Journal of Cleaner Production 207 (2019) 163–181

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Modeling and solving a sustainable closed loop supply chain problem with pricing decisions and discounts on returned products

Ata Allah Taleizadeh [a], Farnoosh Haghighi [a], Seyed Taghi Akhavan Niaki [b,*]

[a] School of Industrial Engineering, College of Engineering, University of Tehran, Tehran, Iran
[b] Department of Industrial Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 18 November 2017
Received in revised form
27 August 2018
Accepted 24 September 2018
Available online 29 September 2018

Keywords:
Sustainable supply chain
Closed-loop supply chain
Multi-objective mixed integer programs
Pricing
Discount offer

ABSTRACT

Increasing rates of environmental and social concerns involved in various communities have recently attracted researchers' attention to consider them in proper designs of sustainable supply chains (SSCs). In this paper, the planning problem of a multi-period multi-echelon sustainable closed loop supply chain (SCLSC) is investigated. A comprehensive model that seriously takes into account the social and environmental aspects of the supply chain (SC) decisions and measures their social and environmental effects using the GRI (Global Reporting Initiative) guideline indicators is proposed. The proposed planning model includes tactical decisions comprising the price of the product and logistic decisions. A discount offer is used on the returned product as an incentive policy to increase customers' willingness to return back the used products. In this offer, the discount depends on the quality of the returned products. Besides, as the discount for upcoming purchases stimulates customers to buy new products more, the product demand depends on the discount offer in addition to the product price. Moreover, two recovery approaches including remanufacturing and recycling alongside disposing of very low quality returned products are considered. Categorizing returned products according to their quality, quality-dependent recovery decisions for returned products, and the quality-dependent discount offer is the other novel points of this paper. The proposed model is implemented in a case study involving a CFL light bulbs supply chain. The TH (Torabi-Hassini) procedure is employed to solve the newly-developed three-objective optimization problem. The results of sensitivity analyses on the case-study demonstrate that the discount offer significantly improve the collecting rate of used products, which in turn helps improving sustainability. Finally, the Pareto optimal solutions show that the proposed approach provides a comprehensive planning model for SSCs which enables the decision makers to use a proper solution that considers legislation, social preference, cost, and environmental objectives.

1. Introduction

The scarcity of natural resources and increasing environmental pollution rate concerns different human societies on the future of human life. Throughout history, however, industrial achievements and development improved the economics of the societies, lead to higher employment rate, and brought advantages to individuals and organizations. On the other hand, it resulted in more complicated environmental and social problems that caused an increasing attention to sustainability in the recent years. Supply chains (SCs) are known as the main source of carbon emission which causes global warming (Ahmed and Sarkar, 2018). As economic, environmental, and social effects of each decision made in an SC are taken into account, sustainability has become one of the most important issues to be considered in designing many SCs.

One of the most harmful effects of production is the growing number of end-of-life (EOL) products. Traditional supply chains, called forward supply chains, ignore the EOL products regardless of the damage they impose on the environment. However, a properly designed sustainable SC brings the least damage to the environment. The reverse logistics in closed-loop supply chains (CLSCs) is the best solution for EOL products by collecting and reusing the used products in the forward direction again. As CLSCs help sustainability in many aspects including reductions in the energy, in material consumption, and in discarded obsolete products, in this

* Corresponding author.
E-mail addresses: taleizadeh@ut.ac.ir (A.A. Taleizadeh), haghighi.farnoosh@ut.ac.ir (F. Haghighi), niaki@sharif.edu (S.T.A. Niaki).

https://doi.org/10.1016/j.jclepro.2018.09.198
0959-6526/

paper, the planning problem of a multi-period multi-echelon sustainable closed-loop supply chain (SCLSC) is investigated.

A CLSC can meet several needs if the reverse logistics perform efficiently. One critical factor that influences the performance of a reverse logistics is the consumers' willingness to bring back their used products (Shaharudin et al., 2015a). However, there are a few people with proper social responsibility in any community who return back their used products to collection centers. This leads to collection centers having low performances. Nonetheless, the efficacy of a collection process is a prerequisite for an efficient CLSC network (Geyer and Blass, 2010). Thus, incentive plans are needed to increase customers' willingness to return their used products. In the recent literature, researchers suggested different promotional offers to increase the collection rate of used products by increasing the consumers' willingness to return back their obsolete products (Guide et al., 2003; Das and Dutta, 2013; Litvinchev et al., 2014; Govindan et al., 2015). It has also been shown in these works that some of the incentive policies to increase the return rate of used products influence the demand for new products. For instance, Das and Dutta (2013) demonstrated that a product exchange policy employed in a CLSC not only enhances the total demand but also increases the collection rate of the used products concurrently. The other important aspect of collecting products in reverse logistics is the quality of the returned products. Guide et al. (2003) presented a model which demonstrates that the buy-back price of the used products should be proportionate to their quality. A few years later, Aras and Aksen (2008) suggested a mixed integer model which determines the optimal price of the buy-back offer for each used parts based on its quality.

Obviously, returned products with various qualities need different planning. In most of the studies in the existing literature on reverse logistic, the quality of returned products is not considered for planning purposes. In other words, it is usually assumed that all of the collected products can be used for remanufacturing, recycling, or other recovery options and that the quantity of returned products selected for each recovery is a decision variable. This is not true in the real world, where returned products with various sizes, different ages, and diverse way of uses are worn. For example, one cannot remanufacture very low quality returned products, as they should be recycled or disposed of. In other words, contrary to what assumed in most of reverse logistics and CLSCs works, the quantity of returned products chosen for different recovery options including remanufacturing, recycling, disposal, etc. is not an independent decision variable but depends on the quality of the returned products.

One of the contributions of the current study is to plan for returned products according to their quality. To this aim, the returned products are classified into three categories based on their quality, each suitable for remanufacturing, recycling, and disposal. In addition, a quality-dependent incentive policy is used to increase consumers' willingness to returning back their used products. In short, the current study tries to find the answers to the following questions:

- How can one plan for the collected used products based on their quality such that the waste is minimized?
- How can one increase the rate of returning back the used products and also to increase the product demand by employing an incentive plan?
- Considering the conflicts between minimizing the cost and minimizing the negative environmental and social impacts, is it possible to reach an optimum solution based on the existing legislation, limitations, and priorities?

To answer the above questions, a multi-echelon SCLSC that consists of a plant, a remanufacturing center, a retailer, a recycling center, a collection center, and a disposal center is considered in this paper. The investigated SC is assumed to be a centralized chain because in a decentralized SC each participant aims to minimize its own cost not the total cost of the SC (Panda et al., 2017a). A mixed integer multi-objective programming is proposed to determine tactical decisions comprising the product price, the price involved in the discount offer, the decision on installing an additional capacity from a set of accessible capacities, inventory decisions, and length of periods. Besides, logistics decisions including the total production, procurement decisions, determining production technology, and the number of vehicles are determined. Three objective functions are defined to minimize the cost, the negative environmental and social effects. The main contribution of the current work is developing a comprehensive programming model to planning an SCLSC and evaluating all of the social and environmental aspects of the decisions that employ the global reporting initiative (GRI) guideline indicators. A discount policy is employed as an incentive plan to increase the return rate of the used products. Customers can use the discount offer in their future purchases. The discount depends on the quality of the used products. As another novelty in this study, the returned products are categorized according to their quality, based on which the recovery decisions are made. On the other hand, the proposed discount offer influences the demand for new products. In other words, in addition to the product price and the goodwill, the demand for new products is considered as a function of the discount offer price. The proposed programming is implemented on a case study of a CFL light bulbs supply chain. An efficient solution approach called TH (Torabi-Hassini) is utilized to solve the tri-objective optimization problem at hand. In the fuzzy TH approach, the degree of each objective satisfaction is measured; enabling one to find the best solutions considering various legislations and priorities of the social, environmental, and financial issues.

The rest of this paper is organized as follows. In Section 2, a short literature of reverse logistics and CLSC models evaluating environmental and social effects in SSCs is presented. The problem description, the incentive plan to return the used products, alongside the way the returned products are categorized based on their qualities all come in Section 3. Section 4 demonstrates the formulation of the problem including the objective functions and the constraints. Section 5 presents the employed solving approach. Section 6 provides a case study, based on which the tradeoffs among the objective functions are analyzed. Finally, Section 7, exposes the conclusions and suggests some future research directions.

2. Literature review

As the concentration in this paper is on planning an SCLSC, the literature is briefly reviewed in the following two streams: (1) reverse logistics and CLSCs models and (2) evaluating environmental and social effects in SSCs.

2.1. Reverse logistics and CLSCs models

The known activities involved in a forward SC include providing raw materials, planning the production, product delivery, and sales (Krikke et al., 2003). Meanwhile, reverse logistics incorporate all of the activities related to the reuse of raw materials and products including the returned product collection, sorting the returned products based on their quality, repairing, remanufacturing, refurbishing, and proper disposal of the returned products. In addition, a CLSC is a network that integrates all the activities involved in both forward and reverse logistics in order to avoid sub-optimality.

CLSCs also cause amplifying of products' created values in their lifecycles.

There is an extensive literature on the reverse logistics and CLSC studied in different fields such as remanufacturing (Xia et al., 2015; Abdulrahman et al., 2015; Du et al., 2012), waste management (Ning et al., 2013; Song et al., 2015; Kurdve et al., 2015), reuse (Matsumoto, 2010; Gelbmann and Hammerl, 2015), recycling (Murakami et al., 2015; Demirel et al., 2016), recovery (Ziout et al., 2014; Shaharudin et al., 2015b), disassembling (Go et al., 2011), and other aspects of CLSCs. Interested readers are referred to Sasikumar and Kannan (2009), Junior and Filho (2012), and De Giovanni (2016) for exhaustive reviews of the CLSC literature.

2.2. Evaluating environmental and social effects in SSCs

The increase of interests in environmental and social problems in the last decade leads to a significant rise in the tendency of designing sustainable supply chains. Nowadays, sustainability is one of the most important topics in supply chain network design, because all economic, environmental, and social effects of each SC decision are taken into account in SSCs.

The environmental influence is frequently measured by the carbon emissions indicator. While there is an extensive literature focused on the destructive effects of SCs on the environment, some of the recent studies are listed below. Elhedhli and Merrick (2012) designed an SC network by measuring the emissions cost based on the relation of gas emissions and the weight of the vehicle load. Fahimnia et al. (2015) proposed an SC planning problem which prospects the tradeoffs amongst the environmental costs and damages with different aspects of genuine SCs such as warehouses with flexible capacities and different sizes of shipping orders. Diabat and Al-Salem (2015) presented a mutual location-inventory problem and developed a model to decrease the gas emissions. This study considered environmental effects alongside inventory management. Although many studies in recent years focused on the relation between the environmental impacts and the total cost of SCs, the body of literature is very thin in evaluating the social impacts of SCs, some of them mentioned below.

Cruz (2009) proposed a structure to model an SC network with social responsibility considerations. He used a multi-criteria decision-making approach which includes the minimization of waste, emissions, or risk and maximization of net returns. With the aim of maximizing the social responsibility alongside minimizing the total cost and the environmental impacts, Dehghanian and Mansour (2009) presented a planning model for a tire recycling network taking into account four factors; the number of employees, the harm of the workers, product risk, and local development. Devika et al. (2014) studied a multi-objective SC problem with three pillars of sustainability. In his work, the fixed and the variable number of jobs were considered as a social factor which depends on the level of the utilized capacity. Pishvaee et al. (2014) developed a probabilistic programming model for a medicinal SC problem by employing the life cycle method to measure the applicable environmental and social effects. They used job creation, local development, damage to the worker, and consumer risk as the factors involved in social responsibility. Lin and Tseng (2016) proposed a hierarchical structure to find the competitive priorities of SSC management of a firm that manufactures electronic focal in Taiwan. They showed that the innovation is the first priority of all SSCM aspects. Panda et al. (2017b) worked on the influence of corporate social responsibility and channel coordination in a two-stage CLSC considering both the profit and the social responsibility. They concluded that corporate social responsibility is merely costly to the manufacturer. However, the environmental aspect which is one of the sustainability pillars were not considered in their work. While various sustainability measurement approaches have been used in the SSC literature, there is no approach that performs the best in all SCs. In other words, the performance of a sustainability measurement approach depends on the SC characteristics under investigation. Qorri et al. (2018) analyzed these approaches which have been employed in 104 articles. They first showed how the existing approaches evaluate the SC sustainability and then they provided some new insights into the performances of the sustainability measurement approaches.

To fill the gap for a comprehensive planning model of an SCLSC with a structural evaluation of social and environmental impacts of decisions with quality-dependent recovery decisions for returned products, a tri-objective mixed integer programming model is proposed in this paper for multi-period planning of a chain which employs the GRI guideline indicators to evaluate the environmental and social impacts of decisions. As a novelty in the current study, the returned products are categorized according to their qualities, where the recovery decisions on the returned products depend on their quality. Moreover, a quality-dependent discount offer is employed as an incentive on the returned products to increase the return rate of used products. This, in turn, increases the demand for the new products as well.

3. Problem definition

The structure of the closed-loop supply chain under investigation is depicted in Fig. 1. In this CLSC, new products are manufactured in the production center and are either shipped to the retailer or are stored in the plant. In addition, the products which have been sold in the last periods are collected by the collection center. To increase the number of returned products to the collection center, a discount price which is explained in Section 2.1 is offered. Returned products in the collection center are inspected, based on which they are classified on the basis of their quality (details are provided in Section 2.2.) The proposed model of the problem aims to determine the price of the product, the discount offer in each period, and other logistic decisions such as the production level in each period, the quantity of items (products, raw material, etc.) that must be shipped between centers, selecting the transportation vehicle, the technology used in production, installing additional capacity and so on. The length of the periods is determined based on the inventory cost (explained in Section 2.3.)

Noting that the most important aspect in the design of a sustainable chain is to satisfy the current demands without compromising the resources available for future generations to meet their own needs, environmental and social effects of different decisions must be taken into account. Inventive decisions are the most difficult tasks involved in a sustainable development. While advancements in information are leading to the economic improvement, they likewise can possibly eliminate the dangers and risks to the sustainability of the economics, environments and social relations. To assess the environmental impacts (EI) and the social impacts (SI) of the decisions, the GRI indicators are used. GRI is a trustworthy guideline to be used by all kind of organizations to provide a trusted and tenable structure for sustainability reporting. GRI Guideline considers all economic, environmental and social aspects.

3.1. Assumptions

- A single product is considered.
- There are multiple periods to make decisions.
- The locations of the suppliers and the retailers are specified.
- The suppliers have an unlimited capacity.
- All customers' demands should be satisfied.

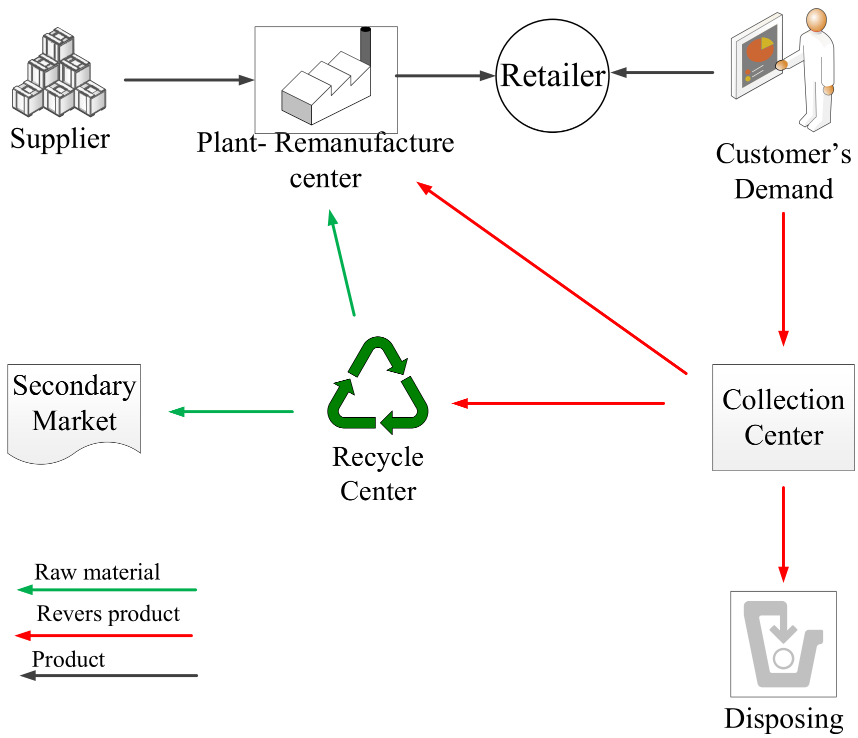

Fig. 1. The framework of the CLSC.

- Shortages are not allowed.
- Different raw materials share a unique holding cost.

3.2. Notation

As there is only one center for each party involved in the supply chain under investigation, the following abbreviations are first used to simplify the notation: supplier (SU), recycle center (RC), plant (P), retailer (RE), collection center (C), secondary market (SE), disposing center (DI), and remanufacture center (R). Then, the indices, the parameters, and the decision variables involved in the mathematical formulation of the problem are defined as:

Symbol	Description
Indices:	
r	Index of raw material ($r = 1,2,\ldots,R$)
t	Index of time periods ($t = 1,2,\ldots,T$)
kc	Index of additional capacities which can be installed on the recycling center ($kc = 1,2,\ldots,KC$)
kr	Index of additional capacities that can be installed on the remanufacturing centerrter ($kr = 1,2,\ldots,KR$)
kd	Index of additional capacities which can be installed on the disposal center ($kd = 1,2,\ldots,KD$)
km	Index of additional capacities that can be installed on the plant ($km = 1,2,\ldots,KM$)
v	Index of available vehicles ($v = 1,2,\ldots,V$)
s	Index of employee support types ($s = 1,2,\ldots,S$)
q	Index of the quality of the returned product ($q = q_d, q_{rc}, q_{re}$)
e	Index of possible technologies ($e = 1,2,\ldots,E$)

Symbol	Description
Parameters:	
$\overline{q}$	Expected quality of the returned product
α_r	The quantity of raw material type 'r' used in a product
β_r	The quantity of raw material type 'r' obtained by recycling a product
C^M	The unit manufacturing cost of the product
C^{RE}	Unit remanufacturing cost of the product
C^C	Unit collecting cost of the product
C^{RC}	Unit recycling cost of the product
C^D	Unit disposing cost of the product
C_e	The fixed cost of using technology type 'e'

(*continued*)

Symbol	Description
PR_r	Unit purchasing cost of raw material 'r'
RR_r	Price of recycled raw material type 'r' in the secondary market
$TC^{i,j}$	Unit transportation cost of the product from origin i to destination $ji \in \{P,C\}, j \in \{RE,DI,RC,R\}$
$TR^{i,j}$	Unit transportation cost of the product from origin i to destination $ji \in \{SU,RC\}$, $j \in \{P\}$
$CS_{s,t}$	Cost of employee support type 's' in period t
λ	The minimum collection limit set by the legislator
ξ	The coefficient of production effect on self-sufficiency
lmw	The local minimum wage
d_1	An uncertain coefficient having a uniform distribution in $[di, da]$
di	The minimum probable demand quantity
da	The maximum probable demand quantity
d_2	A parameter between (0,1) which exposes the effect of the price on the demand
d_3	A parameter between (0,1) which shows the effect of the discount offer on the demand
d_4	A parameter between (0,1) which denotes the effect of goodwill on the demand
σ	A fixed parameter which determines the effect of age on the quality of the product
δ	A parameter between (0,1) which determines the decreasing rate of goodwill
G_t	The goodwill level within period t
$\tilde{G}_t$	The goodwill change at time t
$\overline{q}$	The expected quality of the returned product
$ds^{i,j}$	The distance between origin i and destination$j$; $i,j \in \{P,DI,SU,D,RC,RE,SE,C\}$(no need for the remanufacturing place as it is located in the plant)
$Ck_{KC,t}$	The cost of establishing additional capacity 'KC' on the recycle center within period t
$Ck_{KR,t}$	The cost of establishing additional capacity 'KR' on the remanufacturing center within period t
$Ck_{KD,t}$	The cost of establishing additional capacity 'KD' on the disposal center within period t
$Ck_{KM,t}$	The cost of establishing additional capacity 'KM' on the plant within period t
MP	The maximum price of the product
PK^i	The primary capacity of center i; $i \in \{P,DI,RC,R\}$
AC_{KC}^{RC}	The quantity of added capacity by installing 'KC' on the recycling center
AC_{KR}^{R}	The quantity of added capacity by installing 'KR' on the remanufacturing center
AC_{KD}^{DI}	The quantity of added capacity by installing 'KD' on the disposing center
AC_{KM}^{P}	The quantity of added capacity by installing 'KM' on the plant
M^i	The maximum capacity of center$i \in \{P,DI,RC,R\}$
msu	The maximum budget assigned to employee supports
m_q	The least discount offer price which guarantees the return of a quality-q product
J_{KC}	The number of created jobs by installing additional capacity 'KC' on the recycling center
J_{KR}	The number of created jobs by installing additional capacity 'KR' on the remanufacturing center
J_{KD}	The number of created jobs by installing additional capacity 'KD' on the disposal center
J_{KM}	The number of created jobs by installing additional capacity 'KM' on the plant
Js_s	The amount of job satisfaction created by employee support type 's'
CO^i	CO_2 generated by processing one unit of the product in the center $i \in \{P,DI,RC,R\}$
CO_v	CO_2 emitted from transportation vehicle 'v' per mile
L_v	The capacity of the vehicle 'v'
Ep^e	Energy consumption to produce one unit of the product using technology e
W^e	The volume of industrial wastewater generated by producing one unit of the product using technology e
Id^e	The annual average number of lost days per capita due to labor's harms when technology 'e' is used
ha^e	The fraction of potentially perilous products when technology 'e' is employed
vp	The volume of a product
vr_r	The volume of the raw material 'r'
be	The benefit or positive environmental effect of collecting used products
w^c	The weight of carbon emission per cubic meter
w^w	The weight of wastewater in the environmental objective function
w^{ec}	The weight of energy consumption in the environmental objective function
w^p	The positive effect of collecting product in the environmental objective function
w^d	The weight of employee safety in the social objective function
w^{jc}	The weight of job creation in the social objective function
w^s	The effect of production on self-sufficiency in the social objective function
w^h	The weight of customer health in the social objective function
w^j	The weight of job satisfaction in the social objective function

Symbol	Description
Decision variables:	
P_t	The price of the product in period 't'
$do_{q,t}$	The discount offer for quality-level 'q' product within period 't'
QM_t^e	The number of products to be manufactured within period 't' using technology type 'e'
QR_t	The number of products to be remanufactured within period 't'
QT_t	Total number of manufactured and remanufactured products in period 't'
QD_t	The number of disposed of products within period 't'
QRC_t	The number of recycled products within period 't'
$RP_{r,t}$	The number of recycled raw material 'r' to be shipped from the recycling center to the plant in period 't'

(*continued on next page*)

(*continued*)

Symbol	Description
$RS_{r,t}$	The number of recycled raw material 'r' to be sold in a secondary market in period 't'
$R_{r,t}$	The number of raw material 'r' to be shipped from the supplier to the plant in period 't'
$RET_{q,t}$	The quantity of returned products with quality 'q' within period 't'
RCQ_t^i	The number of returned products with quality level 'q_{rc}' which shipped to the center$i \in \{DI, RC\}$within period 't'
REQ_t^i	The number of returned products with quality level 'q_{re}' which shipped to the center$i \in \{DI, RC, R\}$within period 't'
T	The length of a period
Tp_t	The production time duration in period 't'
a_t	The allocated advertising budget within period 't'
$Y_{KM,t}$	A binary variable, it is 1: if additional capacity 'KM' has been installed on the plant in period t; otherwise 0
$Y_{KR,t}$	A binary variable, it is 1: if additional capacity 'KR' has been installed on the remanufacturing center in period t; otherwise 0
$Y_{KD,t}$	A binary variable, it is 1: if additional capacity 'KD' has been installed on the disposal center in period t; otherwise 0
$Y_{KC,t}$	A binary variable, it is 1: if additional capacity 'KC' has been installed at the recycling center in period t; otherwise 0
$UP_{q,t}$	The quantity of quality-q products that are with customers in period 't'
$O_{s,t}$	A binary variable; it is 1 if employee support type 's' has been decided in period 't', 0 otherwise
$nv_{v,t}^{i,j}$	An integer variable that shows the number of vehicles type 'v' used to ship products from origin 'i' to destination 'j' in period 't', $i,j \in \{P, DI, SU, D, RC, RE, SE, C\}$
u_t^e	A binary variable; it is 1 if technology type 'e' is used in period 't', otherwise 0

3.3. Discount offer to motivate customers to return used products more

As a collection strategy, a discount offer $(do_{q,t})$ is paid to the customers for returning back their used products. Employing this strategy motivates customers to return their used products more. The discount offer price depends on the quality of the returned product. It is assumed that the quality of the used products depends on its age of use. Equation (1) determines the quality of a used product (q) as a function of its age at the returning time.

$$q = \overline{q} - \sigma g, \tag{1}$$

where $\overline{q}$ is the expected quality of the returned product,σ is a fixed parameter that determines the effect of age on the quality, and g denotes the age of the used product. Moreover, the customer decision in accepting the discount offer in exchange for the used product depends on the price of the discount offer paid. The probability of returning back the used product and acquiring the discount offer is defined using$PA(do_{q,t})$ as a piecewise linear function with a breakpoint m_q as follows:

$$PA(do_{q,t}) = \begin{cases} \eta_q(do_{q,t}) \big/ m_q & ; \quad if\ 0 \le do_{q,t} < m_q \\ 1 & ; \quad if\ do_{q,t} \ge m_q \end{cases}, \tag{2}$$

where $\eta_q = 1/q$ and m_q is the least price of the discount offer which guarantees the return of a q-quality product if this price suggested to the customers. As it can be seen in the proposed probability function, the quality of the used product has a reverse effect on the probability of returning back the product. It means that for a constant discount offer, the probability of returning back an older product is bigger than a younger one. Because the owner of an older used product with less quality expects a lower discount offer compared to an owner of a younger used product.

As can be seen, the customer's probability of accepting a discount offer is a concave function and depends on the amount of the discount offer and the quality of the used product. In other words, η_q/m_q is the probability of returning the used product per one unit of the discount offer when $do_{q,t}$ranges between 0 and m_q. Fig. 2 depicts this function.

As shown in Fig. 2, the probability of accepting a certain discount offer depends on the quality of the used product, where the return of a low-quality product is more likely than the high-quality one. On the other hand, the amount of the discount offer in each period affects the demand for that period. In this paper, it is assumed that the product demand in each period depends on the price of the product in more recent periods, the discount offer, and the goodwill of customers to purchase products in the current period. Eq. (3) exposes the mentioned demand function.

$$D_t = d_1 - d_2(wp) + d_3\left(\sum_q do_{q,t}\right) + d_4(G_t) \tag{3}$$

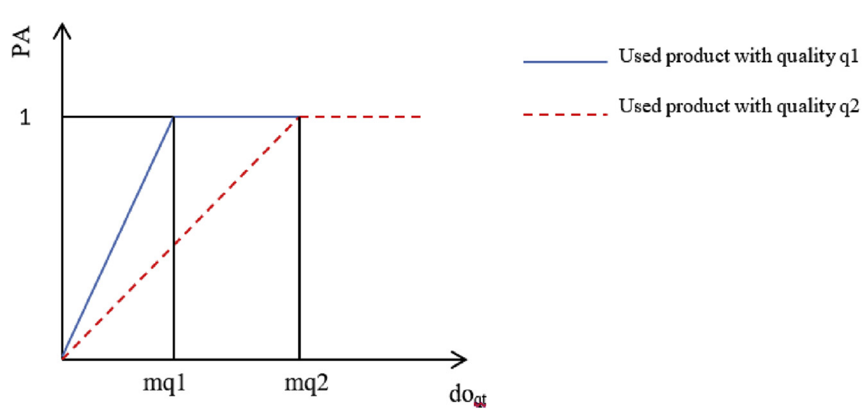

Fig. 2. Piecewise linear probability function of returning back the used products.

In Equation (3), the product demand in each period $(D_t)$is a function ofd_1,wp,$\sum_q do_{q,t}$ and G_t, each with a proper coefficient. In addition, $d_1$is an uncertain coefficient having a uniform distribution in $[di, da]$where di is the minimum probable demand and da shows the maximum probable demand. Besides, $d_2$and $d_3$are the coefficients between zero and one which respectively expose the impact of price and discount offer on the demand in each period and wp is the weighted moving average of price which includes the price of five recent periods. Eq. (4) determines the weighted moving average of the price.

$$wp = (w_1 p_t + w_2 p_{t-1} + w_3 p_{t-2} + w_4 p_{t-3} + w_5 p_{t-4}) \Big/ \sum_{i=1}^{5} w_i \\ w_1 > w_2 > w_3 > w_4 > w_5 \tag{4}$$

As seen in Equation (3), an increase of the discount offer leads to an increase in the demand, while a price increase causes the demand to decrease. Moreover, $G_t$is the goodwill in the period $t$with a coefficient $d_4$between (0,1) which denotes the effect of goodwill on the demand. Briefly, the demand in each period is a function of the discount offer, the goodwill of the consumers on the product, a random number (within the lower and the upper limit of the demand quantity) and the weighted moving average of the price in the last five periods, in which heavier weights are assigned to the prices of the more recent periods.

According to GRI (2011), the local minimum wage (lmw) is an indicator that determines the minimum lawful salary of employees in a city or country per unit of time. lmwvaries depending on the country, state or cities involved. In this study, the effect of the lmwon job satisfaction is defined in the social objective function. Besides, the local minimum wage is used as a criterion to show the income level of individuals in the community. The income level affects the demand sensitivity to price. Obviously, the lower the income of individuals in a community, the more important criterion the price of the product in buying the product will be. In other words, the lower income individuals are not willing to buy expensive products. Consequently, the demand sensitivity to price depends on the individual's income level. The amount of the local minimum wage cannot lonely reflect the economic condition of people of the community; because it may only be a very small percentage of people in the community that receive these minimum wages. Thus, one should consider a percentage of the people with a local minimum wage. Mathematically speaking, we define d_2 as follows:

$$d_2 = ps/lmw \tag{5}$$

As seen in Eq. (5), the effect of the product price on the product demand increases when a higher percentage of the population receives lower lmw.

As mentioned above, the product demand in the current period is related to the discount offer proposed in that period and also to the price of the product in the current period alongside the last four periods, where the current period price is the most influential one. In other words, the product demand in each period is a function of a random number (within the lower and the upper limit of the demand quantity), discount offer, and the weighted moving average of the price in five periods, in which heavier weights are assigned to the prices of the more recent periods.

The advertisement is another effective factor affecting the demand. Although advertisement can have both a positive and a negative effect on the demand, in this study, the positive and beneficiary effect of advertisement is considered. In other words, it is assumed that advertisement investment leads to increasing level of the goodwill level and hence results in demand increase. Sethi (1977) used the Nerlove-Arrow relation shown in (6) to model the goodwill evolution over time.

$$\tilde{G}_t = a_t - \delta G_t \quad ; \quad G(0) = G_0 \tag{6}$$

In Equation (6), G_t is the goodwill level within the period t, a_t is the advertising effort at the time t (advertising cost in period t or the budget allocated to advertising) and $\tilde{G}_t$ is the goodwill change at the time t. Besides, the parameter $\delta$is between zero and one determining the decreasing rate of goodwill as a percentage of the current goodwill level, and that $G_0 > 0$ is the initial goodwill. From Equation (6), advertising effort leads to increasing goodwill, while the passage of time depreciates goodwill level due to consumer forgetting of past advertisements.

3.4. Use of the collected products

The quantity of quality-q used products returned in each period depends on the probability of accepting the discount offer$PA(do_{q,\ t})$. It is defined as

$$RET_{q,t} = \left(\sum_{\tau=1}^{t-1} D_\tau - \sum_q \sum_{\tau=1}^{t-1} RET_{q,\tau} \right) PA(do_{q,t}) \quad \forall q, t \tag{7}$$

The first term in Equation (7) determines the number of used products with quality level q. It is equal to the difference between the number of sold products and the number of returned used products with quality level q in past periods. Besides, the variable $RET_{q,\ t}$shows the quantity of the returned products with the q-quality level in the period t.

The quality of returned products depends on the classes defined in three recovery options including remanufacturing, recycling, and disposal. Thus, as a new contribution, the returned products are classified into three categories on the base of their quality (q) as

1. If $q < q_d$, then the returned product is disposed of. These returned products have quality level denoted by q_d.
2. If $q_d \le q < q_{rc}$, then the returned product can be disposed of or recycled. These returned products have the q_{rc} quality level. In fact, considering the cost of recycling and other factors, the decision maker determines whether or not the used product should be recycled. The quantity in the recycling category is denoted by RCQ_t^{RC}, among them the number of items selected for disposal isRCQ_t^{DI}.
3. If $q \ge q_{rc}$, then the returned product can be remanufactured or recycled or disposed of. These returned products have quality level q_{re}. The quantities in this category are shown respectively, by the variablesREQ_t^R, $REQ_t^{RC}$and REQ_t^{DI}.

While Equation (9) exposes the quantity of quality-q products that are with customers in period t,$(UP_{q,t})$, Equations (10)-(12) are used to determine the number of returned used products to be disposed of within period t, $(RET_{q_d,t})$, the quantity of the returned used products to be recycled or disposed of in period t, $(RET_{q_{rc},t})$, and the number of returned used products to be remanufactured, recycled, or disposed of in period t, $(RET_{q_{re},t})$. In addition, QT_t is the quantity of the manufactured products obtained using Equation (8).

$$QT_t = \sum_e QM_t^e + QR_t \tag{8}$$

$$UP_{qt} = \left(\sum_{\tau=1}^{t-1} QT_t - \sum_{\tau=1}^{t-1} RET_{qt} \right) \tag{9}$$

$$RET_{q_d,t} = \int_{q=0}^{q_d} RET_{q,t} \quad ; \quad \forall t \tag{10}$$

$$RET_{q_{rc},t} = \int_{q=q_d}^{q_{rc}} RET_{q,t} \quad ; \quad \forall t \tag{11}$$

$$RET_{q_{re},t} = \int_{q=q_{rc}}^{\overline{q}} RET_{q,t} \quad ; \quad \forall t \tag{12}$$

Equations (16) and (17) determine the variables for the total number of used products which are disposed of (QD_t), recycled (QRC_t), and remanufactured (QR_t):

$$RET_{q_{rc},t} = RCQ_t^{RC} + RCQ_t^{DI} \quad ; \quad \forall t \tag{13}$$

$$RET_{q_{re},t} = REQ_t^{R} + REQ_t^{RC} + REQ_t^{DI} \quad ; \quad \forall t \tag{14}$$

$$QD_t = RET_{q_d,t} + RCQ_t^{DI} + REQ_t^{DI} \quad ; \quad \forall t \tag{15}$$

$$QRC_t = RCQ_t^{RC} + REQ_t^{RC} \quad ; \quad \forall t \tag{16}$$

$$QR_t = REQ_t^{R} \quad ; \quad \forall t \tag{17}$$

4. Formulation of the problem

The multi-objective model of the problem involves three objectives defined as the profit to be maximized, the environmental effect to be minimized, and the social objective to be minimized. In this section, each of these objective functions is described in detail.

4.1. The cost objective function

The costs involved in the first objective function include (1) product and raw material holding cost, (2) cost of proposing a discount offer, (3) purchasing cost of raw materials from the supplier, (4) operation cost that consists of manufacturing, remanufacturing, collecting, recycling and disposal costs, (5) shipping cost, (6) cost of installing additional capacity, (7) advertisement cost, (8) cost of employing a technology, and (9) cost of employee supports. In addition, the revenues are obtained selling the products and the recycled raw materials. In what comes next, all these items are specified.

4.1.1. Inventory holding costs

The inventory holding costs of the products and the raw materials are counted as the main cost of the supply chain. To calculate these costs, it is assumed that all of the periods have an equal length defined as a decision variable to be optimally determined. Consider the following notations:

Variables:	
T	The length of a period
$ISR_{r,t}$	The inventory of raw material type ‘r’ at the start of period ‘t’ in the plant
$IFR_{r,t}$	The inventory of raw material type ‘r’ at the end of period t in the plant
IS_t	The inventory of the products at the beginning of period t in the plant
IF_t	The inventory of the products at the end of period t in the plant
TP_t	The production duration in period t
Parameters:	
pr	Production rate
h_1	Unit holding cost of raw material per unit time
h	Unit holding cost of product per unit time

Using the above notations, the production duration in a period is calculated as

$$TP_t = \frac{IF_t - IS_t}{pr} = \frac{\sum_e QM_t^e}{pr} = \frac{ISR_t - IFR_t}{\alpha_r (pr)} \quad ; \quad \forall t \tag{18}$$

where $\alpha_r$is the number of raw materials type ‘r’used in a product. Moreover, the production duration cannot be greater than the period length, i.e.

$$T \geq TP_t \quad ; \quad \forall t \tag{19}$$

Assuming remanufactured products cannot be stored and must be sold in the period of their production; Equations (20)-(23) determine the inventory of the raw material and the product in the plant at beginning and end of each period.

$$ISR_{r,t} = IFR_{r,t-1} + RP_{r,t-1} + R_{r,t-1} \quad ; \quad \forall t, r \tag{20}$$

$$IFR_{r,t} = ISR_{r,t} - \alpha_r \left(\sum_e QM_t^e \right) \quad ; \quad \forall t, r \tag{21}$$

$$IS_t = IF_{t-1} \quad ; \quad \forall t \tag{22}$$

$$IF_t = IS_t + \sum_e QM_t^e - (D_t - \mathrm{QR}_t) \quad ; \quad \forall t \tag{23}$$

Figures (3) and (4) depict, respectively, the inventory level of the raw material and the product in the plant when $T = TP_t$, based on which the holding costs of the raw materials and the products are obtained using Equations (24) and (25).

$$\text{Raw material holding cost} = h_1 \left((ISR_{r,t} - IFR_{r,t}) T/2 + (IFR_{r,t}) T \right) \tag{24}$$

$$\text{Product holding cost} = \sum_t h \left(IS_t T + \left(\sum_e (QM_t^e) T \right) \Big/ 2 \right) \tag{25}$$

However, when$T > TP_t$, the inventories are depicted in Figures (5) and (6). In this case, the holding costs are calculated based on Equations (26) and (27).

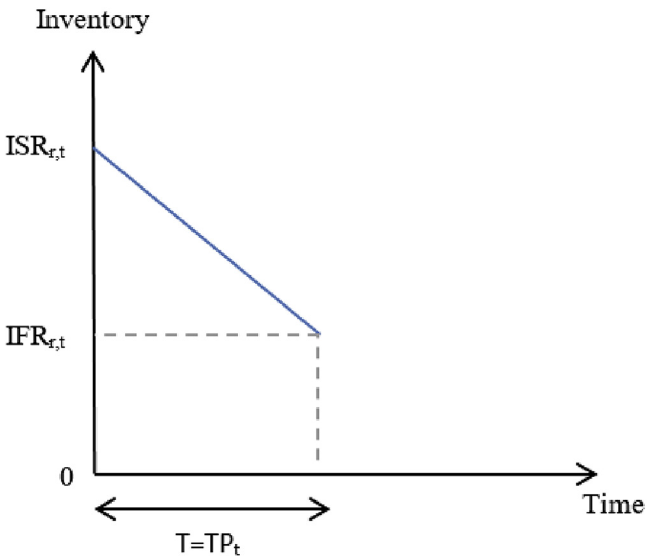

Fig. 3. Inventory of raw material when $T = TP_t$

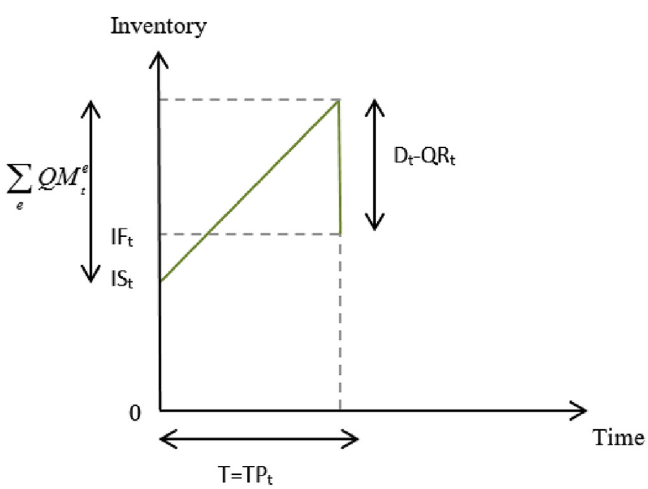

Fig. 4. Inventory of product when $T = TP_t$.

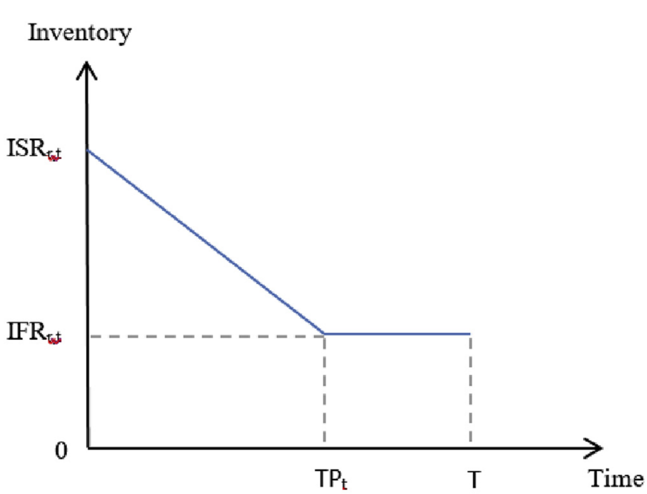

Fig. 5. Inventory of raw material when.$T > TP_t$.

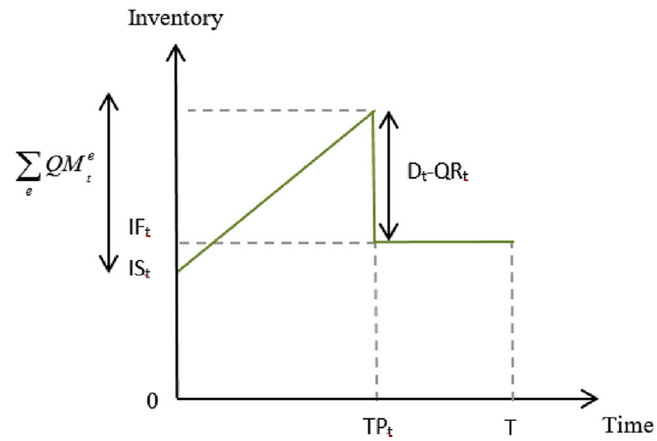

Fig. 6. Inventory of product when $T > TP_t$.

$$phc_t = h\left(IS_t(TP_t) + \left(TP_t\sum_e QM_t^e\right)\Big/2 + IF_t(T - TP_t)\right) \tag{26}$$

$$rhc_t = \sum_r h_1\left(\left(ISR_{r,t} - IFR_{r,t}\right)TP_t/2 + \left(IFR_{r,t}\right)T\right) \tag{27}$$

4.1.2. Cost of proposing a discount offer

Paying discount offer for the next purchases leads to loss of revenue on the products sold by the discount offer. As such, it is considered as a cost in the profit function. The amount of this cost depends on whether or not the customers use the discount offer and purchase their products again. Thus, the demands motivated by the discount offer must be taken into account, as these demands in each period must be sold at a price which is equal to the ordinary price of the product in the period minus the discount offer the customers received in the previous periods. This implies that in each period a percent of the products are sold at a lower price resulted from the discount offers in previous periods. Hence, the mentioned cost is the product of the proposed discount offer and a part of the demands created due to the discount offer. In other words, the total cost resulted from the discount offer in period t is

$$\sum_q \Bigg((\mathrm{do}_{q,t})\ \underbrace{d_3\left(\sum_q do_{q,t}\right)}_{\substack{\text{demand motivated by}\\ \text{the discount offer}}}\Bigg) .$$

4.1.3. Purchasing cost of raw materials

The purchasing cost of the raw materials supplied by the supplier relies on the prices as well as the numbers of different types of raw materials used in the product. It is obtained as $\sum_r (R_{r,t})(PR_r)$.

4.1.4. Operation costs

As mentioned above, the operation cost in a period consists of manufacturing $\sum_e QM_t^e(C^M)$, remanufacturing$QR_t(C^{RE})$, collecting $\left(\sum_q RET_{q,t}\right)C^C$, recycling$QRC_t(C^{RC})$, and disposal cost $QD_t(C^D)$, all depending on the number of products and the unit operating cost. In other words, the total operating cost in period 't' is derived using

$$\sum_e QM_t^e(C^M) + QR_t(C^{RE}) + \left(\sum_q RET_{q,t}\right)C^C + QRC_t(C^{RC}) + QD_t(C^D)$$

4.1.5. Shipping cost

Another cost component is the shipping cost of the products among different levels of the supply chain. This cost depends upon the quantity of the shipped items and the shipping cost per unit between each origin and destination (although this cost relies on the distance from the origin to the destination and many other factors, it is assumed known in this study). Equation (28) calculates the mentioned cost (SHC_t) in period t.

$$SHC_t = \underbrace{QD_t\left(TC^{C,D}\right)}_{\substack{\text{product shipping cost from collection}\\ \text{center to disposal center}}} + \underbrace{QRC_t\left(TC^{C,RC}\right)}_{\substack{\text{product shipping cost from collection}\\ \text{center to recycle center}}} + \underbrace{\sum_r RP_{r,t}\left(TR^{RC,P}\right)}_{\substack{\text{shipping cost of raw material}\\ \text{from recycle center to plant}}} + \underbrace{\left(TR^{S,P}\right)\sum_r R_{r,t}}_{\substack{\text{shipping cost of rawmaterial}\\ \text{from supplier to plant}}} + \underbrace{\left(TC^{C,P}\right)QR_t}_{\substack{\text{shipping cost from collection center}\\ \text{to plant(remanufacture center)}}} + \underbrace{\left(TC^{P,RE}\right)Q_t}_{\substack{\text{shipping cost from plant}\\ \text{to retailer}}} \quad (28)$$

4.1.6. Installation cost of additional capacity

The cost of installing additional capacity is another considerable cost. Each additional capacity installed on each center has a specified cost and is used when it is decided to install additional capacity. Equation (29) determines this cost (IAC_t)in period t.

$$IAC_t = \underbrace{(Ck_{KC,t})Y_{KC,t}}_{\substack{\text{cost of installing additional}\\ \text{capacity on recycle center}}} - \underbrace{(Ck_{KD,t})Y_{KD,t}}_{\substack{\text{cost of installing additional}\\ \text{capacity on disposal center}}} - \underbrace{(Ck_{KR,t})Y_{KR,t}}_{\substack{\text{cost of installing additional}\\ \text{capacity on remanufacture center}}} - \underbrace{(Ck_{KM,t})Y_{KM,t}}_{\substack{\text{cost of installing additional}\\ \text{capacity on plant}}} \quad (29)$$

4.1.7. Advertisement cost

Advertisement leads to increase in demand as mentioned in Section 2.1, where the decision variable a_t exposes the budget allocated in the period t. This implies that the advertisement cost in period t isa_t.

4.1.8. Cost of employing a technology

The technology used to produce the product is an important factor and has effects on the quality of the products for customers and the hazard on the workers. Assuming a fixed cost for using a new technology and denoting u_t^e as a binary variable which is equal one if technology type e is used in period t, the cost of employing a technology depends on the fixed cost of using a considered type of technology. So the total cost of using technology in period t is equal to$\sum_e C_e(u_t^e)$.

4.1.9. Cost of employee support

According to the GRI guideline, employee support such as interest-free loans, redundancy payments, housing, educational grants, etc. all belonging to set S, is one of the indicators which has social effects on organizations, certainly with an implementation cost. Having $O_{s,t}$ as a binary variable which is equal 1 if employee support type ‘s’ is decided in the period t, zero otherwise and denoting $CS_{s,t}$as the cost of this support in the period t, the total cost of employee support in the period t is equal to$\sum_s CS_{s,t}(O_{s,t})$.

4.1.10. The revenue

On the one hand, the chain receives revenue in the amount of P_tD_t by selling D_t units of products with a price of $P_t$in period$t$. On the other hand, revenue is also obtained by selling recycled raw materials to a secondary market. As $RS_{r,t}$is the number of recycled raw material ‘r’ to be sold in a secondary market in the period$t$, each with a price of RR_r, this type of revenue is received in period t using $\sum_r RS_{r,t}(RR_r)$.

The first objective function to be minimized is obtained by the summation of all the costs derived above minus the revenue resulted from selling both the products and the recycled raw materials. In other words, we have

$$E_1 = \underbrace{-\sum_t P_t D_t}_{\text{revenue of selling product}} - \underbrace{\sum_t \sum_r RS_{r,t}(RR_r)}_{\text{revenue of selling recycled raw material}} + \underbrace{\sum_t \sum_q ((\mathrm{do}_{q,t}) d_3 \left(\sum_q do_{q,t} \right))}_{\text{cost of discount offer}} + \underbrace{\sum_t \sum_r R_{r,t}(PR_r)}_{\text{purchasing cost of raw material from supplier}}$$
$$+ \underbrace{\sum_t QR_t \left(C^{RE}\right)}_{\text{remanufacturing cost}} + \underbrace{\sum_t \sum_e QM_t^e \left(C^M\right)}_{\text{manufacturing cost}} + \underbrace{\sum_t \left(\sum_q RET_{q,t} \right) C^C}_{\text{collecting cost}} + \underbrace{\sum_t QRC_t \left(C^{RC}\right)}_{\text{recycling cost}}) + \underbrace{\sum_t QD_t \left(C^D\right)}_{dispo\ \sin g\ \cos t} + \underbrace{\sum_t SHC_t}_{\text{shipping cost}} + \underbrace{\sum_t a_t}_{\text{cost of advertising}} \quad (30)$$
$$+ \underbrace{\sum_t IAC_t}_{\text{cost of installing additional capacity}} + \underbrace{\sum_t \sum_s CS_{s,t}(O_{s,t})}_{\text{cost of employee supports}} + \underbrace{\sum_t \sum_e C_e(u_t^e)}_{\text{cost of using technology}} + \underbrace{\sum_t phc_t}_{\text{product holding cost}} + \underbrace{\sum_t rhc_t}_{\text{raw material holding cost}}$$

4.2. The environmental objective function

The environmental objective function consists of the negative effects of carbon emission, wastewater, energy consumed to produce products, and the positive environmental effects of collecting products. Among these components, just the last one has positive and the rest have negative environmental impacts.

The greenhouse gas emission is the major reason for climate change. According to GRI guidelines, the total direct and indirect greenhouse gas emissions (EN29) is one of the environmental indicators having a significant effect on global warming. The carbon can be emitted by the transportation vehicles of different types when they ship raw materials, finished products, and returned used products to the plant, recycling center, remanufacturing center, disposal center, and retailer. The total gas released by transportation vehicles is the sum of CO2 released by the vehicles that carry the used products from the collection center to the disposal center, from the collection center to the remanufacturing center, from the collection center to the recycle center, as well as carrying recycled raw materials from the recycling center to the plant, carrying purchased raw materials from the supplier to the plant and the finished products from the plant to the retailer (it has been assumed that other shipments are done by the enterprises which are outside of the supply chain). Mathematically speaking, the gas realized by the vehicles in period t, i.e. GA_t, is equal to:

$$\begin{aligned} GA_t = {} & ds^{C,DI} \sum_v \left(CO_v nv_{v,t}^{C,DI} \right) + ds^{C,R} \left(\sum_v CO_v nv_{v,t}^{C,R} \right) \\ & + ds^{C,RC} \left(\sum_v CO_v nv_{v,t}^{C,RC} \right) + ds^{RC,P} \left(\sum_v CO_v nv_{v,t}^{RC,P} \right) \\ & + ds^{SU,P} \left(\sum_v CO_v nv_{v,t}^{SU,P} \right) + ds^{P,RE} \left(\sum_v CO_v nv_{v,t}^{P,RE} \right). \end{aligned} \quad (31)$$

In Equation (31), $nv_{v,t}^{ij}$ is an integer variable which shows the number of vehicles type 'v' used to ship the products from origin 'i' to destination 'j' in period 't'. It means that for each pair of origin-destination in each period, one can select one or more types of vehicles with predetermined capacities. Obviously, bigger vehicles have more capacities and emit more volume of gas. On the other hand, if one uses smaller vehicles with fewer capacities, he/she will need more vehicles to ship the items. The proposed model tries to find the optimal number of each type of vehicles for each pair of origin-destination so that the total amount of emitted gas is minimized. The volume of the emitted gas by the vehicles depends on the number of used vehicles, the selected types of vehicles, and the amount of released gas by selected vehicles per mile. Also, it depends on the distance between the origins to their destinations($ds^{i,j}$). Thus, in the second objective function, GA_t reflects the volume of released gas by transportation vehicles in period t.

Another supply of released gas is the production process. The volume of gas released in the production process in period t depends on the number of manufactured products and the volume of CO_2 generated by producing one unit of the product. Thus, the generated gas in the plant is equal to $CO^P\left(\sum_e QM_t^e\right)$. Similarly, the gas generated in the recycling center, in the remanufacturing center, and in the disposal center in the period t are respectively equal to$CO^{RC}(QRC_t), CO^R(QR_t)$, and $CO^{DI}(QD_t)$. Besides, the weight of the total emitted carbon (gr) in the environmental objective function is w^c $\mathrm{in} gr/m^3$.

As another environmental indicator corresponds to the waste, the second part of the environmental objective function of this paper reflects the effect of wastewater (EN25 in GRI). A basic worry of many stakeholders is the perilous waste management. The best way to dispose of any kind of waste is the prevention of produced waste. It is assumed here that the volume of wastewater depends on the number of manufactured products using a specific technology. As different levels of the employed technology lead to different volumes of wastewater, the total water wasted by the production process in period t is $\sum_e W^e(QM_t^e)$. The weight of wastewater in cubic meter in the environmental objective is w^w.

According to GRI, energy consumption is an environmental indicator (EN3, EN5) to determine the efficiency level of energy consumption. As such, the third part of the environmental objective function is the amount of consumed energy that depends on the number of production and the employed technology obtained by $\sum_e Ep^e(QM_t^e)$ in period t. The weight of the energy consumption in the environmental objective isw^{ec}.

Collecting products have some benefits with positive environmental effects. As the fourth part of the environmental objective function, these effects depend on the probability of returning used products which in turn depends on the discount offer, i.e. higher discounts lead to more positive effect. It may seem that the intensity of these positive effects is related to the number of collected used products. However, this is a false look at the issue because the number of collected used products also relies on the quantity of produced products. In other words, the positive environmental effect of the collecting used products in the period t, as the fourth part of the environmental objective function, is determined using $\sum_q (be)PA(do_{qt}) = \sum_q (be)\eta_q(do_{qt})/m_q$.

In summary, Equation (32) shows the environmental objective function (E_2) of the SC in all periods.

The effect of the production on the self-sufficiency is the second part of the social objective function. Certainly, more production leads to more self-sufficiency of the country, resulting in the less affiliated economy. This effect is modeled using the term $\xi\sum_e QM_t^e$ in a period.

According to GRI regulations, the physical protection and comfort of labors should be considered as an important social aspect, where the health and safety of the employees is a social indicator (LA9). In this paper, the lost working days due to employees sickness and accidents is used as a measure of labor health and safety. It is assumed to depend on the employed technology in each period. Having the lost days due to employees' sickness and accidents

$$E_2 = w^c\left(-\left(\underbrace{\sum_t CO^{RC}(QRC_t)}_{co_2\text{emission by the recycling center}}\right) + \underbrace{\sum_t CO^P\left(\sum_e QM_t^e\right)}_{co_2\text{emission by the plant}} + \underbrace{\sum_t CO^R(QR_t)}_{\substack{co_2\text{emission by the}\\ \text{remanufacturing center}}} + \underbrace{\sum_t CO^{DI}(QD_t)}_{co_2\text{emission by the disposal center}} + \underbrace{\sum_t GA_t}_{\substack{\text{emission of } co_2 \text{ by}\\ \text{the } v \text{ ehicles}}}\right) + w^w\left(\underbrace{\sum_t\sum_e W^e(QM_t^e)}_{\substack{\text{industrial wastewater caused by}\\ \text{the production process with}\\ \text{technologye}}}\right) + w^{ec}\left(\underbrace{\sum_t\sum_e Ep^e(QM_t^e)}_{\substack{\text{energy consumption of}\\ \text{producing products}}}\right) - w^p\underbrace{\sum_t\sum_q (be)\eta_q(do_{qt})\Big/m_q}_{\substack{\text{positive environmental effect of}\\ \text{collecting used products}}} \tag{32}$$

4.3. The social objective function

As the third objective of the mathematical formulation of the problem, the social objective function involves the positive effect of job creation, the positive effect of the production on the self-sufficiency, the negative effect of issues related to employee health and safety (lost days due to sickness and accidents), the negative effect of issues related to customer health (hazard of products for customers when technology e is employed), and the positive effect of employees' job satisfaction. Moreover, jobs are created by extending the capacity of (1) the recycling center, (2) the remanufacturing center, (3) the disposal center, and (4) the plant. These effects are modeled in the social objective function as follows.

Installing additional capacities in each part of the supply chain provides more job opportunities. More job opportunities cause increasing local employment rate and decreasing the rate of migration and prevent unfavorable delocalization. As the number of created jobs depends on the capacity of the plant, the total number of jobs created in a period becomes $\sum_{km} J_{km}(Y_{\mathrm{km},t})$. Similarly, the total number of jobs created in a period in the recycling center, in the remanufacturing center and in the disposal center is, $\sum_{kc} J_{kc}(Y_{\mathrm{kc},t})$, $\sum_{kd} J_{kd}(Y_{\mathrm{kd},t})\sum_{KD} J_{KD}(Y_{KD,t})$, respectively. These numbers are added up in all periods to be multiplied by the weight associated with the job creation,w^{jc}, to become the first part of the social objective function.

as $\sum_e Id^e(u_t^e)$ in a period, the third part of the social objective function is obtained by multiplying w^w as the weight of this factor by the total number of lost days in all periods.

The employed technology affects the quality and the standard level of the product. Having the number of products manufactured within period t using technology type 'e' and also the fraction of potentially perilous products when technology 'e' is employed as ha^e, the fourth part of the social objective function in a period is derived as $\sum_e (ha^e)QM_t^e$.

Employee support is another social indicator in GRI regulations, which is considered as job satisfaction in this paper. Denoting the amount of job satisfaction created by employee support s by Js_s, and knowing that the effects of this support depend on the local community condition such as the local minimum wage (lmw), the fifth part of the social objective function in a period is obtained by $\sum_s (1/lmw)(Js_s)O_{s,t}$. Note that this support creates more value for employees in worse economic situations and harder livelihood conditions. That is why the local minimum wage is considered as a factor to reflect the general financial conditions of the employees. In a situation in which less local minimum wage is involved, the employee support is more important and makes more job satisfaction.

In short, the social objective function of the mathematical formulation (E_3) is shown in Equation (33).

$$E_3 = -w^{jc}\left(\underbrace{\sum_{KC}\sum_{t} J_{kc}(Y_{\mathrm{kc},t})}_{\substack{\textit{job creation in the}\\ \textit{recycling center}}} + \underbrace{\sum_{kr}\sum_{t} J_{kr}(Y_{\mathrm{kr},t})}_{\substack{\textit{job creation in the}\\ \textit{remanufacturing}\\ \textit{center}}} + \underbrace{\sum_{kd}\sum_{t} J_{kd}(Y_{\mathrm{kd},t})}_{\substack{\textit{job creation in the}\\ \textit{disposal center}}} + \underbrace{\sum_{km}\sum_{t} J_{km}(Y_{\mathrm{km},t})}_{\substack{\textit{job creation in the}\\ \textit{plant}}}\right) - w^{s}\left(\underbrace{\xi\sum_{t}\sum_{e} QM_t^e}_{\substack{\textit{effect of production on}\\ \textit{self-sufficiency}}}\right)$$

$$+ w^{d}\left(\underbrace{\sum_{t}\sum_{e} Id^{e}(u_t^e)}_{\substack{\textit{lost days due to worker}\\ \textit{sickness and accidents}}}\right) + w^{h}\left(\underbrace{\sum_{t}\sum_{e}(ha^{e})QM_t^e}_{\substack{\textit{hazard of products for customers}\\ \textit{when techno}\log y\ e \textit{ is employed}}}\right) - w^{j}\left(\underbrace{\sum_{t}\sum_{s}(1/lmw)(Js_s)O_{s,t}}_{\textit{job satisfaction}}\right) \tag{33}$$

4.4. Constraints

Four types of constraints are involved in the mathematical formulation of the problem at hand. They are described as follows.

4.4.1. Balance constraints

Equalities (34) and (35) are the balance constraints to guarantee the conservation of the returned products for the recycle and the collection center in each period.

$$\beta_r(QRC_t) = RS_{r,t} + RP_{r,t} \quad ; \quad \forall r,t \tag{34}$$

$$\sum_q RET_{q,t} = QR_t + QRC_t + QD \quad ; \quad \forall t \tag{35}$$

4.4.2. Capacity constraints

Constraints (36)-(39) ensure that the capacity needed for the recycling center, the remanufacturing center, the disposal center, and the plant in each period should be less than the available capacity.

$$QRC_t \le PK^{RC} + \sum_{\tau=1}^{t}\sum_{KC} AC_{KC}^{RC}(Y_{KC,t}) \quad ; \quad \forall t \tag{36}$$

$$QR_t \le PK^{R} + \sum_{\tau=1}^{t}\sum_{KR} AC_{KR}^{R}(Y_{KR,t}) \quad ; \quad \forall t \tag{37}$$

$$QD_t \le PK^{DI} + \sum_{\tau=1}^{t}\sum_{KD} AC_{KD}^{DI}(Y_{KD,t}) \quad ; \quad \forall t \tag{38}$$

$$\sum_e QM_t^e \le PK^{P} + \sum_{\tau=1}^{t}\sum_{KM} AC_{KM}^{P}(Y_{KM,\,t}) \quad ; \quad \forall t \tag{39}$$

Inequalities (40)-(43) expose the upper limits for the installed capacity on each facility. In addition, Equality (44) guarantees that at most one type of technology (the one in the previous period or a new one) is employed in each period. Constraint (45) assures that products can be produced with technology type 'e' in each period only if it is chosen in that period.

$$PK^{RC} + \sum_t\sum_{KC} AC_{KC}^{RC}(Y_{KC,t}) \le M^{RC} \tag{40}$$

$$PK^{R} + \sum_t\sum_{KR} AC_{KR}^{R}(Y_{KR,t}) \le M^{R} \tag{41}$$

$$PK^{DI} + \sum_t\sum_{KD} AC_{KD}^{DI}(Y_{KD,t}) \le M^{DI} \tag{42}$$

$$PK^{P} + \sum_t\sum_{KM} AC_{KM}^{P}(Y_{KM,t}) \le M^{P} \tag{43}$$

$$\sum_e u_t^e = 1 \quad ; \quad \forall t \tag{44}$$

$$QM_t^e \le M(u_t^e) \quad ; \quad \forall t,e \tag{45}$$

Inequality (46) satisfies the legislation criterion of the minimum collection rate and Constraints (47) is set for the customer demands in each period.

$$\sum_q RET_{q,t} \ge \lambda\left(\sum_q UP_{q,t}\right) \quad ; \quad \forall t \tag{46}$$

$$\sum_e QM_t^e + QR_t \ge D_t \quad ; \quad \forall t \tag{47}$$

4.4.3. The vehicle capacity constraints

The following constraints guarantee that there are enough vehicle capacities to transport the items between all pairs of origin and destination nodes in all periods. Note in these constraints that the required capacities are determined by the multiplication of the numbers of the items by their volumes.

$$\sum_v L_v\left(nv_{v,t}^{C,DI}\right) \ge QD_t(vp) \quad ; \quad \forall t \tag{48}$$

$$\sum_v L_v\left(nv_{v,t}^{C,RC}\right) \ge QRC_t(vp) \quad ; \quad \forall t \tag{49}$$

$$\sum_v L_v\left(nv_{v,t}^{RC,P}\right) \ge \sum_r RP_{r,t}(vr_r) \quad ; \quad \forall t \tag{50}$$

$$\sum_v L_v\left(nv_{v,t}^{SU,P}\right) \geq \sum_r R_{r,t}(vr_r) \quad ; \quad \forall t \tag{51}$$

$$\sum_v L_v\left(nv_{v,t}^{C,R}\right) \geq QR_t(vp) \quad ; \quad \forall t \tag{52}$$

$$\sum_v L_v\left(nv_{v,t}^{P,RE}\right) \geq QT_t(vp) \quad ; \quad \forall t \tag{53}$$

In addition, Constraints (54) impose an upper limit on the price of the product and Constraints (55) assign a limit on the budget spent for employee support within each period.

$$P_t \leq MP \quad ; \quad \forall t \tag{54}$$

$$\sum_s (CS_{s,t}) O_{s,t} \leq msu \quad ; \quad \forall t \tag{55}$$

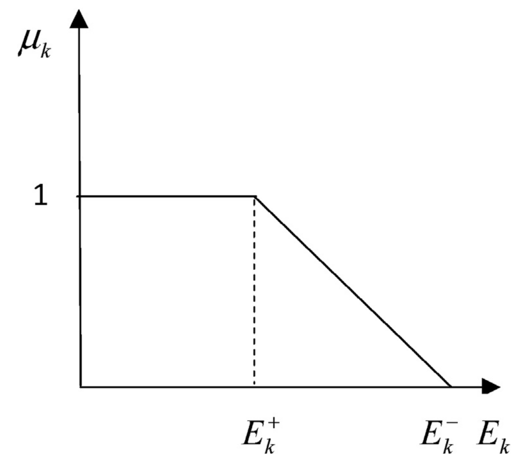

Fig. 7. Linear membership function.

5. The solving procedure

Although there are many methods available in the literature to solve multi-objective optimization problems, the ones that use fuzzy approaches are more suitable to solve the problem at hand due to their ability to measure the degree of satisfaction of each objective function associated with a decision. The degree of satisfaction of an objective function comes into the picture here due to a variety of legislation involved in different countries, as they impose different importance to each objective. This enables the decision-maker to select an efficient solution. Consequently, the fuzzy approach proposed by Torabi and Hassini (2008), the TH method thereafter, is utilized in this paper to solve the multi-objective optimization problem at hand. The TH method is selected here due to robust and reliable solutions it provides with the preference of the decision maker. Moreover, it can produce both balanced and unbalanced solutions based on the decision maker selection of the weight vector of the objective satisfaction (Torabi and Hassini, 2008).

The steps involved in the TH method to solve the problem at hand are described as follows.

1. Specify the positive ideal solution (PIS) and the negative ideal solution (NIS) defined in Table 1.

Here, three problems are solved separately. In the first problem, E_1 is minimized to obtain $E_1^*(x_1^*)$. In the second problem, E_2 is minimized to obtain $E_2^*(x_2^*)$, and finally, E_3 is minimized in the third problem to obtain $E_3^*(x_3^*)$. Note that $E_k^+ \leq E_k \leq E_k^-$.

2. Specify a linear membership function for the cost, the environmental and the social objectives as:

$$\mu_k(x) = \begin{cases} 1 & \text{if } E_k \leq E_k^+ \\ \dfrac{E_k^- - E_k}{E_k^- - E_k^+} & \text{if } E_k^+ \leq E_k \leq E_k^- \\ 0 & \text{if } E_k \geq E_k^- \end{cases} \tag{56}$$

Fig. 7 shows this linear membership function.

3. Finally, convert the multi-objective optimization problem into its equivalent single-objective problem as follows:

$$\begin{aligned} &Max\ Z = \gamma\lambda_0 + (1-\gamma)\sum_k w_k(\mu_k) \\ &s.t. \\ &\mu_k \geq \lambda_0 \quad \forall k \\ &x \in F(x) \end{aligned} \tag{57}$$

where γ is a parameter in $[0,1]$ which governs the minimum satisfaction level of the objectives.

6. A case study

In this section, the proposed mathematical model and the solution procedure is implemented in a case study. The case involves the supply chain of fluorescent CFL light bulbs. CFL light bulbs use approximately 1/4 similarly as much vitality as radiant bulbs. As a large percentage of electricity is generated by fossil fuels (natural gas, coal, petroleum), reducing electricity consumption has a real impact on the environment and reduces the greenhouse gas emissions. Despite the benefits mentioned above for these light bulbs, some disadvantages must be considered when they reach their end of life. In most of the time, burned CFLs are disposed of to a landfill, causing their mercury element to release into the environment when they break or leak. Additionally, broken fluorescent light bulbs thrown in a wastebasket have the potential of disclosing mercury. As these bulbs are manufactured in a very large volume globally, the discarded bulbs become the major factor of releasing a large volume of mercury into the earth every year. As they can be converted to an organic form acquired by living organisms, they harm the global food chain. To decrease these disruption effects of released mercury, a reverse logistics for the CFLs supply chain should be designed to recover the mercury element for remanufacturing.

As CFL bulbs have become popular in Iran recently. Knowing the fact that the reverse logistics and the collection process in this country are poor, the case study in this paper involves the Iranian supply chain of CFL bulb.

6.1. Fluorescent lighting system components

CFLs based on the fixture class include two or three physical components. Most of the fluorescent lamps like neon lighting consist of argon gas. Fig. 8 illustrates these components.

In the current study, the database of the ECO-it software is used ("http://www.pre.nl/eco-it") to determine the environmental indicator, i.e. the CO_2 emission value. To access these indicators, the

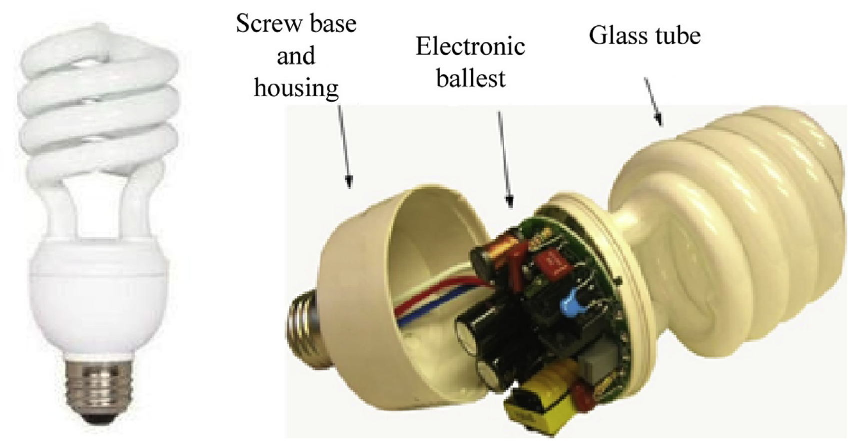

Fig. 8. Fluorescent lighting bulb.

Table 1
The Payoff table.

	E_1	E_2	E_3
Min E_1	$E_1^*(x_1^*)$	$E_2(x_1^*)$	$E_3(x_1^*)$
Min E_2	$E_1(x_2^*)$	$E_2^*(x_2^*)$	$E_3(x_2^*)$
Min E_3	$E_1(x_3^*)$	$E_2(x_3^*)$	$E_3^*(x_3^*)$
$NIS: E_k^-$	$Max(E_1(x_2^*), E_1(x_3^*))$	$Max(E_2(x_1^*), E_2(x_3^*))$	$Max(E_3(x_1^*), E_3(x_2^*))$
$PIS: E_k^+$	$E_1^*(x_1^*)$	$E_2^*(x_2^*)$	$E_3^*(x_3^*)$

parts of CFLs bulbs and their weights must be specified first. The specifications of a usual CFL bulb are listed in Table 2.

ECO-it software database expresses the amount of CO_2 emission for the unit mass of each material in each process, i.e. in production, in use, or in the disposal. For example, considering the material in Table 2, the CO_2 emissions of producing a CFL light bulb is calculated as:

$COPR$ = Gas emissions from production process of a product = CO_2 emissions of 1 kg glass in production process $\times$ weight of glass in a bulb (kg) + CO_2 emissions of 1 kg tin $\times$ weight of tin in a bulb (kg) + CO_2 emissions of 1 kg copper $\times$ weight of copper in a bulb (kg) + CO_2 emissions of 1 kg PVC plastic $\times$ weight of PVC in a bulb + CO_2 emissions of 1 kg of foam$\times$ weight of foam in a bulb + CO_2 emissions of 1 m^3 of electrode $\times$ volume of electrode in a bulb + CO_2 emissions of 1 kg of printed board (fiber) $\times$ weight of printed board (fiber) in a bulb+ CO_2 emissions of 1 kg of black glass in production process $\times$ weight of black glass in a bulb (kg)

$$\begin{aligned} &= 2.46(0.03307) + 17.1(0.0048) + 2.02(0.0019) \\ &\quad + 1.97(0.0168) + 0.19(0.003) + 1.91(0.0016) \\ &\quad + 0.0075(0.0287) + 0.73(0.0049) \\ &\quad = 0.2077 \end{aligned}$$

Other indicators of CO_2 emissions include$CORE$,COD,$CORC$, which are calculated similarly.

In addition, three types of vehicles with different capacities are considered in the supply chain under consideration of shipping the items. According to the Standard Unit Fuel Consumption (SUFC), 1 g of CO_2 released by gasoline diesel per kilometer can be estimated for a liter per 100 km. In other words, 1 g/ kilometer CO_2 equals 0.043 L/100 km as each standard truck emits 23.2 g of CO_2 per kilometer. While this value is assumed for mid-size trucks, a larger value of 23.4 g/kilometer is used for bigger trucks and a smaller value of 23.0 g/kilometer is assumed for small-size trucks.

The other environmental indicators, i.e. the produced wastewater and the energy consumption are assessed by the questioning of the experts. The required data are presented in Table 3. It should be noted that due to space limitation, the values of the other input parameters such as the distance between two centers are not provided in this table. Moreover, three planning horizons, each with a one-year duration and six types of raw materials and three types of production technology are considered here. Besides, all types of the costs involved in the mathematical formulation rise at

Table 2
Mass breakdown of a CFL.

Component	Mass(g)
Assembled lamp	93.6
Metal base (tin plate)	4.8
Base pins (copper)	1.9
Base insulation (black glass)	4.9
Tube glass	33.7
Plastic base (PVC)	16.8
Printed board	4
Printed board assembly	24.7
Foam	3
Electrode assembly (includes mercury)	1.6
Total mass	95.4

Table 3
Input for the case study.

Parameter	Value	Parameter	Value
CO^R	0.09	w^{jc}	0.148
CO^{DI}	0.15	w^s	0.148
CO^{RC}	0.17	w^h	0.288
CO^P	0.2077	w^j	0.288
w^d	0.128	be	30

Table 4
Pay off table.

	E_1	E_2	E_3
Min E_1	−4785520	536225.5	539243.5
Min E_2	38634.21	147.958	236.146
Min E_3	4729402.108	946.949	208.303
$NIS\ : E_k^-$	4729402.11	536225.5	539243.5
$PIS\ : E_k^+$	−4785520	147.958	208.303
$E_k^- - E_k^+$	9514922.11	536077.6	539035.2

Table 5
The results.

variable	value
P_t	$P_{t1} = 20,\ P_{t2} = 20,\ P_{t3} = 100$
do_{qt}	$do_{qre,t2} = 4.532, do_{qre,t3} = 15.701, do_{qrc,t2} = 17.845, do_{qrc,t3} = 14.003 do_{qd,t1} = 10, do_{qd,t2} = 15,\ do_{qd,t3} = 15.853$
QM_t^e	$QM_{t2}^{e2} = 43, QM_{t1}^{e3} = 54$
Q_t	$Q_{t1} = 53,\ Q_{t2} = 43,\ Q_{t3} = 24$
D_t	$D_{t1} = 54, D_{t2} = 43,\ D_{t3} = 24$
T	2.143
Tp_t	$Tp_{t1} = 1.076,\ Tp_{t2} = 0.864$
a_t	$a_{t1} = 96.229,\ a_{t2} = 51.062,\ a_{t3} = 1.021$
$Y_{j,t}$	$Y_{KM,t} = Y_{KR,t} = Y_{KD,t} = Y_{KRC,t} = 0$
GA_t	$GA_{t1} = 240,000, GA_{t2} = 400,000,\ GA_{t3} = 460000$
SHC_t	$SHC_{t1} = 161.431,\ SHC_{t2} = 302.554,\ SHC_{t3} = 283.467$
u_t^e	$u_{t1}^{e3} = 1, u_{t2}^{e2} = 1, u_{t3}^{e3} = 1$
$e1$	−1530.726
..	537.842
$e3$	626.462
obj	9.003751E-6

a 9% rate annually, as the annual inflation rate in Iran is 9%.

As mentioned above, the GRI indicators are used for the environmental and the social effects. These indicators should be compared together in order to determine the importance weight of each indicator. To this aim, the fuzzy analytical hierarchy process (F-AHP) is utilized here. This method is applied by the aid of an expert group to obtain the weight vector containing job satisfaction weight, the worker safety weight, the weight associated with the health and safety of the customers, and the weight for economic development and self-sufficiency as (0.128, 0.148, 0.148, 0.288, 0.288), respectively.

The positive ideal solution (*PIS*) and the negative ideal solution (*NIS*) are shown in Table 4, based on which the linear membership function for the cost, the environmental and the social objectives, i.e.$\mu_k$is obtained using relation (56).

The equivalent single-objective optimization problem of the multi-objective model using the TH method based on the weights of 0.2, 0.6, and 0.2 for the first, the second, and the third objective function and $\gamma = 0.2$ is as follows:

$$
\begin{aligned}
&w = (\omega_1, \omega_2, \omega_3) = (0.2, 0.6, 0.2)\\
&Max\ Z = \gamma\lambda_0 + (1-\gamma)\sum_k w_k(\mu_k)\\
&s.t.\\
&\mu_k \geq \lambda_0 \quad \forall k\\
&(C1 - C28)
\end{aligned}
$$

The result of solving the above problem using the GAMS software is shown in Table 5.

The results obtained show the created customers' willingness to returning back their used products achieved by offering a proportional discount. They demonstrate that employing a proper discount offer enhances the collection rate of the utilized products and demand for new products because the demand for new products and the return rate of the used products are higher in the periods with higher discount rates.

By changing γ and w_k in the equivalent single-objective model, other optimal solutions can be obtained. The objective function values are shown in Tables 6–11.

Eliminating the defeated solutions (the solution points which we have at least a feasible point with better cost, environmental and social objective functions) the best solutions are selected as seen in Table 12. The 3-D Pareto frontier that presents a portfolio of

Table 6
Effect of γ on the objectives.

$(\omega_1, \omega_2, \omega_3)$= 0.4,0.3,0.3			
γ	E_1	E_2	E_3
0.9	6677.420	979.500	1067.876
0.8	2042.968	763.059	836.291
0.6	−11463.400	786.247	914.844
0.5	−4826.910	520.218	621.689
0.3	15650.500	604.145	686.007

Table 7
Effect of γ on the objectives.

$(\omega_1, \omega_2, \omega_3)$= 0.3,0.4,0.3			
γ	E_1	E_2	E_3
0.9	7099.507	7099.507	955.333
0.8	3897.364	856.810	568.527
0.6	3240.990	693.866	423.075
0.5	−3477.550	792.559	890.517

Table 8
Effect of γ on the objectives.

$(\omega_1, \omega_2, \omega_3)$= 0.2,0.2,0.6			
γ	E_1	E_2	E_3
0.9	18247.520	914.475	979.782
0.8	9650.092	941.218	1010.708
0.6	3236.317	679.564	804.268
0.5	−2440.800	1053.487	887.205
0.4	7911.181	376.569	443.422
0.3	4711.202	646.503	722.930
0.2	−1530.726	537.842	626.462
0.1	12881.557	277.933	331.843

Table 9
Effect of γ on the objectives.

$(\omega_1, \omega_2, \omega_3)$= 0.6,0.2,0.2			
γ	E_1	E_2	E_3
0.9	6167.268	451.335	527.398
0.8	4462.245	820.031	577.292
0.6	6718.430	721.034	796.678
0.5	−1021.657	802.257	881.386
0.4	−304.312	416.434	493.512
0.3	−7832.473	963.070	1059.933
0.2	−4932.472	935.594	1024.881
0.1	−3650.719	1014	1082

Table 10
Effect of γ on the objectives.

$(\omega_1, \omega_2, \omega_3)$= 0.8,0.1,0.1			
γ	E_1	E_2	E_3
0.6	−732.910	783.415	919.330
0.2	−24370.501	1053.487	1102.656
0.1	−23083.971	1053.075	1053.371

Table 11
Effect of γ on objectives.

$(\omega_1, \omega_2, \omega_3)$= 0.1,0.1,0.8			
γ	E_1	E_2	E_3
0.9	8543.503	583.538	286.465
0.8	4194.699	873.489	660.207

alternative "optimal solutions" to the decision-maker is shown in Fig. 9.

To demonstrate the tradeoff between each pair of the objective functions, Pareto frontiers are generated in Figures (10) and (11). The tradeoff between the total cost and the environmental objective function shown in Fig. 10 demonstrates that lower environmental effects can only be reached using more investment to use a high-level technology at the plants which lead to less CO2 emission and less energy consumption and wastewater.

Table 12
The best solutions.

e1	e2	e3
−11463.400	786.247	914.844
−4826.910	520.218	621.689
−3477.550	792.559	890.517
−2440.800	1053.487	887.205
−1530.726	537.842	626.462
12881.557	277.933	331.843
−7832.473	963.070	1059.933
−4932.472	935.594	1024.881
−732.910	783.415	919.330
−24370.501	1053.487	1102.656
−23083.971	1053.075	1053.371
8543.503	583.538	286.465

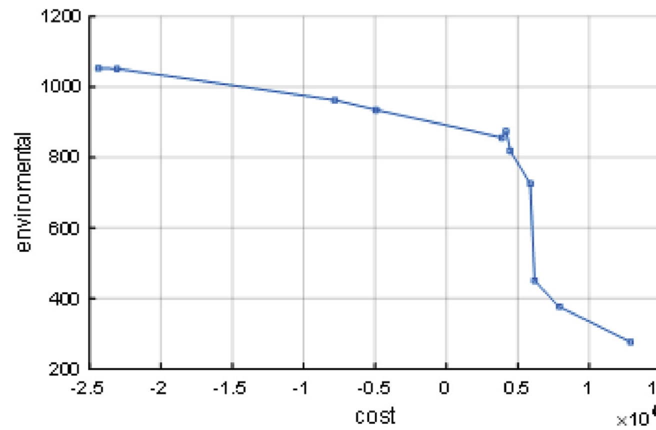

Fig. 10. The tradeoff between the environmental and the total cost objectives of the solutions.

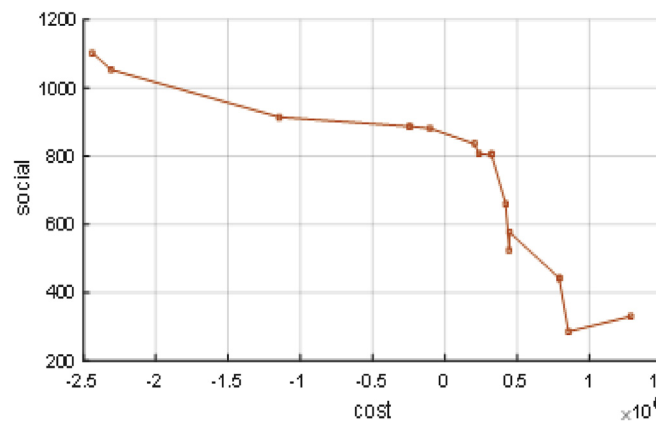

Fig. 11. The tradeoff between the total cost and the social objectives of the solutions.

Fig. 11 shows the tradeoff between the social and the total cost objective functions. It implies that creating more job satisfaction and providing more safety to employees and customers is also obtained by more investments. However, Fig. 12 does not show a meaningful relationship between the social and the environmental objectives.

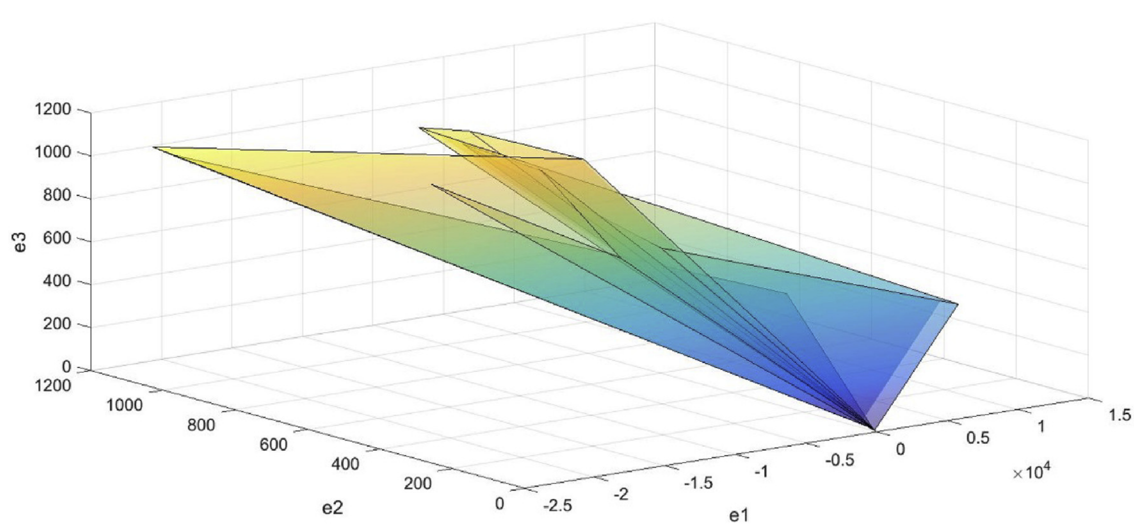

Fig. 9. The 3-D Pareto front obtained.

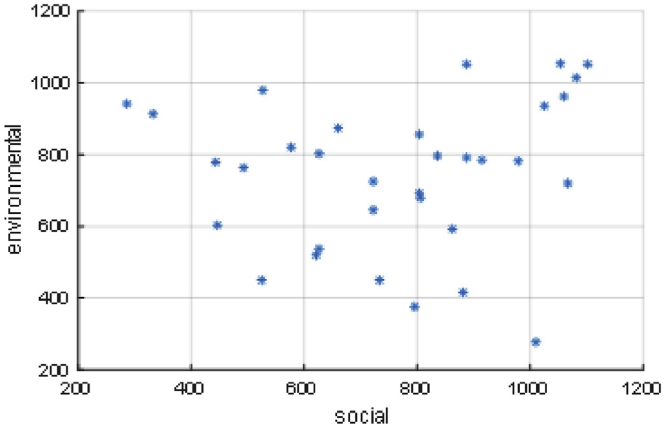

Fig. 12. The tradeoff between the environmental and the social objectives of the solutions.

7. Conclusion and future works

In this paper, we proposed a comprehensive mixed integer optimization model to planning a multi-period multi-echelon SCLSC. The social and environmental effects of the supply chain decisions have been measured by GRI guideline indicators. A discount offer on the returned product was used as an incentive policy to increase customers' willingness to return back their used products more. The amount of the proposed discount depended on the quality of the returned products. The demand for the product was assumed as a dependent variable which relies on the price of the product, the discount offer price, and the goodwill of product in the current period. Moreover, returned products collected by the collection center were categorized according to their quality and that the recovery decisions of returned products were based on their quality level.

The tradeoffs between the cost, the environmental and the social objectives have been analyzed. The results implied that creating more job satisfaction and providing safety for employees and customers were achievable by spending more investment and using high-level technologies in the plant. On the other hand, spending more capital expenditures and employing expensive technologies was in contrast with minimizing the cost objective. Besides, the Pareto optimal solutions were determined to show that the proposed planning model enables the decision makers to use a proper solution based on the existing legislation, social preference, cost, and environmental objectives. In addition, results depicted that the created customers' willingness to returning back their used products by offering a proper proportional discount enhanced the collection rate of utilized products.

Extending the model to consider the uncertainty involved in some parameters such as the shipment cost and the raw material price is suggested for future studies. This extension may bring the model to be more applicable and closer to real-world problems, especially in developing countries with low economic stability. The proposed model can be used for planning an existing SC and can be extended to design and planning that involves some more strategic decisions. Moreover, different sustainability measurement approaches can be used to evaluating the sustainability of the considered SC. Comparing the measurement results will give more insights to construct an SC with a higher degree of sustainability.

Acknowledgments

The authors are thankful for constructing comments of the respected anonymous reviewers. Taking care of the comments significantly improved the presentation. The second author would like to thank the financial support of the University of Tehran for this research under grant number 30015-1-04.

References

Abdulrahman, M.D.A., Subramanian, N., Liu, C., Shu, C., 2015. Viability of remanufacturing practice: a strategic decision making framework for Chinese autoparts companies. J. Clean. Prod. 105, 311–323.
Ahmed, W., Sarkar, B., 2018. Impact of carbon emissions in a sustainable supply chain management for a second generation biofuel. J. Clean. Prod. 186, 807–820.
Aras, N., Aksen, D., 2008. Locating collection centers for distance-and incentive dependent returns. Int. J. Prod. Econ. 111 (2), 316–333.
Cruz, J.M., 2009. The impact of corporate social responsibility in supply chain management: multicriteria decision-making approach. Decis. Support Syst. 48 (1), 224–236.
Das, D., Dutta, P., 2013. A system dynamics framework for integrated reverse supply chain with three way recovery and product exchange policy. Comput. Ind. Eng. 66 (4), 720–733.
De Giovanni, P., 2016. State-and control-dependent incentives in a closed-loop supply chain with dynamic returns. Dynam. Game. Appl. 6 (1), 20–54.
Dehghanian, F., Mansour, S., 2009. Designing sustainable recovery network of end-of-life products using genetic algorithm. Resour. Conserv. Recycl. 53 (10), 559–570.
Demirel, E., Demirel, N., Gökçen, H., 2016. A mixed integer linear programming model to optimize reverse logistics activities of end-of-life vehicles in Turkey. J. Clean. Prod. 112, 2101–2113.
Devika, K., Jafarian, A., Nourbakhsh, V., 2014. Designing a sustainable closed-loop supply chain network based on triple bottom line approach: a comparison of metaheuristics hybridization techniques. Eur. J. Oper. Res. 235 (3), 594–615.
Diabat, A., Al-Salem, M., 2015. An integrated supply chain problem with environmental considerations. Int. J. Prod. Econ. 164, 330–338.
Du, Y., Cao, H., Liu, F., Li, C., Chen, X., 2012. An integrated method for evaluating the remanufacturability of used machine tool. J. Clean. Prod. 20, 82–91.
Elhedhli, S., Merrick, R., 2012. Green supply chain network design to reduce carbon emissions. Transport. Res. Transport Environ. 17 (5), 370–379.
Fahimnia, B., Sarkis, J., Eshragh, A., 2015. A tradeoff model for green supply chain planning: a leanness-versus-greenness analysis. Omega 54, 173–190.
Gelbmann, U., Hammerl, B., 2015. Integrative re-use systems as innovative business models for devising sustainable product–service-systems. J. Clean. Prod. 97, 50–60.
Geyer, R., Blass, V.D., 2010. The economics of cell phone reuse and recycling. Int. J. Adv. Manuf. Technol. 47 (5–8), 515–525.
Go, T.F., Wahab, D.A., Rahman, M.A., Ramli, R., Azhari, C.H., 2011. Disassemblability of end-of-life vehicle: a critical review of evaluation methods. J. Clean. Prod. 19, 1536–1546.
Govindan, K., Soleimani, H., Kannan, D., 2015. Reverse logistics and closed-loop supply chain: a comprehensive review to explore the future. Eur. J. Oper. Res. 240 (3), 603–626.
GRI, 2011. Sustainability Reporting Guidelines, version 3.1.
Guide Jr., V.D.R., Teunter, R.H., Van Wassenhove, L.N., 2003. Matching demand and supply to maximize profits from remanufacturing. Manuf. Serv. Oper. Manag. 5 (4), 303–316.
Junior, M.L., Filho, M.G., 2012. Production planning and control for remanufacturing: literature review and analysis. Prod. Plann. Contr. 23 (6), 419–435.
Krikke, H., Bloemhof-Ruwaard, J., Van Wassenhove, L.N., 2003. Concurrent product and closed-loop supply chain design with an application to refrigerators. Int. J. Prod. Res. 41 (16), 3689–3719.
Kurdve, M., Shahbazi, S., Wendin, M., Bengtsson, C., Wiktorsson, M., 2015. Waste flow mapping to improve sustainability of waste management: a case study approach. J. Clean. Prod. 98, 304–315.
Lin, Y.H., Tseng, M.L., 2016. Assessing the competitive priorities within sustainable supply chain management under uncertainty. J. Clean. Prod. 112, 2133–2144.
Litvinchev, I., Rios, Y.A., Özdemir, D., Hernández-Landa, L.G., 2014. Multiperiod and stochastic formulations for a closed loop supply chain with incentives. J. Comput. Syst. Sci. Int. 53 (2), 201–211.
Matsumoto, M., 2010. Development of a simulation model for reuse businesses and case studies in Japan. J. Clean. Prod. 18, 1284–1299.
Murakami, F., Sulzbach, A., Pereira, G.M., Borchardt, M., Sellitto, M.A., 2015. How the Brazilian government can use public policies to induce recycling and still save money? J. Clean. Prod. 96, 94–101.
Ning, S.K., Chang, N.B., Hung, M.C., 2013. Comparative streamlined life cycle assessment for two types of municipal solid waste incinerator. J. Clean. Prod. 53, 56–66.
Panda, S., Modak, N.M., Cárdenas-Barrón, L.E., 2017a. Coordination and benefit sharing in a three-echelon distribution channel with deteriorating product. Comput. Ind. Eng. 113, 630–645.
Panda, S., Modak, N.M., Cárdenas-Barrón, L.E., 2017b. Coordinating a socially responsible closed-loop supply chain with product recycling. Int. J. Prod. Econ. 188, 11–21.
Pishvaee, M.S., Razmi, J., Torabi, S.A., 2014. An accelerated Benders decomposition

algorithm for sustainable supply chain network design under uncertainty: a case study of medical needle and syringe supply chain. Transport. Res. E Logist. Transport. Rev. 67, 14–38.
Qorri, A., Mujkić, Z., Kraslawski, A., 2018. A conceptual framework for measuring sustainability performance of supply chains. J. Clean. Prod. 189, 570–584.
Sasikumar, P., Kannan, G., 2009. Issues in reverse supply chain, part III: classification and simple analysis. Int. J. Sustain. Eng. 2 (1), 2–27.
Sethi, S.P., 1977. Optimal advertising for the Nerlove-Arrow model under a budget constraint. J. Oper. Res. Soc. 28 (3), 683–693.
Shaharudin, M.R., Govindan, K., Zailani, S., Tan, K.C., 2015a. Managing product returns to achieve supply chain sustainability: an exploratory study and research propositions. J. Clean. Prod. 101, 1–15.
Shaharudin, M.R., Zailani, S., Tan, K.C., 2015b. Barriers to product returns and recovery management in a developing country: investigation using multiple methods. J. Clean. Prod. 96, 220–232.
Song, Q., Li, J., Zeng, X., 2015. Minimizing the increasing solid waste through zero waste strategy. J. Clean. Prod. 104, 199–210.
Torabi, S.A., Hassini, E., 2008. An interactive possibilistic programming approach for multiple objective supply chain master planning. Fuzzy Set Syst. 159 (2), 193–214.
Xia, X., Govindan, K., Zhu, Q., 2015. Analyzing internal barriers for automotive parts remanufacturers in China using grey-DEMATEL approach. J. Clean. Prod. 87, 811–825.
Ziout, A., Azab, A., Atwan, M., 2014. A holistic approach for decision on selection of end-of-life products recovery options. J. Clean. Prod. 65, 497–516.