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Fuzzy multi-objective sustainable and green closed-loop supply chain network design

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ABSTRACT

This article addresses a design problem of a closed loop supply chain, including suppliers, manufacturers, distribution centers, customers, warehouse centers, return centers, and recycling centers. The problem entails three choices regarding recycling, namely, product recycling, and components recycling raw material recycling. Modeling this chain is carried out by accounting for environmental considerations, total profit optimization, and reduction of lost working days due to occupational accidents, we well as maximizing responsiveness to customer demand. In order to solve the model, genetic algorithm has been used and multiple scenarios with different aspects have been studied. Solving this model provides decisions regarding opening or closing of each of the components of the network and the optimal product flow among them. The results prove the feasibility of the presented model and the applicability of the developed solution methodology.

1. Introduction

In recent years, due to governmental regulations as well as the ever-increasing attention to environmental impacts and preserving natural resources, reverse logistics and closed loop supply chains have come to the forefront of agendas by researchers and decision-makers. A classic or forward (progressive) supply chain consists of a network of suppliers, manufacturers, and distributors that is formed to produce and deliver a specific product or service. Reverse logistics involves all the matters related to collecting the used products, controlling and collecting them, as well as recycling, reprocessing, refurbishing, and disposing of them. If both forward and reverse supply chains are considered simultaneously, the resulting network is referred to as closed loop supply chain (Govindan, Soleimani, & Kannan, 2015). These concepts guide organizations to make conscious decisions on their products – whether they have reached their end-of-life or have been used – to either recycle or dismount them. In order to design such a chain, it is necessary for the organization to plan for the design of their reverse logistics network as well as their forward supply chains. Also, the increase of the attention to the environmental and societal outcomes has led to the coining of concepts such as green and sustainable supply chains.

In various industries, as well as in academic publications, as conventional selection criteria, an acceptable trade-off between cost and quality have been proposed and considered among suppliers. The mere means by which firms can stand out from the competition is to reduce operational costs and to improve the quality of services while taking into account the economic and social matters related to their respective supply chains (Özkır & Başlıgil, 2013). This also highlights the need for organizations to designing a sustainable close loop supply chain network to increase their overall competitive advantage. According to the new definition, a closed loop supply chain entails the design, control, and implementing of a system to maximize value creation in the lifetime of a product, with a dynamic value generation from different returned products over time (Govindan et al., 2015).

A green supply chain is a supply chain in which environmental considerations have been addressed during its design. For instance, new raw materials would have higher prices if their manufacturing process has lower energy consumption. Recycled materials would have lower buying price while their processing has higher energy consumption (Su, 2014). Implementing sustainable supply chain management is a key enabler that pressures organizations to reduce their negative environmental impacts, and results in increased social and economic benefits (Zailani, Jeyaraman, Vengadasan, & Premkumar, 2012). Also, the reduction of the destructive environmental impacts should be considered as an aim in the supply chain. The CO_2 emission indicator is widely used

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to quantitatively identify the environmental impacts, and could be used in modeling supply chains. Several other indicators are also considered in studying the environmental impacts, including the amount of energy consumption, solid waste, water consumption, and water waste. These indicators are analyzed in an article by Ahi and Searcy (2015).

The social responsibility of firms has also various dimensions. The dimensions are categorized by the International Standardization Organization (ISO) in ISO26000 into six major groups, including human rights, workforce issues, the environment, proper working conditions, customer care, and societal development. In general, there are three types of decision variables including strategic (e.g., locating, capacities, etc.), tactical (e.g., allocation, planning, etc.), and operational (e.g., order size, inventory, etc.) (Chopra & Meindl, 2007). Designing the logistics network as a strategic decision in organizations has a remarkable impact on the effectiveness of supply chains. In the closed loop supply chain problem, simultaneously, two decisions – including locating facilities and the flows between them – are considered.

Dealing with the problem of designing and planning a closed loop supply chain as a NP-hard problem requires an efficient approach to provide a reliable solution in a logical time, specially, in problems with realistic dimensions. Prior articles which have attempted to provide new solutions to the problem confirm this (Soleimani, Seyyed-Esfahani, & Shirazi, 2013). As a result, using different precise and imprecise approaches have been overviewed. In larger dimensions and in more complex problems, using precise approaches are extremely time-consuming or impossible. In order to provide a solution for these types of problems, innovative approaches could be used to reach an acceptable solution in a relatively shorter time.

The components of the closed loop supply chain considered in this study include customers, factories, distribution centers, warehouses, and recycling centers. This chain has three forward levels and three reverse levels, which will be modeled with a multi-objective fuzzy approach. The model reviewed in this article, is a multi-product, multi-level, multi-periodic model which includes almost all activities from the suppliers to the recycling centers and customers.

The new approach of the developed model of this study considers components and raw materials simultaneously. The products consist of several components which can be disassembled and used as a unit or be recycled as raw materials. For example, a bicycle is made of several components including frame, saddle, front set, wheels, pedals and chains. There is a huge market in selling such components.[1] On the other hand, the components which are not in an acceptable quality of recovering and selling in second markets can be recycled to the metals and rubbers so as to be used as raw materials.[2] Various similar instances can be mentioned in the automotive industry, electronic, and computer equipment. This approach made the proposed multi-product model so complicated, especially in terms of solving large-scale instances with metaheuristic approaches. Strictly speaking, a multi-product, multi-components, multi-material model is developed in this study as a more practical model.

In the following, and in the second section of this article, a literature review is provided followed by a thorough explanation of the model in Section 3. Section 4 includes the solution and the suggested algorithm. In Section 5, different scenarios are overviewed and the numerical results from solving the model are analyzed and interpreted. Finally, in Section 6, the results of this article are presented and future research areas are suggested.

2. Literature review

2.1. Closed loop supply chain design

The design of a closed loop supply chain is a problem that has been given much academic attention in the recent years. In general, most of the existing research is single objective in which mainly the objective function consists of minimizing the fixed costs of setup, operations, and transportation (Pishvaee, Rabbani, & Torabi, 2011).

Pishvaee, Farahani, and Dullaert (2010) and Pishvaee, Kianfar, and Karimi (2010) provided a robust linear complex planning model for minimizing the cost of transportation and the fixed setup costs in a multilevel reverse logistics network using simulation algorithms. Following the mentioned study, Pishvaee et al. (2011) presented a robust linear complex planning model with the objective functions of minimizing cost and maximizing the level of responsiveness, in which for reaching a set of robust results, a multi-objective mimetic algorithm is used.

In 2013, three rather related papers can be mentioned here; Ramezani, Bashiri, and Tavakkoli-Moghaddam (2013) provided a multi-object model for the problem of an integrated logistics network under the conditions of uncertainty with the objective of maximizing profit, customer responsiveness, and quality. Amin and Zhang (2013) considered a closed loop supply chain network with multiple manufactures, warehouses, demand markets and products. They used linear integer planning to reduce the total cost. In their work, the effect of uncertainty on demand and returns in networks is considered using contingency planning. Özkır and Başlıgil (2013) used fuzzy logic to model the activities in a closed loop supply chain in a multi objective fashion. They applied the model to investigate the effects of the quality and quantity of returned products on customer satisfaction and supply chain profitability. The objectives of this model include maximizing service levels, maximizing buyer and seller satisfaction in the chain, and decreasing the total cost in the supply chain.

Ramezani, Kimiagari, Karimi, and Hejazi (2014) considered a closed loop supply chain with decentralized decision makers including raw material suppliers, manufactures, and retailers which directly collect recycled products from the market. They studied the convergence of suggested algorithms which could include the effects of competition, investment on distribution centers, as well as profits and returns. The reviewed model in this research is a multi-objective model for designing an integrated logistics network under uncertainty with the objective to maximize profits, customer responsiveness, and quality. Finally, Alshamsi and Diabat (2015) utilized a mixed-integer linear programming in reverse logistics using a case study approach.

2.2. Sustainable and green supply chain

Attention to the concepts of sustainable and green supply chains has been on the rise in the recent years, and many researchers have included environmental and social responsibility issues in their studies. Paksoy, Özceylan, and Weber (2010) provided a multi-objective linear model to minimize costs and CO_2 emissions in supply chains. Millet (2011) studied the elements in achieving a sustainable supply chain which simultaneously considers economic, social, and environmental issues. Kannan, Diabat, Alrefaei, Govindan, and Yong (2012) considered carbon emissions as the decision variable in their suggested model. In their research, they considered a reverse logistics network in the plastic industry and modeled it as a linear integer planning problem. Pishvaee, Razmi, and Torabi (2012) and Pishvaee, Torabi, and Razmi (2012) considered minimizing costs and maximizing social impacts in their

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[1] http://www.bicycling.com/bikes-and-gear-features/lifestyle/where-sell-your-used-cycling-gear.

[2] http://www.ibike.org/environment/recycling/.

suggested dual objective model for a forward supply chain. To solve the model, they suggested a new combined approach based on robust optimization and stochastic planning. Abdallah, Farhat, Diabat, and Kennedy (2012) developed a mixed-integer programming in a supply chain network focusing on reducing CO_2 emissions. Besides, three scenarios of reducing carbon emission are regarded in their study. Amin and Zhang (2013) developed a closed loop supply chain network including production centers, warehouses, and demand markets, entailing multiple products under uncertainty. In order to do so, they suggested a linear integer model planning which minimizes the total costs. Furthermore, an environmental function which includes weighted environmental issues is added to their problem.

Su (2014) carried out a study focusing on the relationship between new and recycled materials considering variable production costs, machine productivity, and energy consumption. In that research, a linear multi-objective fuzzy planning model was used to analyze the relationship between the factors involved in effective costs and CO_2 emissions. Ahi and Searcy (2015) reported a research determining and reviewing the factors used in sustainable and green supply chain articles. Also, Diabat and Theodorou (2015) presented a location-inventory problem in a supply chain analyzing the amounts of emissions, which is optimized using genetic algorithm.

2.3. Uncertainty in supply chains

When it comes to qualitative and quantitative analyses, researchers could either account for known parameters, or consider various uncertainties which reflect the actual market characteristics (Govindan et al., 2015). Several ways have been suggested to consider uncertainties, including applying fuzzy logic. In cases when the available information is vague, fuzzy set theory and fuzzy mathematical planning could be used to deal with the actual real world actual uncertainties. Uncertainty in supply chain has been widely studied in the recent decade. Chen, Yuan, and Lee (2007) carried out a study with the premise of demand uncertainty. Petrovic, Xie, Burnham, and Petrovic (2008) studied uncertainty in demand. Also, Efendigil, Önüt, and Kahraman (2009) considered demand as an uncertainty parameter in their research.

El-Sayed, Afia, and El-Kharbotly (2010) used stochastic planning to deal with parameter uncertainty in their problem. Similarly, Pishvaee, Farahani, et al. (2010) and Pishvaee, Kianfar, et al. (2010) applied a stochastic planning approach to explain uncertainty in their research. Qin and Ji (2010) used a fuzzy approach to model their suggested supply chain design problem. Pishvaee, Razmi, et al. (2012) and Pishvaee, Torabi, et al. (2012) used fuzzy mathematical modeling to model their problem. Özkır and Başlıgil (2013) applied fuzzy mathematical planning to model the problem of maximizing the satisfaction of the parties as well as the customers in a supply chain.

2.4. Solving the problem of the closed loop supply chain

In prior research, solving the problems of closed loop supply chains has been done in different ways. Most of the suggested solutions are robust solutions using mathematical modeling software packages such as Lingo and GAMS. The problems modeled with these software packages generally have fewer echelons. El-Sayed et al. (2010) used CPLEX to solve their suggested model in smaller scales. Wang, Lu, and Zhang (2013) used GAMS to solve a single product, single period model. Ramezani et al. (2013) used a robust solution approach to solve their single period multi product model. Also, Özkır and Başlıgil (2013) used GAMS to solve their multi objective fuzzy model involving a multi-period multi-product model. Santibanez-Gonzalez and Diabat (2013) utilized metaheuristic algorithm in order to solve a developed reverse logistics. Kannan, Sasikumar, and Devika (2010) used genetic algorithm to propose a solution for problems in smaller scales. Later, Soleimani et al. (2013) used CPLEX to provide a robust solution for smaller scales, and heuristic and genetic algorithm for problems in larger scales. Soleimani and Kannan (2015) proposed a hybrid particle swarm-genetic algorithm to solve larger scale models, which proved to have higher accuracy than either of the two comprising algorithms. Diabat and Theodorou (2015) and Al-Salem, Diabat, Dalalah, and Alrefaei (2016) developed a reformulated supply chain network which they converted a nonlinear model to a linear one. They used a similar piecewise linear programming model for their proposed network. In addition, genetic algorithm and other metaheuristic algorithms in reverse logistics and closed-loop supply chain networks is used frequently in the recent publications (Alshamsi & Diabat, 2017; Diabat & Deskoores, 2016; Hiassat, Diabat, & Rahwan, 2017; Kumar, Soleimani, & Kannan, 2014; Wang, Soleimani, Kannan, & Xu, 2016; Zohal & Soleimani, 2016).

A summary of the literature review and the role of the current paper is presented in Table 1.

Based on the literature review and the associated summarization in Table 1 (which has been discussed in this section), it is evident that modeling and solving the problem of a multi-period multi-product closed loop supply chain in a large scale which considers environmental and social responsibility issues could be an interesting and relevant research topic, especially in case each of the products consists of multiple components and each component consists of various raw materials. This study follows the scholarly article by Özkır and Başlıgil (2013) to provide a solution for the proposed model considering the concerns of environmental and

Table 1
Summary of the literature review.

No.	Paper	Multi-objective	Multi-period	Multi-component	Multi-material	Green approach	Sustainable approach	Large scale instances	Metaheuristic method
1	Pishvaee, Farahani, et al. (2010) and Pishvaee, Kianfar, et al. (2010)	Yes	No	No	No	No	No	Yes	Memetic
2	Ramezani et al. (2013)	Yes	No	No	No	No	No	No	No
3	Özkır and Başlıgil (2013)	Yes	Yes	Yes	Yes	No	Yes	No	No
4	Ramezani et al. (2014)	Yes	Yes	No	No	No	No	No	No
5	El-Sayed et al. (2010)	No	Yes	No	No	No	No	No	No
6	Paksoy et al. (2010)	No	No	No	No	Yes	Yes	No	No
7	Wang et al. (2013)	No	No	No	No	No	No	No	No
8	Pishvaee, Jolai, and Razmi (2009)	No	No	No	No	No	No	No	No
9	Soleimani and Kannan (2015)	Yes	Yes	No	No	No	No	Yes	Hybrid GA-PSO
10	Soleimani et al. (2013)	Yes	Yes	No	No	No	No	Yes	GA
11	This research	Yes	Yes	Yes	Yes	Yes	Yes	Yes	GA

social impacts of a supply chains. The contributions of this paper can be roughly summarized as follows:

- The model is a green and sustainable extension of Özkır and Başlıgil in 2013 to which two objective functions are added. Based on the green approach of this paper, a minimum CO_2 emission function is considered. Besides, in order to consider sustainable issues and regarding the requirements of ISO 26000:2010, minimizing the number of missed days of labor due to occupational accidents are taking into account. In order to consider the two mentioned objective functions, associated constraints are added to the main model and the related extensions are considered. On the other hand, the new approach of developing a multi-product, multi-components, multi-material model can make this study more practical. The final model is unique in the literature for the presented problem.
- The extended model is solved using an elevated genetic algorithm and LINGO software. The genetic algorithm is updated in order to achieve the solutions faster and more reliable. Strictly speaking, a heuristic is developed in the first stage of the original algorithm, which can generate the feasible solutions absolutely faster. In fact, the initial step of the presented genetic algorithm starts with a developed heuristic algorithm.
- Although the structure of the genetic algorithm of this study is very similar to the classic one, as it will be explained, the initial population is produced in a way that many of the constraints are met based on a heuristic production of feasible solutions. Therefore, this can help the genetic algorithm to be more agile in iterations and generating populations.

Consequently, this paper tries to elevate the closed-loop supply chain planning problem in both modeling and solution algorithm regarding green and sustainable factors.

3. Problem description

The problem addressed in this section is extensively described. First, some general issues in the model are presented, then uncertainties in the system are discussed. Later, the premises of the problem are presented, and finally, following a presentation of some of the parameters and variables of the problem, the solution is discussed.

The model consists of three levels in a forward chain and includes raw materials provision, new product production, and product distribution. It also comprises three levels in the returns chain involving used product collection, recycling, and redistribution. These levels are illustrated in Fig. 1.

In the first level of this chain, the necessary raw material for production in the factories are supplied by the collecting centers using the recycled components. In case the components are not supplied by the reverse centers, factories could supply their necessary items from external suppliers. At this stage, it is required that the recycled components meet the minimum quality and functional standards for product design. The product is sent to the recycling centers for repair. The second level of the reverse chain involves repair and recycling of the product and sending it to the distributors after quality control and packaging. In the final level of this reverse chain, the recycled products are delivered to the customers at a lower price than new products to meet their demand of recycled products.

If the controlled product is not in proper condition for recycling, demounting it would be the option, and in that case, it is sent to factories. Finally, if the major components are not recyclable for use in factories, they are decomposed to their raw materials, and then these raw materials are sold to external suppliers.

In this article, the proposed closed loop supply chain is meant for manufacturing, supplying, collecting, and recycling products that have multiple major components, and each of these components are composed of several raw materials in different quantities. The first objective of this model is to increase the overall profit of the whole chain. The social responsibility concerns, including missed working days due to occupational hazards and accidents, is considered as the second objective. The third objective of the model is to maximize meeting customer demand for new and recycled products.

3.1. Uncertainties in the model

In real world and during a supply chain design, various parameters are faced which cannot be considered certain. To reach more realistic results, it is reasonable to incorporate these uncertainties to the possible extent.

3.1.1. Demand uncertainty

For meeting the changes in customer orders, it is necessary to understand the demand pattern. Perhaps, the most important principle in supply chain is focusing on customer demand to be able to meet them properly. Although the customer demand forecast is generally not precise, fully satisfying customer demand is of extreme value. It is taken that we have all the available information regarding individual customer demand for every product in a specific period at hand. In this model, the demand of customer *c* in period *t* for the recycled product *i*, with $\mathrm{D}^{\mathrm{r}}_{\mathrm{ict}}$ is presented as well as and for the new product *i* with $\mathrm{D}^{\mathrm{n}}_{\mathrm{ict}}$. Since fully meeting customer demand is not always possible, we use fuzzy logic to maximize meeting customer demand. Also, the maximum allowed met demand based on demand forecast is limited. If we present the actual new product *i* shipped in period *t* from center *d* to customer *c* with $\mathrm{FD}_{\mathrm{idct}}$ and use $\mathrm{F'D}_{\mathrm{idct}}$ for recycled products, Eqs. (1)–(6) show the membership functions of meeting demand of new products (Eqs. (1)–(3)) and recycled products (Eqs. (4)–(6)).

$$\sum_{d\in D} F'D_{idct} \cong D^{n}_{ict} \tag{1}$$

$$\mu^{nd}_{ict} = \begin{cases} 0, & \sum_{d\in D} FD_{idct} \leqslant (1-\eta)D^{n}_{ict} \\ 1-\frac{D^{n}_{ict}-\sum_{d\in D} FD_{idct}}{(1-\eta)D^{n}_{ict}}, & (1-\eta)D^{n}_{ict} \leqslant \sum_{d\in D} FD_{idct} \leqslant D^{n}_{ict} \\ 1-\frac{\sum_{d\in D} FD_{idct}-D^{n}_{ict}}{(1-\eta)D^{n}_{ict}}, & D^{n}_{ict} \leqslant \sum_{d\in D} FD_{idct} \leqslant (1+\eta)D^{n}_{ict} \\ 0, & \sum_{d\in D} FD_{idct} \geqslant (1+\eta)D^{n}_{ict} \end{cases} \tag{2}$$

$$\sum_{d\in D} FD_{idct} \leqslant D^{n}_{ict} \tag{3}$$

$$\sum_{d\in D} F'D_{idct} \cong D^{r}_{ict} \tag{4}$$

$$\mu^{rd}_{ict} = \begin{cases} 0, & \sum_{d\in D} F'D_{idct} \leqslant (1-\eta)D^{r}_{ict} \\ 1-\frac{D^{r}_{ict}-\sum_{d\in D} F'D_{idct}}{(1-\eta)D^{r}_{ict}}, & (1-\eta)D^{r}_{ict} \leqslant \sum_{d\in D} F'D_{idct} \leqslant D^{r}_{ict} \\ 1-\frac{\sum_{d\in D} F'D_{idct}-D^{r}_{ict}}{(1-\eta)D^{r}_{ict}}, & D^{r}_{ict} \leqslant \sum_{d\in D} F'D_{idct} \leqslant (1+\eta)D^{r}_{ict} \\ 0, & \sum_{d\in D} F'D_{idct} \geqslant (1+\eta)D^{r}_{ict} \end{cases} \tag{5}$$

$$\sum_{d\in D} F'D_{idct} \leqslant D^{r}_{ict} \tag{6}$$

3.1.2. Social impact uncertainty

Social responsibility of the organizations has multiple facets, and includes several indicators regarding social and environmental

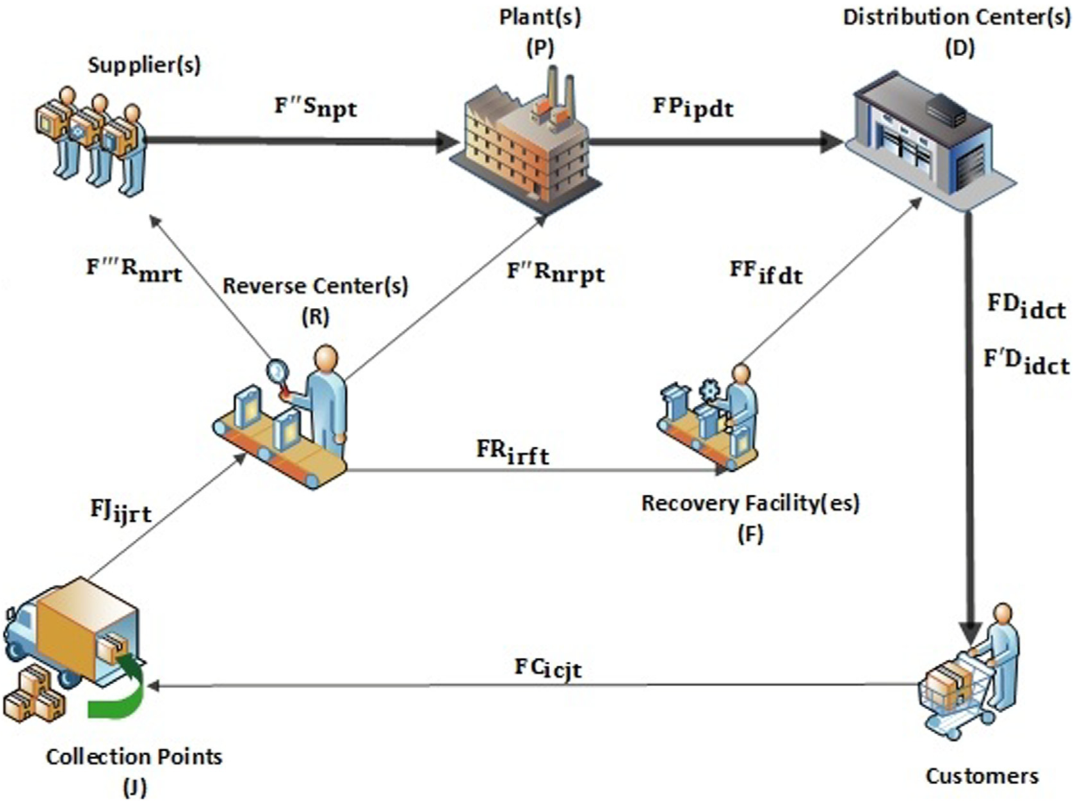

Fig. 1. The studied model and flows among the centers.

issues. To achieve a standard framework and to further develop the concept, ISO proposed ISO26000 which is an international standard guideline for social responsibility [28]. In this article, one of the most important social issues which pertains to occupational accidents is considered. This factor concerns the opening or closing each of the entities in the system. In accounting for social responsibility, deterministic, stochastic, or fuzzy modelling could be used. Depending on the technology level and the location of each center, they deal with the number of missed working days due to occupational accidents, while the maximum permitted number of days in each period is known. In this model, using fuzzy modelling it is intended to minimize the total missed days in the whole system.

According to Fig. 2 and considering LDIDEAL as the ideal number of missed days, and LDMAX as the maximum permitted number of missed days, Eqs. (7)–(9) are formed. In this model, the occupational hazards resulting from establishing collecting centers and distribution centers are considered to be negligible.

$$\mu^{l}_{rt} = \begin{cases} \frac{l^{max}_{rt} - \sum_{r\in R} l_{rt} W_{rt}}{l^{max}_{rt}}, & 0 \leqslant \sum_{r\in R} l_{rt} W_{rt} \leqslant l^{max}_{rt} \\ 0, & l^{max}_{rt} \leqslant l_{rt} \end{cases} \tag{7}$$

$$\mu^{l}_{ft} = \begin{cases} \frac{l^{max}_{ft} - \sum_{f\in F} l_{ft} X_{ft}}{l^{max}_{ft}}, & 0 \leqslant \sum_{f\in F} l_{ft} X_{ft} \leqslant l^{max}_{ft} \\ 0, & l^{max}_{ft} \leqslant l_{ft} \end{cases} \tag{8}$$

$$\mu^{l}_{pt} = \begin{cases} \frac{l^{max}_{pt} - \sum_{p\in P} l_{pt} Y_{pt}}{l^{max}_{pt}}, & 0 \leqslant \sum_{p\in P} l_{pt} Y_{pt} \leqslant l^{max}_{pt} \\ 0, & l^{max}_{pt} \leqslant l_{pt} \end{cases} \tag{9}$$

3.2. Three objective closed loop supply chain

Designing a closed loop supply chain could be done with several objectives. The proposed model in this article has three objectives, namely, increasing the chain profit, reducing the number of missed working days due to occupational accidents, and maximizing meeting customer demand. This model is a multi-product multi-level multi-period model for deciding on the required number of centers, their locations, and the flow of products between them, while reaching the stated objectives. The defined sets for modelling this problem are shown in Table 2. The symbols used in modelling this closed loop supply chain are described in Tables 3 and 4.

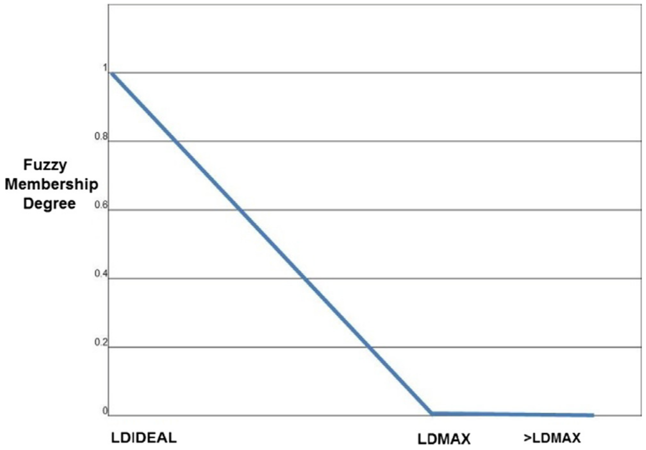

Fig. 2. Membership levels for missed working days due to occupational accidents for each labor force.

The assumptions in modelling this problem are as follows:

- There exists at least one type of center in the closed loop supply chain.
- The collecting and reverse points do not have the capacity for more than one period.

Table 2
The defined sets for modelling (Özkır & Başlıgil, 2013).

Set	Definition
P	Possible locations for establishing factories
D	Possible locations for establishing distribution centers
R	Possible locations for establishing return centers
J	Possible locations for establishing collecting centers
F	Possible locations for establishing recycling centers
C	Customer locations
T	Period
I	Products
N	Product components
M	Raw materials

Table 3
Decision variables.

Variable	Description
V_{jt}	Indicator for opening collecting center j in period t
W_{rt}	Indicator for opening returning center r in period t
X_{ft}	Indicator for opening recycling center f in period t
Y_{pt}	Indicator for opening factory p in period t
Z_{dt}	Indicator for opening distribution center d in period t
$F'D_{idct}$	Number of recycled product I, shipped from distribution center d to customer c in period t
FD_{idct}	Number of new product i, shipped from distribution center d to customer c in period t
FC_{icjt}	Number of returned product I from customer c to collecting center j in period t
FJ_{ijrt}	Number of returned product i, transferred from returning center r to factory p in period t
FR_{irft}	Number of returned product i, moved transferred from returning center r to recycling center f in period t
$F''R_{nrpt}$	Number of transferred components n, from returning center r to factory p in period t
FF_{ifdt}	Number of recycled product i, transferred from recycling center f to distribution center d in period t
FP_{ipdt}	Number of new products i, transferred from factory p to distribution center d in period t
$F''{}'R_{mrt}$	Number of decomposed material m, in returning center r in period t
$F''S_{npt}$	Number of supplied components n, from external suppliers in period t
$\boldsymbol{\mu}^{l}_{rt}$	Membership degree for number of missed working days due to occupational accidents for each worker resulting from establishing returning centers in period t
$\boldsymbol{\mu}^{l}_{ft}$	Membership degree for number of missed working days due to occupational accidents for each worker resulting from establishing distribution centers in period t
$\boldsymbol{\mu}^{l}_{pt}$	Membership degree for number of missed working days due to occupational accidents for each worker resulting from establishing factories in period t
$\boldsymbol{\mu}^{rd}_{ict}$	Minimum membership degree for meeting customer demand c for recycled product i in period t
$\boldsymbol{\mu}^{nd}_{ict}$	Minimum membership degree for meeting customer demand c for new product i in period t

- The reverse centers do not have any limitation for demounting and decomposing.
- The price of recycled products in consistent regardless of quality.
- Recycled products are sold as they are and at a lower price than new products.
- Transportation (shipping) costs are equal for new and old products in any period.
- CO_2 emissions for controlling and compiling, demounting, refurbishing, and disposing wastes, and reproduction (other activities) can be neglected compared to CO_2 emissions resulting from transportation.
- The number of missed working days due to occupational accidents in collecting and distribution centers could be neglected.
- Supply of recycled products for distribution centers could only be done via recycling centers.

3.2.1. Objective function 1: Maximizing the profit of the whole chain

In the first objective function that pertains to maximizing the profit of the chain, the profit function is formulated as follows:

$$Max:\ Profit = TREV - TSC - TFC - TPC - TPUC - TTC - THC - TPEC \tag{10}$$

$$TREV = \sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{c\in C} P_i^n FD_{idct} + \sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{c\in C} P_i^r F'D_{idct} + \sum_{t\in T}\sum_{r\in R}\sum_{m\in M} P_m^m F'''R_{mrt}^m \tag{11}$$

$$TSC = \sum_{j\in J} c_j^s (V_{jt} - V_{j0}) + \sum_{r\in R} c_r^s (W_{rt} - W_{r0}) + \sum_{p\in P} c_p^s (Y_{pt} - Y_{p0}) + \sum_{f\in F} c_f^s (X_{ft} - X_{f0}) + \sum_{d\in D} c_d^s (Z_{dt} - Z_{d0}) \tag{12}$$

$$TFC = \sum_{j\in J} c_j^f \sum_{t\in T} V_{jt} + \sum_{r\in R} c_r^f \sum_{t\in T} W_{rt} + \sum_{p\in P} c_p^f \sum_{t\in T} Y_{pt} + \sum_{f\in F} c_f^f \sum_{t\in T} X_{ft} + \sum_{d\in D} c_d^f \sum_{t\in T} Z_{dt} \tag{13}$$

$$\begin{aligned} TPC = {} & \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} C_{irt}^{sc} FJ_{ijrt} + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} C_{irt}^{di} r_t^{di} FJ_{ijrt} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} C_{irt}^{dm} r_t^{di} r_t^{dm} FJ_{ijrt} + \sum_{t\in T}\sum_{i\in I}\sum_{f\in F}\sum_{r\in R} C_{ift}^{rr} FR_{irft} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{p\in P}\sum_{d\in D} C_{ipt}^{pr} FP_{ipdt} + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} C_{irt}^{dp} w^{dm} r_t^{di} FJ_{ijrt} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} C_{irt}^{dp} w^{di} r_t^{dm} r_t^{di} FJ_{ijrt} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{f\in F}\sum_{r\in R} C_{ift}^{df} w^{rr} FR_{irft} \end{aligned} \tag{14}$$

$$TPUC = \sum_{n\in N}\sum_{p\in P}\sum_{t\in T} p_n^0 F''S_{npt} + \sum_{t\in T}\sum_{i\in I}\sum_{c\in C}\sum_{j\in J} p_i^e FC_{icjt} \tag{15}$$

$$\begin{aligned} TTC = {} & \sum_{t\in T}\sum_{i\in I}\sum_{j\in J}\sum_{c\in C} C_i^t d_{cj} FC_{icjt} + \sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J} C_i^t d_{jr} FJ_{ijrt} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{f\in F}\sum_{r\in R} C_i^t d_{rf} FR_{irft} + \sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{f\in F} C_i^t d_{fd} FF_{ifdt} \\ & + \sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{p\in P} C_i^t d_{pd} FP_{ipdt} \\ & + \sum_{t\in T}\sum_{n\in N}\sum_{p\in P}\sum_{r\in R} C_n^t d_{rp} F''R_{nrpt} \sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{c\in C} C_i^t d_{dc} (FD_{idct} + F'D_{idct}) \end{aligned} \tag{16}$$

$$THC = \sum_{t\in T}\sum_{i\in I}\sum_{d\in D} C_{idt}^h \left(\sum_{f\in F} FF_{ifdt} + \sum_{p\in P} FP_{ipdt} - \sum_{c\in C} FD_{idct} - \sum_{c\in C} F'D_{idct} \right) \tag{17}$$

$$TPEC = \sum_{t\in T}\sum_{i\in I}\sum_{c\in C} C_i^p \left(D_{ict}^n - \sum_{d\in D} FD_{idct} + D_{ict}^r - \sum_{d\in D} F'D_{idct} \right) \tag{18}$$

Eq. (11) stands for the total revenues resulting from the sales of new and recycled products to the customers, as well as the raw material resulting from decomposing the used products to external suppliers. Eqs. (12)–(18) are the existing costs in the systems which will be explained later on. Eq. (12) demonstrates the first-time setup costs of the centers. Eq. (13) shows the fixed costs of

Table 4
Model parameters (Özkır & Başlıgil, 2013).

Parameter	Rate or uniform distribution	Description
Θ	12	Maximum number of periods
w_{dm}	0.35	Waste production rate in decomposing
w_{di}	0.20	Waste production rate in demounting
w_{rr}	0.15	Waste production in refurbishing
c_t^i	[7 8]	Transportation cost of product i per unit of distance
c_n^t	[2 3]	Transportation cost of component n per unit of distance
d_{cj}	–	Distance between customer c and collecting center c
d_{jr}	–	Distance between collecting center j and returning center r
d_{rf}	–	Distance between returning center r and recycling center f
d_{rp}	–	Distance between returning center r to factory p
d_{pd}	–	Distance between factory p and distribution center d
d_{fd}	–	Distance between recycling center f and distribution center d
d_{dc}	–	Distance between distribution d and customer c
c_{irt}^{sc}	[1 3]	Cost of separating and compiling
c_{irt}^{di}	[2 4]	Cost of demounting
c_{irt}^{dm}	[3 4]	Cost of decomposing
c_{ift}^{rr}	[10 15]	Cost of refurbishing
c_{irt}^{dp}	[3 5]	Cost of disposing of waste in returning center r
c_{ift}^{df}	[2 4]	Cost of disposing of waste in recycling center f
c_{ipt}^{pr}	[20 26]	Cost of producing each unit of product i in factory p in period t
c_{idt}^{h}	[14 30]	Cost of handling product i in distribution center d in period t
v_i	[3 12]	Volume of product i
b_j	[40,000 60,000]	Maximum capacity of collecting center j
b_r	[800,000 960,000]	Maximum capacity of returning center r
b_d	[700,000 900,000]	Maximum capacity of distribution center d
b_p	[400,000 600,000]	Maximum capacity of factory p
b_f	[100,000 200,000]	Maximum capacity of recycling center f
c_j^s	[800,000 1,000,000]	Cost of establishing collecting center j
c_r^s	[2,000,000 5,000,000]	Cost of establishing returning center r
c_d^s	[3,000,000 5,000,000]	Cost of establishing distribution center d
c_p^s	[1,500,000 3,000,000]	Cost of establishing factory p
c_f^s	[2,000,000 2,700,000]	Cost of establishing recycling center f
c_j^f	[20,000 40,000]	Fixed cost of opened collecting center j in each period
c_r^f	[20,000 50,000]	Fixed cost of opened returning center r in each period
c_d^f	[4000 75,000]	Fixed cost of opened distribution center d in each period
c_p^f	[12,000 20,000]	Fixed cost of opened factory p in each period
c_f^f	[30,000 54,000]	Fixed cost of opened recycling center f in each period
c_i^p	[60 70]	Penalty for failing to meet each unit of product i
r_t^{di}	[0.5 0.7]	Percentage of used products suitable for demounting
r_t^{dm}	[0.2 0.4]	Percentage of used product suitable for decomposing
r_t^{rr}	$1 - r_t^{di}$	Percentage of used products suitable for recycling
p_n^o	[50 70]	Unit price of buying components from external suppliers
p_i^e	$0.07 * p_i^n$	Buying price of used products
p_m^m	[100 200]	Selling price of material m
p_i^n	[850 1300]	Selling price of new product i
p_i^r	p_n^i	Selling price of recycled product i
q_{in}^c	1	Number of component n used in product i
q_{nm}^m	[0.8 1]	Amount of material m used in component n
D_{ict}^n	[10,000 12,000]	Customer demand c for new product i in period t
D_{ict}^r	[300 600]	Customer demand c for recycled product i in period t
$\boldsymbol{\eta}$	0	Allowed demand variation limit
E_i^t	[0.2 0.3]	CO_2 emission in moving one unit of product i in one unit of distance
E_n^t	[0.1 0.2]	CO_2 emission in moving one unit of component n in one unit of distance
l_{rt}^{max}	$[0.5 * C * I\ 0.66 * C * I]$	Maximum average of missed working days due to occupational accidents per each worker in case of opening returning centers in period t
l_{ft}^{max}	$[0.5 * C * I\ 0.66 * C * I]$	Maximum average of missed working days due to occupational accidents per each worker in case of opening recycling centers in period t
l_{pt}^{max}	$[0.5 * C * I\ 0.66 * C * I]$	Maximum average of missed working days due to occupational accidents per each worker in case of opening factories in period t
E_i^{max}	[6 6.8]	Maximum allowed CO_2 emission per unit of new or recycled product i
l_{rt}	[0 2]	Number of missed days due to occupational accidents in case of opening returning center r in period t
l_{ft}	[0 2]	Number of missed days due to occupational accidents in case of opening recycling center f in period t
l_{pt}	[0 1]	Number of missed days due to occupational accidents in case of opening factory p in period t

each of the established centers in each period. Eq. (14) represents the costs of the all of the processes in the chain, including the costs of separating and compiling, demounting, decomposing, recycling products, disposing of waste, and finally producing each product in the factory. The costs associated with purchasing the components of the products as well as purchasing the returned used products are formulated in Eq. (15). The costs of transmitting are shown in Eq. (16). Eq. (17) demonstrates the costs related to products in distribution centers, and Eq. (18) shows the penalty costs of failing to meet customer demand.

3.2.2. Objective function 2: Minimizing the number of missed working days due to occupational accidents

By maximizing the fuzzy membership according to Eq. (19), the number of missed working days as a result of occupational accidents can be minimized.

$$Max: \; TR = \sum_{r\in R}\mu_{rt}^{l} + \sum_{f\in F}\mu_{ft}^{l} + \sum_{p\in P}\mu_{pt}^{l} \tag{19}$$

3.2.3. Objective function 3: Maximizing satisfying customer demand

According to the defined fuzzy membership functions related to meeting the customer demand, the maximum in meeting customer demand can be achieved by maximizing the membership degree in Eqs. (1)–(6). Membership degree of *one* means meeting all customer demand.

$$\mathrm{MAX}: \; \mathrm{TS} = \sum_{t\in T}\sum_{c\in C}\sum_{i\in I}\mu_{ict}^{\mathrm{nd}} + \sum_{t\in T}\sum_{i\in I}\sum_{c\in C}\mu_{ict}^{\mathrm{rd}} \tag{20}$$

Furthermore, (21)–(54) are the constraints of this problem and are categorized into six groups. These groups include set-up, capacity, balance, environmental, sustainability, binary, and non-negativity constraints.

Opening constraints:

$$\sum_{t\in T}V_{jt} \leqslant \Theta \quad \forall j\in J \tag{21}$$

$$\sum_{t\in T}W_{rt} \leqslant \Theta \quad \forall r\in R \tag{22}$$

$$\sum_{t\in T}Y_{pt} \leqslant \Theta \quad \forall p\in P \tag{23}$$

$$\sum_{t\in T}Z_{dt} \leqslant \Theta \quad \forall d\in D \tag{24}$$

$$\sum_{t\in T}X_{ft} \leqslant \Theta \quad \forall f\in F \tag{25}$$

$$\sum_{j\in J}V_{jt} \geqslant 1 \quad \forall t\in T \tag{26}$$

$$\sum_{r\in R}W_{rt} \geqslant 1 \quad \forall t\in T \tag{27}$$

$$\sum_{p\in P}Y_{pt} \geqslant 1 \quad \forall t\in T \tag{28}$$

$$\sum_{d\in D}Z_{dt} \geqslant 1 \quad \forall t\in T \tag{29}$$

$$\sum_{f\in F}X_{ft} \geqslant 1 \quad \forall t\in T \tag{30}$$

$$V_{j(t+1)} - V_{jt} \geqslant 0 \quad \forall t\in T \text{ and } \forall j\in J \tag{31}$$

$$W_{r(t+1)} - W_{rt} \geqslant 0 \quad \forall t\in T \text{ and } \forall r\in R \tag{32}$$

$$Y_{p(t+1)} - Y_{pt} \geqslant 0 \quad \forall t\in T \text{ and } \forall p\in P \tag{33}$$

$$X_{f(t+1)} - X_{ft} \geqslant 0 \quad \forall t\in T \text{ and } \forall f\in F \tag{34}$$

$$Z_{d(t+1)} - Z_{dt} \geqslant 0 \quad \forall t\in T \text{ and } \forall d\in D \tag{35}$$

Capacity constraints:

$$\sum_{i\in I}\sum_{c\in C}FC_{icjt}\,v_i \leqslant b_j V_{jt} \quad \forall j\in J \text{ and } \forall t\in T \tag{36}$$

$$\sum_{i\in I}\sum_{j\in J}FJ_{ijrt}\,v_i \leqslant b_r W_{rt} \quad \forall r\in R \text{ and } \forall t\in T \tag{37}$$

$$\sum_{i\in I}\sum_{d\in D}FP_{ipdt}\,v_i \leqslant b_p Y_{pt} \quad \forall p\in P \text{ and } \forall t\in T \tag{38}$$

$$\sum_{i\in I}\sum_{r\in R}FR_{irft}\,v_i \leqslant b_f X_{ft} \quad \forall f\in F \text{ and } \forall t\in T \tag{39}$$

$$\sum_{i\in I}\left[\sum_{f\in F}FF_{ifdt} + \sum_{p\in P}FP_{ipdt}\right]v_i \leqslant b_d Z_{dt} \quad \forall d\in D \text{ and } \forall t\in T \tag{40}$$

Balanced constraints:

$$\sum_{c\in C}FC_{icjt} \geqslant \sum_{r\in R}FJ_{ijrt} \quad \forall i\in I,\ \forall j\in J \text{ and } \forall t\in T \tag{41}$$

$$\sum_{f\in F}FR_{irft} \leqslant r_t^{rr}\sum_{j\in J}FJ_{ijrt} \quad \forall i\in I,\ \forall r\in R \text{ and } \forall t\in T \tag{42}$$

$$\sum_{p\in P}F''R_{nrpt} \leqslant r_t^{di}\sum_{j\in J}\sum_{i\in I}FJ_{ijrt}q_{in}^{c} \quad \forall n\in N,\ \forall r\in R \text{ and } \forall t\in T \tag{43}$$

$$\sum_{r\in R}F''R_{nrpt} + X_{npt} = \sum_{i\in I}\sum_{d\in D}FP_{ipdt}q_{in}^{c} \quad \forall n\in N,\ \forall p\in P \text{ and } \forall t\in T \tag{44}$$

$$\sum_{f\in F}FF_{ifdt} \geqslant \sum_{c\in C}F'D_{idct} \quad \forall i\in I,\ \forall d\in D \text{ and } \forall t\in T \tag{45}$$

$$\sum_{p\in P}FP_{ipdt} \geqslant \sum_{c\in C}FD_{idct} \quad \forall i\in I,\ \forall d\in D \text{ and } \forall t\in T \tag{46}$$

$$\sum_{r\in R}FR_{irft} \geqslant \sum_{d\in D}FF_{ifdt} \quad \forall i\in I,\ \forall f\in F \text{ and } \forall t\in T \tag{47}$$

$$X_{mrt} = r_t^{dm}r_t^{di}\sum_{j\in J}\sum_{i\in I}FJ_{ijrt}\sum_{n\in N}q_{in}^{c}q_{nm}^{m} \quad \forall m\in M,\ \forall r\in R \text{ and } \forall t \in T \tag{48}$$

$$1 - \frac{D_{ict}^{r} - \sum_{d\in D}F'D_{idct}}{(1-\eta)D_{ict}^{r}} \geqslant \mu_{ict}^{rd} \quad \forall i\in I,\ \forall c\in C \text{ and } \forall t\in T \tag{49}$$

$$1 - \frac{\sum_{d\in D}F'D_{idct} - D_{ict}^{r}}{(1-\eta)D_{ict}^{r}} \geqslant \mu_{ict}^{rd} \quad \forall i\in I,\ \forall c\in C \text{ and } \forall t\in T \tag{50}$$

$$\sum_{d\in D}F'D_{idct} \leqslant D_{ict}^{r} \quad \forall i\in I,\ \forall c\in C \text{ and } \forall t\in T \tag{51}$$

$$1 - \frac{D_{ict}^{n} - \sum_{d\in D}FD_{idct}}{(1-\eta)D_{ict}^{n}} \geqslant \mu_{ict}^{nd} \quad \forall i\in I,\ \forall c\in C \text{ and } \forall t\in T \tag{52}$$

$$1 - \frac{\sum_{d\in D}FD_{idct} - D_{ict}^{n}}{(1-\eta)D_{ict}^{n}} \geqslant \mu_{ict}^{nd} \quad \forall i\in I,\ \forall c\in C \text{ and } \forall t\in T \tag{53}$$

$$\sum_{d\in D}FD_{idct} \leqslant D_{ict}^{n} \quad \forall i\in I,\ \forall c\in C \text{ and } \forall t\in T \tag{54}$$

Environmental constraints:

$$\begin{aligned}
&\sum_{t\in T}\sum_{i\in I}\sum_{j\in J}\sum_{c\in C}E_{\mathrm{i}}^{\mathrm{t}}d_{cj}FC_{icjt}+\sum_{t\in T}\sum_{i\in I}\sum_{r\in R}\sum_{j\in J}E_{\mathrm{i}}^{\mathrm{t}}d_{jr}FJ_{ijrt}\\
&\quad+\sum_{t\in T}\sum_{i\in I}\sum_{f\in F}\sum_{r\in R}E_{\mathrm{i}}^{\mathrm{t}}d_{rf}FR_{irft}+\sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{f\in F}E_{\mathrm{i}}^{\mathrm{t}}d_{fd}FF_{ifdt}\\
&\quad+\sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{p\in P}E_{\mathrm{i}}^{\mathrm{t}}d_{pd}FP_{ipdt}+\sum_{t\in T}\sum_{n\in N}\sum_{p\in P}\sum_{r\in R}E_{\mathrm{n}}^{\mathrm{t}}d_{rp}F''R_{nrpt}\\
&\quad+\sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{c\in C}E_{\mathrm{i}}^{t}d_{dc}(FD_{idct}+F'D_{idct})\\
&\quad\leqslant\sum_{t\in T}\sum_{i\in I}\sum_{d\in D}\sum_{c\in C}E_{\mathrm{i}}^{max}d_{dc}(FD_{idct}+F'D_{idct})
\end{aligned}\tag{55}$$

Sustainability constraints:

$$\frac{l_{rt}^{max}-\sum_{r\in R}l_{rt}W_{rt}}{l_{rt}^{max}}\geqslant\mu_{rt}^{l}\quad\forall t\in T\tag{56}$$

$$\frac{l_{ft}^{max}-\sum_{f\in F}l_{ft}X_{ft}}{l_{ft}^{max}}\geqslant\mu_{ft}^{l}\quad\forall t\in T\tag{57}$$

$$\frac{l_{pt}^{max}-\sum_{p\in P}l_{pt}Y_{pt}}{l_{pt}^{max}}\geqslant\mu_{pt}^{l}\quad\forall t\in T\tag{58}$$

Binary and non-negativity constraints:

$$\forall j\in J,\ \forall r\in R,\ \forall f\in F,\ \forall p\in P,\ \forall d\in D,\ \forall c\in C,\ \forall i\in I,\ \forall t\in T\tag{59}$$

$$V_{jt,}W_{rt,}X_{ft,}Y_{pt,}Z_{dt}\in\{0,1\}\tag{60}$$

$$\begin{aligned}
&FC_{icjt},FJ_{ijrt},FR_{irft},F''R_{nrpt},FF_{ifdt},FP_{ipdt},F'D_{idct},FD_{idct},F'''R_{mrt},F''S_{npt},\\
&\quad\mu_{rt}^{l},\mu_{ft}^{l},\mu_{pt}^{l},\mu_{ict}^{rd},\mu_{ict}^{rd}\geqslant 0
\end{aligned}\tag{61}$$

Eqs. (21)–(25) limit the maximum periods of activity in the centers. Eqs. (26)–(30) guarantee that at least one of each center is open in each period, and in Eqs. (31)–(35) it is guaranteed that if a center starts its activities, it will remain so in the following periods. In Eqs. (36)–(40), the limitations of each of the centers are described. The balanced limitations are formulated in Eqs. (41)–(48), and the fuzzy limitations related to satisfying customer demand are shown in Eqs. (49)–(54). The limitation concerned with CO_2 emissions is captured in Eq. (55). Eqs. (56)–(58) are the fuzzy limitations related to the missed work days due to occupational accidents. In Eqs. (59)–(61) the binary and non-negativity limitations are shown.

4. Problem solution

In solving the problem, several approaches are taken including precise and heuristics. In solving some instances of a problem and depending on the complexity of the problem, solution is not possible using precise approaches. Also, these approaches are not parsimonious due to their time consumption. Cases in which the solution cannot be achieved via conventional approaches are referred to as NP problems. NP stands for Non Deterministic Problem, meaning that it is possible to guess the solution and validate it. These problems include NP-Complete and NP-Hard problems. In the former, the answers could be yes or no; however, the latter are not limited as in NP-Complete problems.

In solving these problems, some algorithms are used, which can provide acceptable results by validating and improving an array of results. These algorithms are referred to as meta-heuristics algorithms including genetic algorithm. Since the problem of a closed loop supply chain is a NP-Hard problem (Özkır & Başlıgil, 2013), a meta-heuristic approach is used to solve this problem. For instance, if we address this problem with six centers of each type in two periods, three customers, and two products, it will end up with 1587 variables, of which 90 are binary with 612 limitations. The suggested meta-heuristic algorithm is a genetic algorithm. When researchers deal with problems in wide dimensions, generally meta-heuristic approaches, especially genetic algorithms, are proven to be very suitable choices (Soleimani et al., 2013).

4.1. Problem solution approach

Before presenting the algorithm, multi-objective decision making approaches will be used here to convert this multi-objective problem to a mono-objective problem. The E-Constraint approach uses the basic information of a decision maker to convert some of the problem objectives to limitations in order to solve the resulting single objective model. In this approach, the most important objective of the problem remains as an *objective* and the maximums and minimums of the remaining objectives are considered in the *limitations*.

Here, to convert this problem based on the mentioned approach, the objective of maximizing the chain profit remains as the problem *objective*. Also, by defining limits for the objectives of minimizing the missed working days due to occupational accidents and maximizing meeting customer demand, these objectives are added to the *limitations* of the problem.

4.2. The suggested genetic algorithm

Genetic algorithm is a type of evolution algorithms which is inspired by biology where it is applied in heredity, mutation, natural selection, and admixture. The basic idea of this algorithm is to transfer the heredity characteristics by the genes. Supposing that the total characteristics of each generation are transferred to the next generation via its chromosomes, each gene in this chromosome represents a characteristic.

To design this algorithm, the solutions of the problem, or chromosomes should be coded, according to the principles of the genetics science, so as for them to be prepared for mutation. Then, the parameters of the genetic algorithm – including populations and generations, mutation operators, choice strategy and stopping criteria – should be described. Practically, the objective of the algorithm is to reach the best chromosomes using the meiosis of the chosen chromosomes in each generation. Therefore, to evaluate the chromosomes, here, a function to identify the fitness of these chromosomes in each iteration of the algorithm is defined. After the first generation and evaluating their fitness, according to the algorithm parameters and the choice strategy, some members are chosen for producing the new generation and the defined operators are applied on them. These operators include crossover and mutation operators. The new generation is reevaluated and the best among them are kept for producing the next generation. This is continued to reach the stopping criterion.

4.2.1. Adjusting the algorithm parameters

One of the important stages in designing a meta-heuristic algorithm is to adjust the parameters that can affect the effectiveness of the algorithm. Genetic algorithm includes several parameters including iteration, population size, crossover rate. When these parameters change, they can lead to different results (Soleimani et al., 2013). Similar to the other meta-heuristic algorithms genetic algorithm does not have a specific criterion for adjusting the parameter (Soleimani et al., 2013). In this research the parameters of the algorithm including the crossover parameter (pc), mutation parameter (pm), population size (npop) are adjusted using the Taguchi method (Mousavi & Niaki, 2013), and regarding the iterations, two levels are considered. First, the small size instances with

200 iterations are studied, and after verification on the accuracy of the algorithm and comparing the results with those from the LINGO software, it is used for large size instances with 400 iterations.

The considered levels for the algorithm parameters are described in Table 5.

For adjusting the parameters, the L9(3∗∗3) design in the MINITAB software package is used. The resulting required data are presented in Table 6. Using the Related Percentage Deviation (RPD) method, and using formula (62), we can normalize the resulting data.

$$RPD = |Every\ Experiment\ Sol - Best\ Sol| * 100/|Best\ Sol| \tag{62}$$

After executing the Taguchi method, the corresponding SNR and Mean graphs could be depicted as in Figs. 3 and 4.

According to the SNR graph resulting from the experiments, the maximum signal to noise ration have occurred for the "npop" parameter in level 2, for the pc parameter in level three and for the pm parameter in level three. Also, in the Mean graph, the minimum Mean has occurred in levels, which have the highest SNR. According to the results of the experiment, the algorithm parameters can be adjusted as described in Table 7.

Table 5
The levels for each of the parameters.

Level		Factor		
		npop	pc	pm
Low	1	100	0.5	0.1
Medium	2	150	0.7	0.2
High	3	200	0.8	0.3

Table 6
Normalized results from the Taguchi experiments.

Run	Objective function	RPD
1	126154448.7	1.480525
2	125869972.9	1.702684
3	127,739,223	0.242906
4	128050264.5	0
5	127792674.4	0.201163
6	127,812,607	0.185597
7	127,293,300	0.591146
8	127525388.1	0.409899
9	127512570.9	0.419908

4.2.2. Creating the primary chromosomes

4.2.2.1. Opening chromosome for each of the entities in the chain (Zxx)

This chromosome has a matrix structure and represents the opening or non-opening of an entity in the chain (for instance, if the factories, distribution centers, etc. in the chain can be opened or stay closed in each period). Opening each of these centers in every period is shown as zero or one. The matrix rows and columns represent the entity number and the periods, accordingly. To create the primary chromosomes for this matrix, the matrix is randomly filled with zero and one.

4.2.2.2. Product flow chromosome (Xxxxx)

Eight chromosomes are formed with four dimension structures to code the product flow between the different centers. In this structure, each of the entities show the amount of shipped products between the entities. For instance, entity (3,5,2,8) in the new product chromosome *i*, shipped from distribution center *d* to customer *c* in period *t*, represents an amount of product three that is shipped from distribution center number five to customer number two in period eight.

For producing the primary chromosomes, this four-dimensional structure is filled with random zeroes and ones.

4.2.3. Evaluating chromosome fit

For evaluating the chromosome fit, first the resulting random numbers should be converted to usable values in the algorithm. For this purpose, the random numbers are converted to product flow in such a way that they would represent how customer demand is met in each period for any new or recycled product. After producing these data, evaluating their fit could be done using the cost function.

4.2.4. Selection strategy, crossover and mutation

Selection in genetic algorithm means to decide how parents in each generation are selected for reproducing the next generation population. The aim with selection is in fact to underline selecting the merits in the population so that the resulting children would be better fit than the previous generation. Various selection

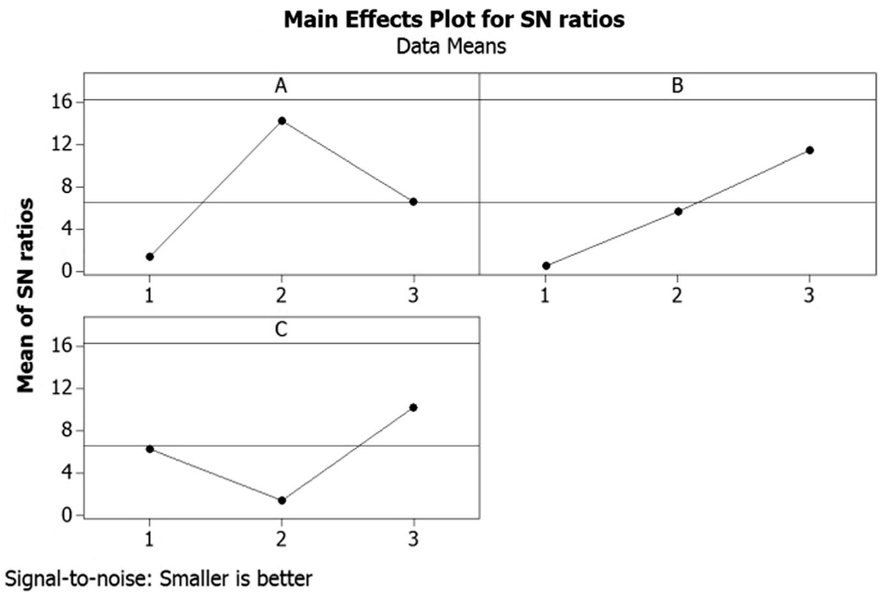

Fig. 3. SNR graph from the Taguchi experiments.

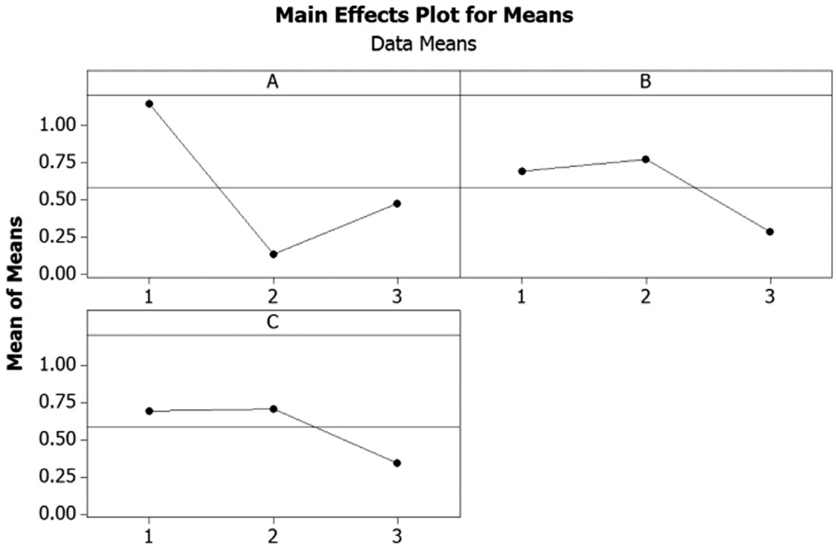

Fig. 4. Mean graph from Taguchi experiments.

Table 7
The adjusted algorithm parameters.

Factor		
npop	pc	pm
150	0.8	0.3

approaches have been discussed in the literature. In the proposed genetic algorithm, the roulette wheel has been used to select the parents for crossover, and also random selection has been used for mutation.

Random crossover or mutation is done on a subset of the chromosomes. Crossover is carried out with combining the parents' genes such that each child would have parts of the characteristics of each of its parents. In mutation on the product flow chromosomes, 10% of the minimum demand, and the maximum variable amount is added or subtracted from it using the normal function. For mutation on the opening chromosomes of the entities, after selecting some genes according to a defined rate – 0.2% in this research – if the nominal value if that gene is one, it will be changed to zero, and if the value is zero, it is converted to one. The stopping criterion in the suggested algorithm is reaching a specified iteration.

5. Calculation results

Table 4 illustrates the parameters of the studied instances, whether they have fixed rates or uniform distributions in the mentioned periods. The dimensions of the investigated instances are defined in Table 8. The dimensions of these instances were small to begin with so as to evaluate the effectiveness of the suggested algorithm. For this, the results have been compared with the

Table 8
Dimensions of the addressed instances in this research.

Problem No.	Number of variables	Number of plants (P)	Number of distribution centers (D)	Number of reverse centers (R)	Number of collection points (J)	Number of facility recovery (F)	Number of customers (C)	Number of periods (T)	Number of products (I)	Number of components (N)	Number of materials (M)
1	94	2	2	2	2	2	2	1	2	2	2
2	156	3	3	3	3	3	2	1	2	2	2
3	176	2	2	2	2	2	2	2	2	2	2
4	256	4	4	4	4	4	2	1	2	2	2
5	318	3	3	3	3	3	2	2	2	2	2
6	500	4	4	4	4	4	2	2	2	2	2
7	966	5	5	4	4	4	3	3	2	2	2
8	1578	6	6	6	6	6	3	3	2	2	2
9	2826	7	7	7	7	7	3	3	3	2	2
10	2940	4	4	4	4	4	2	12	3	2	2
11	8356	12	12	12	12	12	3	3	3	2	2
12	11,361	13	13	13	13	13	4	3	3	2	2
13	18,269	14	14	14	14	14	4	4	4	3	4
14	25,033	15	15	15	15	15	4	4	5	3	4
15	40,781	16	16	16	16	16	4	7	4	3	4
16	53,248	15	15	15	15	15	5	7	6	3	4
17	58,720	16	16	16	16	16	4	10	4	3	4
18	65,620	17	17	17	17	17	4	10	4	3	4
19	78,744	17	17	17	17	17	4	12	4	3	4
20	87,480	18	18	18	18	18	4	12	4	3	4
21	96,672	19	19	19	19	19	4	12	4	3	4
22	106,320	20	20	20	20	20	4	12	4	3	4

Table 9
The comparison of results in running the model with LINGO and genetic algorithm.

Problem No.	Differences to optimum (%)	Numerical results of solving the problems using GA		Numerical results of solving the problems using LINGO			
		Best objective	Elapsed time	Objective bound	Best objective	LINGO global optimum	Elapsed time
1	0.04	15,330,284	34	–	–	15,336,400	<1
2	0.04	16,858,352	40	–	–	16,864,470	1
3	0.03	38,822,749	46	–	–	38,833,880	1
4	0.04	17,044,392	47	–	–	17,050,510	1
5	0.29	41,585,058	60	–	–	41,707,920	1
6	0.27	43,196,166	81	–	–	43,312,990	5
7	1.26	126,857,642	113	–	–	128,470,500	4
8	2.05	170,737,993	151	–	–	174,306,600	43
9	9.03	240,414,212	194	–	–	264,290,100	181
10	1.23	397,553,322	304	–	–	402,496,200	41
11	20.89	196,815,209	787	–	–	248,791,600	4092
12	9.64	431,329,267	1073	483,040,000	477,321,000	–	33,767<
13	21.69	466,730,630	1546	607,176,000	596,040,000	–	32,959<
14	26.42	628,188,558	1932	883,980,000	853,732,000	–	29,828<
15	–	776,755,551	3203	1143170000	–	–	31,783<
16	–	1562757692	3846	2912970000	–	–	28,047<
17	–	1133562142	4293	–	–	–	–
18	–	1166980464	4815	–	–	–	–
19	–	1302170654	5761	–	–	–	–
20	–	1568547760	6130	–	–	–	–
21	–	1189351038	6700	–	–	–	–
22	–	1270540710	7459	–	–	–	–

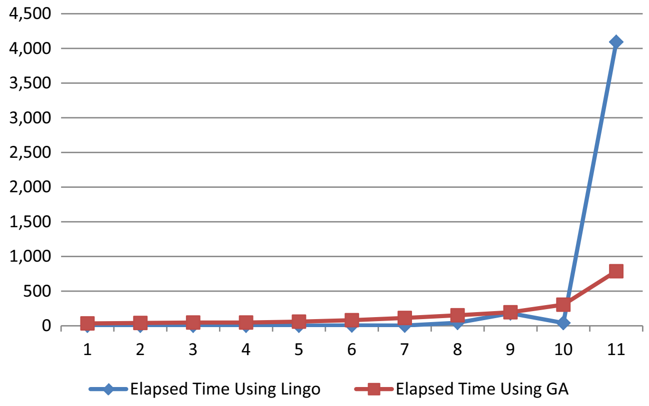

Fig. 5. Comparing the results from LINGO and genetic algorithm.

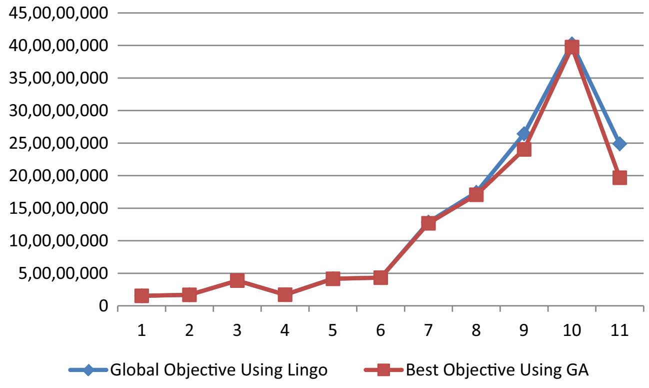

Fig. 6. Comparing the solution time in LINGO and genetic algorithm.

results from solving the model using the LINGO software package, and the error is determined. Then, larger instances are addressed using this algorithm. The results of running the algorithm for solving the instances with different dimensions are shown in Table 9.

The deviation in Table 9 could be calculated by dividing the difference of the results from LINGO and genetic algorithm to the results from LINGO, and is reported in percentage.

According to Table 9, in evaluating the first eleven instances, the precise solution was achieved by LINGO. The precise solution from LINGO and the results from the algorithm are compared in Fig. 5. The results show that the solutions from the proposed algorithm are to a great extent close to the precise solution to the problem. Therefore, this algorithm is capable of providing solutions that are very approximate to the precise solution.

In evaluating the eleventh instance by this software, the time required to provide a solution was increased drastically, surpassing that of the genetic algorithm. In evaluating the eleventh instance and onwards, the stopping criterion in the genetic algorithm was changed from 200 iterations to 400. Meanwhile, the time required by the algorithm to provide a solution was much better and more logical than that by LINGO. The results of this comparison are shown in Fig. 6. In instances 12–16, no precise solution was provided by LINGO is more than 28,000 s. However, the proposed genetic algorithm provided acceptable solutions for these instances in less than one hour. These results are illustrated in Table 9. Instances 17–22 have larger dimensions and their solutions are depicted in Table 9.

According to the investigations, the proposed genetic algorithm is effective for addressing the described model in large dimensions, and provides acceptable results. Also, the time required by the algorithm to solve the model described in this research is acceptable.

6. Conclusions

In this article, closed loop supply chain was studied as an ever-important problem in the contemporary world. Based on the existing research gaps in the literature, a closed loop supply chain with multiple levels, multiple products, and multiple periods, determining all the components and raw materials of the products, was investigated. The modelling was carried out by emphasizing high profitability and customer satisfaction via meeting their demand, and meanwhile adhering to environmental and societal responsibilities. To investigate the different instances in this regard, a genetic algorithm was proposed. For proving the power of this algorithm, the proposed model was coded in the LINGO 8 software package, and the results of running the algorithm in lower dimensions were compared with the results of solving the model with LINGO. According to the results, the proposed algorithm is capable of providing a solution with great approximation in appropriate time. Later, six random scenarios with large dimensions were investigated with the model and the results were presented.

As for future research, we suggest applying this algorithm in real world instances. Incorporating other environmental and sustainable considerations could also be practical and important issues for further research. These considerations could first of all relate to the most significant concerns of contemporary societies, including lack of potable water, and global warming. Using multi-objective genetic algorithm, and comparing this algorithm with other meta-heuristic algorithms could also be prominent areas for future research.

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