period t under scenario s

Figures

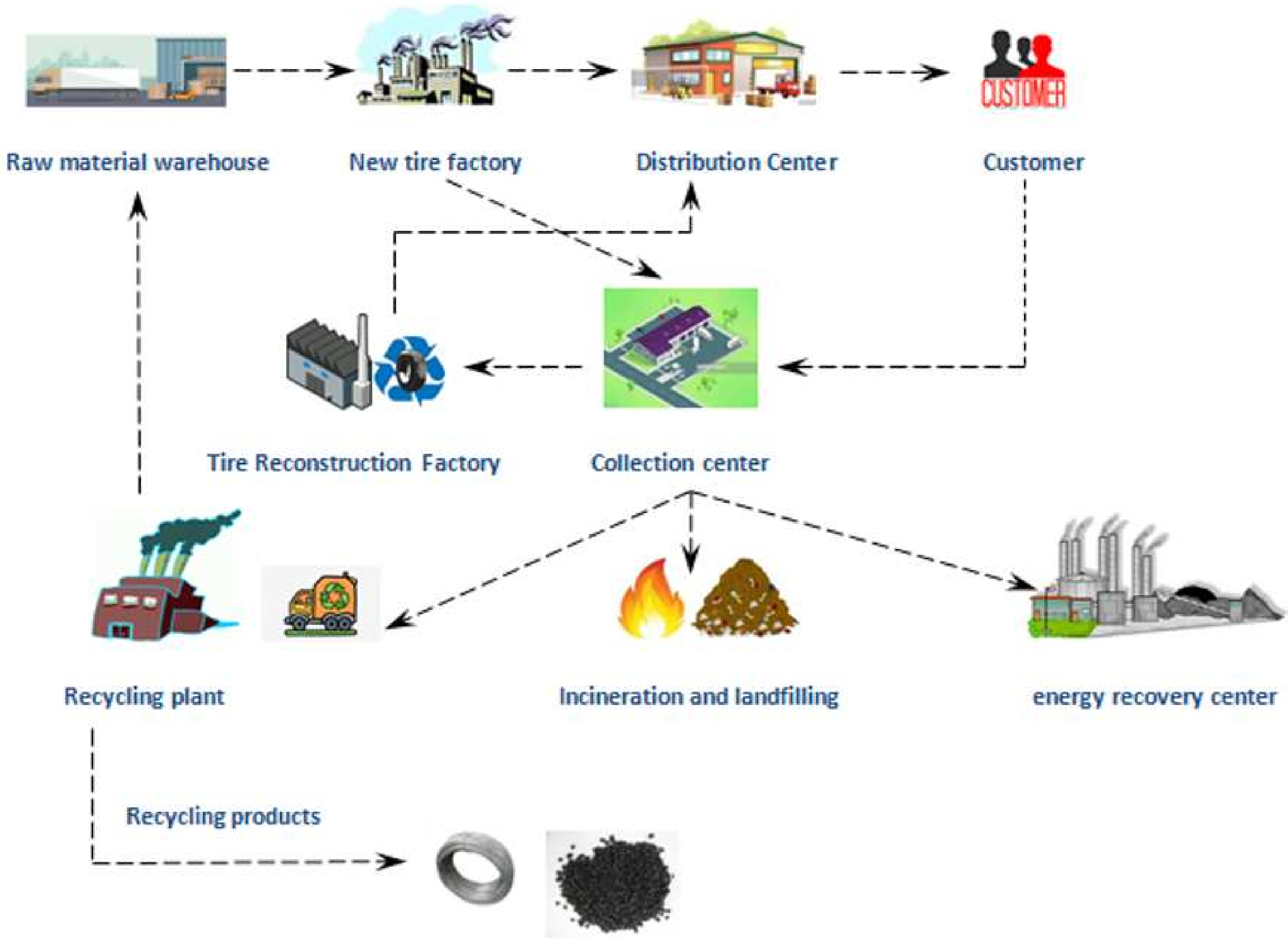

Figure 1

The tire closed-loop supply chain network

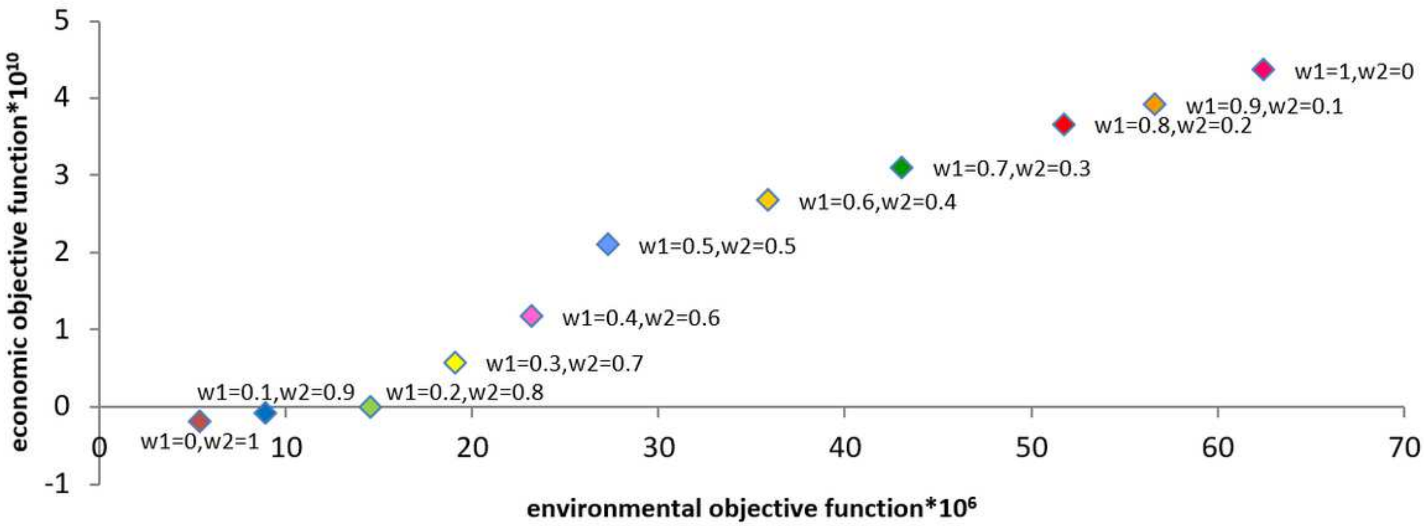

Figure 2

The Pareto-optimal solutions

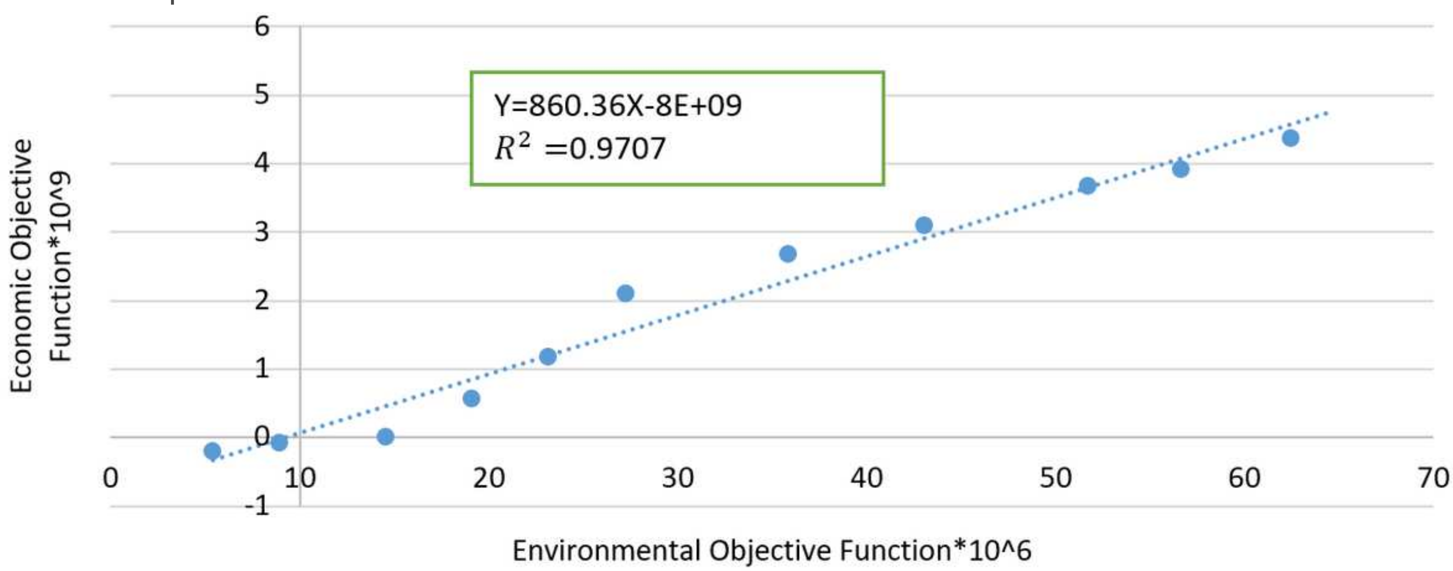

Figure 3

The trend line for the economic and environmental objective function values

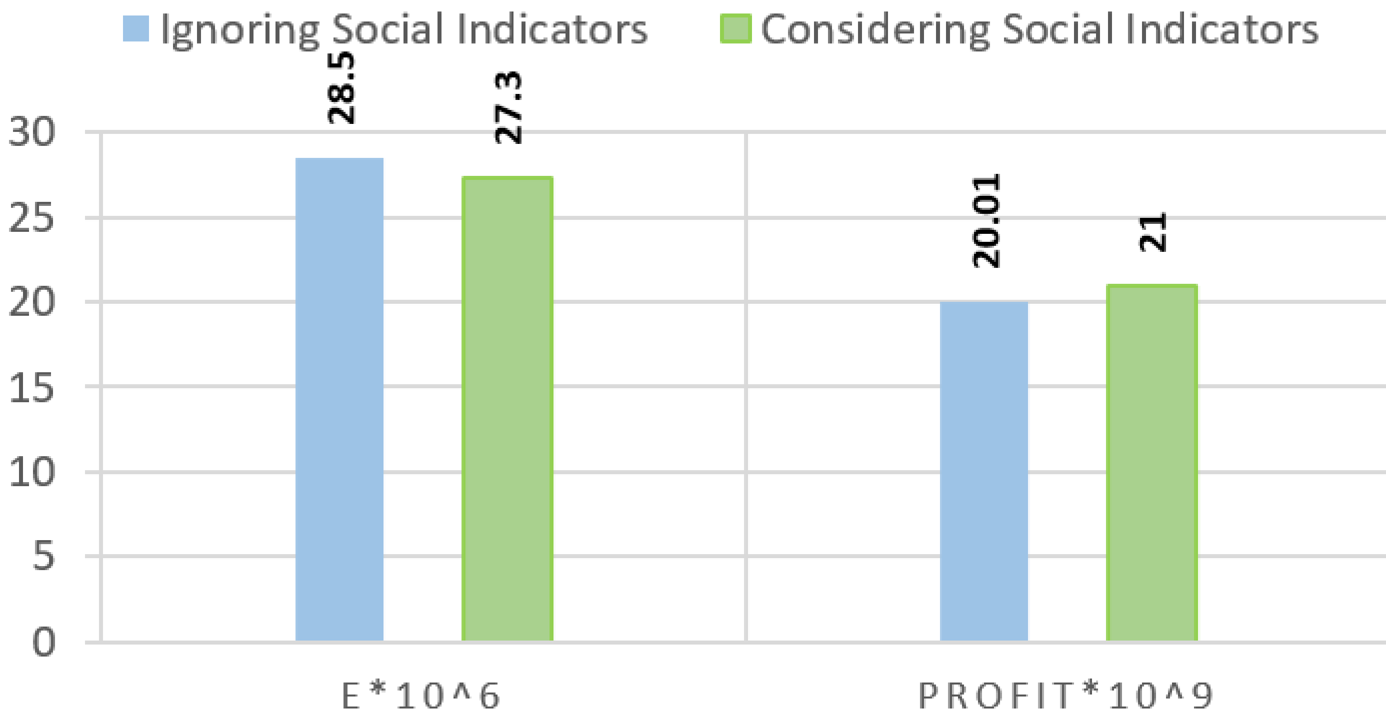

Figure 4

The economic and environmental objective function values