TECHNOLOGICAL AND ECONOMIC DEVELOPMENT OF ECONOMY
ISSN 2029-4913 / eISSN 2029-4921

2017 Volume 23(3): 520–548
doi:10.3846/20294913.2017.1312630

DESIGNING A MULTI-PRODUCT MULTI-PERIOD SUPPLY CHAIN NETWORK WITH REVERSE LOGISTICS AND MULTIPLE OBJECTIVES UNDER UNCERTAINTY

Mehdi KESHAVARZ GHORABAEE, Maghsoud AMIRI,
Laya OLFAT, S. M. Ali KHATAMI FIROUZABADI

Department of Industrial Management, Faculty of Management and Accounting, Allameh Tabataba'i University, Tehran, Iran

Received 19 January 2017; accepted 24 March 2017

Abstract. Integration of reverse logistics processes into supply chain network design can help to achieve a network that incorporates environmental factors as well as economic factors. In this study, a new integrated approach is proposed to address designing a multi-product, multi-period supply chain network with reverse logistics. The framework of the proposed approach includes green supplier evaluation and a mathematical model in an uncertain environment. To the best of our knowledge, integration of green supplier evaluation into the designing supply chain network with reverse logistics has not been considered in the literature. This integration can help to incorporate experts' opinions about environmental impact of suppliers in the network design. Minimization of total cost and maximization of total greenness score of purchased raw materials/components are two objectives of the model. The fuzzy EDAS method is used to determine the greenness scores of suppliers. Also, demand of customers and capacity of suppliers are defined using fuzzy numbers and a fuzzy method is used to obtain trade-off solutions. The proposed approach is applied to designing the supply chain network of a home appliance company. The results show that the proposed approach is feasible and efficient to obtain solutions to design the supply chain network.

Keywords: supply chain network design, reverse logistics, multi-objective decision-making (MODM), fuzzy EDAS, fuzzy MODM, closed-loop supply chain.

JEL Classification: C44, C61, D80, L60, Q21, Q50.

Online supplementary material: Supporting information for this paper is available as online supplementary material at https://doi.org/10.3846/20294913.2017.1312630

Corresponding author Maghsoud Amiri
E-mails: *amiri@atu.ac.ir*; *m.amiri.atu@gmail.com*

Copyright © 2017 Vilnius Gediminas Technical University (VGTU) Press
http://www.tandfonline.com/TTED

Introduction

In a supply chain, the product flow starts with suppliers and manufactures, and then final products are delivered by distributors to the customer groups to meet their demands (Hugos 2010). Because of increasing competition in global markets, designing an optimal supply chain network becomes one of the important strategic processes for any business (Moncayo–Martínez, Mastrocinque 2016). In the past, economic objectives like cost or benefit were the most prevalent measures to optimize a supply chain network design. However, in recent years, environmental requirements have affected manufacturing operations, and these requirements lead to an increasing attention to development of environmental management strategies for the supply chain (Beamon 1999).

One of the approaches that can help to improve the environmental aspects of a supply chain is recovery of used products using reverse logistics. Reverse logistics can increase the environmental performance of a supply chain by reducing waste and used energy and resources (Diabat *et al.* 2013). In general, there are two kinds of supply chains with reverse logistics: closed-loop supply chain and open-loop supply chain. In a closed-loop supply chain design, recovered products and/or materials are usually reused in the original supply chain, i.e. in the production process of the same supply chain. On the other hand, in an open-loop design returned products are recovered/recycled and reused in other production processes out of the original supply chain (Fleischmann *et al.* 1997; Geyer, Jackson 2004; Krikke *et al.* 2005). There are many studies that have been made on the supply chain network design with reverse logistics in both closed-loop and open-loop modes.

Jayaraman *et al.* (2003) used a mixed-integer linear programming (MILP) approach to model an open-loop supply chain and introduced a heuristic solution methodology for this problem. The network which was addressed by them was very simple. Only one objective was considered for optimization, and the solution methodology cannot be utilized in a situation with multiple products. Moreover, a single period was used as the planning horizon. However, this model can provide a basis for more extended models.

One of the studies which used multi-objective programming in designing open-loop supply chains was made by Pati *et al.* (2008). They proposed a multi-objective mathematical model to assist in proper management of the paper recycling logistics systems. They used a goal programming approach to solve the model. The supply chain network in their study was designed with multiple products. However, optimization of the model with a single period and using crisp values for all parameters of the model are two main disadvantages of their study. In another study, Yu and Solvang (2016) suggested a novel framework for designing and planning a general reverse logistics network based on the multi-objective mixed integer programming. Minimization of total cost and carbon emissions were the objectives of their model. They used a weighted normalization method and solved the multi-objective decision-making (MODM) model.

Some of studies on open-loop supply chain design have used metaheuristic algorithms. Pishvaee *et al.* (2010) developed a MILP model to minimize the transportation and fixed opening costs in a multistage reverse logistics network. The network examined was in the open-loop mode. They applied a simulated annealing (SA) algorithm with special neighborhood search mechanisms to determine near optimal solutions. Using metaheuristic algorithm is an advantage of their study because it can help to decrease computational time of solving the model. However, their model is a single-period and single-product model which is optimized with respect to one objective. Qin and Ji (2010) also proposed an approach to design the product recovery network in the open-loop mode. Their approach was based on the fuzzy programming tool. A hybrid intelligent algorithm which integrates fuzzy simulation and genetic algorithm was developed by them to solve the model. Consideration of uncertainty is an important feature of their study. The research of Eskandarpour *et al.* (2014) presented a model to design a comprehensive seven-layer (primary customers, collection/redistribution centers, recovery, recycling and disposal centers, and secondary customers) recovery network by MILP approach. They also developed a metaheuristic method based on Tabu search to determine optimal or near-optimal solutions in an open-loop network. Uncertainty of parameters, nevertheless, was not addressed in their model. Zandieh and Chensebli (2016) addressed an open-loop reverse logistics network including collection/inspection, recovery and disposal centers and used MILP approach to model it. A water flow-like algorithm approach was proposed to obtain solutions of the model and the results of the algorithm were compared with those of the genetic algorithm. Although the metaheuristic proposed was novel, multi-product and multi-period modes were not considered in their model, and only one objective was used to optimize the model.

Soleimani and Govindan (2014) and Alshamsi and Diabat (2015) studied on designing open-loop network design with consideration of multiple products. Soleimani and Govindan (2014) proposed a risk-averse two-stage stochastic programming approach for designing and planning a supply chain network with reverse logistics. Although their model was formulated in an uncertain environment, the horizon of planning was defined with respect to a single period. Alshamsi and Diabat (2015) proposed a mixed-integer linear programming model to address the complex network configuration of a supply chain with reverse logistics. Optimal selection of sites, the capacities of inspection centers and remanufacturing facilities were some of decision variables of their model. Their model was formulated in a multi-period mode, but uncertainty of parameters was not addressed in the model.

There are many studies which have been done in the field of closed-loop supply chain design. Some of these studies used single-product and single-period modes for network design. Mirakhorli (2014) proposed a fuzzy programming approach and a metaheuristic based on the genetic algorithm to deal with bi-objective reverse logistics network design problems. A case study in a bread producing factory was used to show the feasibility of the proposed approach. Garg *et al.* (2015) considered a closed-loop supply chain network with four echelons in the forward chain and five echelons in the backward chain. The network was formulated using a bi-objective integer nonlinear programming approach and solved by an interactive multi-objective decision-making algorithm, but the uncertainty of parameters was not addressed in the model. Mohajeri and Fallah (2016) presented an optimization model for a closed-loop supply chain network. In the considered model, carbon emission limit was regarded as an environmental constraint. Their model was developed in an uncertain environment based on fuzzy sets.

Some other researches considered multi-product mode for designing networks. Güleş *et al.* (2013) proposed a MILP model for designing network of a multi-phase flexible closed-loop supply chain with environmental considerations. However, uncertainty of parameters was not involved in the design. Jindal and Sangwan (2014) applied a fuzzy mixed integer linear programming approach to optimize a multi-product, multi-facility capacitated closed-loop supply chain with some uncertain parameters like demand of products. Vahdani and Mohammadi (2015) proposed a bi-objective interval-stochastic robust model for optimization of designing a closed-loop supply chain network with multi-priority queuing system. Moreover, a self-adaptive imperialist competitive meta-heuristic algorithm was proposed to solve the model. Subulan *et al.* (2015) considered a lead/acid battery closed-loop supply chain network design under risk and uncertainty and proposed a scenario-based multi-objective stochastic and possibilistic mixed integer programming model to optimize it. Moghaddam (2015) developed a model for supplier selection and order allocation in a closed-loop supply chain network. Multi-objective decision-making approaches and Monte Carlo simulation were used to obtain Pareto-optimal solutions of the model. Talaei *et al.* (2016) proposed a multi-objective MILP model to investigate a facility location/allocation problem in a multi-product closed-loop green supply chain network and minimization of the total cost of the network. The ε-constraint was utilized for optimization of the model. Dai (2016) developed a model for a multi-product, multi-echelon, and multi-objective closed-loop supply chain network in a fuzzy environment. A fuzzy MODM approach was utilized to solve the model by minimization of total cost, waste, carbon dioxide, and risks of the network. Ma *et al.* (2016) proposed a robust multi-objective mixed integer nonlinear programming model to deal with an environmental closed-loop supply chain network problem. They used the LP-metrics method to find optimum solutions of the problem.

In addition, there are some studies which focused on designing closed-loop supply chain networks with multiple products and multiple periods. Pazhani *et al.* (2013) developed a bi-objective model for a multi-period, multi-product closed-loop supply chain. Minimization of total costs and maximization of service efficiency of the warehouses and hybrid facilities were two objectives of the model, and the goal programming approach was used to obtain solution of the model. Ramezani *et al.* (2014) presented a multi-objective model for a multi-product, multi-period, closed-loop supply chain network. A fuzzy programming approach was used for maximization of profit, minimization of delivery time, and maximization of quality. Zeballos *et al.* (2014) proposed a design and planning approach to address a general closed-loop supply chain with multiple periods and products. The multi-stage stochastic programming and MILP approaches were used to determine optimum design. Tavakkoli-Moghaddam *et al.* (2015) presented a bi-objective model for designing a network of bi-directional facilities in a closed-loop supply chain under uncertainties. A hybrid solution approach based on the fuzzy possibilistic programming and fuzzy multi-objective programming was also developed by them to solve the model. Kalaitzidou *et al.* (2015) addressed a multi-product, multi-echelon and multi-period closed-loop supply chain network design problem and modeled it using MILP approach. They used standard branch-and-bound techniques to determine global optimum of the proposed model. Considering uncertainty is an advantage of the researches of Ramezani *et al.* (2014), Zeballos *et al.* (2014) and Tavakkoli-Moghaddam *et al.* (2015).

Green supplier evaluation can be considered as another activity that can help to improve environmental aspect of a supply chain. The green supplier evaluation and selection problem has been the interest of many researchers during the past years (Keshavarz Ghorabaee *et al.* 2016a; Khaksar *et al.* 2016; Liao *et al.* 2016; Shahryari Nia *et al.* 2016). Govindan *et al.* (2015) performed a review of multi-criteria decision-making approaches in green supplier evaluation and selection problem, and Nielsen *et al.* (2014) presented the most important criteria for this problem. However, there have been only a few studies that this problem is involved in supply chain network design. For example, Govindan and Sivakumar (2016) and Kannan *et al.* (2013) proposed integrated models for green supplier selection and order allocation, but their models were limited to optimization of the order quantity from, and the other decision variables of a supply chain network were not included. This research aims to improve supply chain network design by considering the green supplier evaluation as a part of designing process.

The above-mentioned studies are summarized with respect to some of the important characteristics of them in Table 1. In the last row of this table, we present the main features of the present research in comparison with the other studies which have been reviewed. The main contributions of this research are (i) to present an approach for designing a supply chain in an uncertain environment with closed-loop and open-loop modes, and (ii) consideration of green supplier evaluation in the process of designing the supply chain network with reverse logistics.

Table 1. Studies on supply chain network design with reverse logistics

Author(s) and year	Closed-loop	Open-loop	Multi-product	Multi-period	Multi-objective	Under uncertainty	Supplier evaluation	Approach
Jayaraman *et al.* (2003)	×	✓	×	×	×	×	×	MILP/ Heuristic
Pati *et al.* (2008)	×	✓	✓	×	✓	×	×	MILP/ Goal programming
Pishvaee *et al.* (2010)	×	✓	×	×	×	×	×	MILP/ Metaheuristic
Qin and Ji (2010)	×	✓	×	×	×	✓	×	Fuzzy programming/ Metaheuristic
Pazhani *et al.* (2013)	✓	×	✓	✓	✓	×	×	MILP/ Goal programming
Güleş *et al.* (2013)	✓	×	✓	×	×	×	×	MILP
Kannan *et al.* (2013)	×	×	×	×	✓	✓	✓	MILP/ Fuzzy MCDM
Eskandarpour *et al.* (2014)	×	✓	×	×	×	×	×	MILP/ Metaheuristic
Soleimani and Govindan (2014)	×	✓	✓	×	×	✓	×	Stochastic programming
Jindal and Sangwan (2014)	✓	×	✓	×	×	✓	×	MILP/ Fuzzy programming

End of Table 1

Author(s) and year	Closed-loop	Open-loop	Multi-product	Multi-period	Multi-objective	Under uncertainty	Supplier evaluation	Approach
Ramezani *et al.* (2014)	✓	×	✓	✓	✓	✓	×	MILP/ Fuzzy programming
Mirakhorli (2014)	✓	×	×	×	✓	✓	×	MILP/ Fuzzy programming
Zeballos *et al.* (2014)	✓	×	✓	✓	×	✓	×	MILP/ Stochastic programming
Vahdani and Mohammadi (2015)	✓	×	✓	×	✓	✓	×	Metaheuristic
Subulan *et al.* (2015)	✓	×	✓	×	✓	✓	×	MILP/ Possibilistic and Stochastic programming
Tavakkoli-Moghaddam *et al.* (2015)	✓	×	✓	✓	✓	✓	×	MILP/ Fuzzy programming
Alshamsi and Diabat (2015)	×	✓	✓	✓	×	×	×	MILP
Garg *et al.* (2015)	✓	×	×	×	✓	×	×	MINLP/ Interactive programming
Kalaitzidou *et al.* (2015)	✓	×	✓	✓	×	×	×	MILP
Moghaddam (2015)	✓	×	✓	×	✓	×	✓	Goal programming/ Simulation
Mohajeri and Fallah (2016)	✓	×	×	×	×	✓	×	Fuzzy programming
Yu and Solvang (2016)	×	✓	×	×	✓	×	×	MILP
Talaei *et al.* (2016)	✓	×	✓	×	✓	✓	×	Robust fuzzy programming
Zandieh and Chensebli (2016)	×	✓	×	×	×	×	×	Metaheuristic
Dai (2016)	✓	×	✓	×	✓	✓	×	Fuzzy programming
Ma *et al.* (2016)	✓	×	✓	×	✓	✓	×	MINLP/ Robust programming
Govindan and Sivakumar (2016)	×	×	×	×	✓	✓	✓	MILP/ Fuzzy MCDM
This research	✓	✓	✓	✓	✓	✓	✓	MINLP/ Fuzzy MCDM/ Fuzzy programming

In this study, a multi-objective mathematical model is proposed for designing a supply chain network with reverse logistics. The reverse logistics in the considered supply chain network includes both the closed-loop and open-loop modes. Two objectives are defined for the optimization process. The first objective is minimization of total cost of the network and the second objective, which is related to the green supplier evaluation, is maximization of total greenness score of purchased raw materials/components. To define the second objective, we need the greenness score of each supplier which are determined using a fuzzy multi-criteria decision making method. The fuzzy EDAS method is used in this step of the proposed approach (Keshavarz Ghorabaee *et al.* 2015; Keshavarz Ghorabaee *et al.* 2016b). The demand of customers and capacity of suppliers are two uncertain parameters in the proposed model. The uncertainty of these parameters is defined by using fuzzy numbers. A fuzzy MODM approach is used in this research to solve the model and obtain Pareto (near-Pareto) optimal solutions. The global criterion method is used to compare and validate the results of the fuzzy MODM approach. We use a numerical example of designing the supply chain network of a home appliance company to illustrate the procedure and efficiency of the solution approach.

The rest of this paper is organized as follows. In Section 1, the characteristics of the considered supply chain network are described, and important assumptions are stated. In Section 2, a multi-objective mathematical model is proposed to design the considered supply chain network. In Section 3, we present the framework of a solution approach based on the fuzzy EDAS and a fuzzy MODM method to optimize the proposed mathematical model. In Section 4, a numerical example is solved using the solution approach. Finally, conclusions are presented.

1. Problem description

The general structure of the proposed supply chain network with reverse logistics is illustrated in Figure 1. As can be seen in this figure, the network includes four stages in the forward direction (i.e. suppliers, production centers, distribution centers, and customers) and four stages in the backward (reverse) direction (i.e. customers, collection centers, recovery centers and recycled material markets). The forward flow begins with the procurement of raw materials/components from suppliers and transportation of them to the production centers for manufacturing the products. The new products are transported from production centers to customers via distribution centers to meet the customer demands. The used products are returned to the collection centers by the customers. Some of the returned products are disposed and the remainder is processed and grouped into some recoverable materials/components. Then these recoverable materials/components are transported to the recovery centers. In the recovery centers, a portion of the received materials/components are disposed and process of the recovery is done on the remnant on them. The process of the recovery centers resulted in two types of items: the recovered/recycled raw materials/components that can be used in the production centers, and the recycled materials that can be sold in a market. In this problem the facilities of each stage with their predetermined parameters are needed to be established in some potential locations.

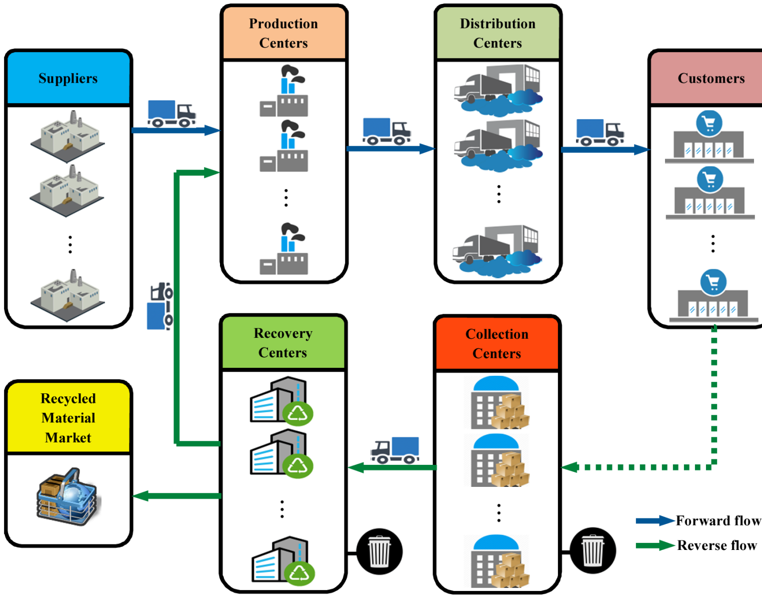

Fig. 1. Structure of the proposed supply chain network

The aim of the proposed model is to design the network by optimization of two objective functions. The first objective function is minimization of total cost of supply chain network, and the second one is maximization of total greenness score of purchased raw materials/components. The important assumptions used in developing the proposed model are stated as follows:

- Demand of customers and capacity of suppliers are two uncertain (fuzzy) parameter of model and the other parameters are deterministic.
- The potential locations for establishing facilities and distances between them are predetermined.
- The required number of facilities to be established in each stage is known.
- Physical locations of the recycled material markets and disposal sites have no impact on the design of the proposed network.
- The capacity of required facilities and cost parameters related to them are definite.
- The planning horizon is divided into multiple time-periods.
- Multiple products are manufactured, distributed and returned.
- There is no flow between facilities of the same stage.
- Shortage is not possible and there is no discount.
- The greenness score of suppliers is determined according to evaluations of experts.
- Returned quantity of a product in a period is a fraction of the average demand of that product in previous periods.
- Transportation costs between facilities of stages are dependent on distances between them.

2. Model formulation

This section describes a multi-objective mathematical model for the proposed supply chain network. As previously mentioned, the proposed model consists of two objectives. The first objective is economic and the second function is environmental. Some important constraints are also imposed to make the optimization model. The notations of sets and indices, parameters and variables which are used in the proposed model are defined in Table 2.

Table 2. Notations and their descriptions

		Description
Sets	LC^P; LC^D; LC^C; LC^R	Set of potential locations of production, distribution, collection and recovery centers; j
	I	Set of required production centers i
	K	Set of required distribution centers k
	L	Set of required collection centers l
	M	Set of required recovery centers m
	N	Set of suppliers n
	P	Set of products p
	Q	Set of customers q
	R	Set of raw materials/components r
	T	Set of time-periods t
	Z	Set of recoverable materials/components z
	G	Set of recycled materials for selling in markets g
Parameters	S_{rn}^{SUP}	Greenness score of raw material/component r of supplier n
	C_j^{LP}	Fixed cost for establishing a production center at potential location $j \in LC^P$
	C_j^{LD}	Fixed cost for establishing a distribution center at potential location $j \in LC^D$
	C_j^{LC}	Fixed cost for establishing a collection center at potential location $j \in LC^C$
	C_j^{LR}	Fixed cost for establishing a recovery center at potential location $j \in LC^R$
	C_{pit}^{FP}	Fixed cost for setting up the production line of product p in production center i at time-period t
	C_{pit}^{VP}	Variable cost for manufacturing product p in production center i at time-period t
	C_{pit}^{IPP}	Inventory cost of product p in production center i at time-period t
	C_{rit}^{IRP}	Inventory cost of raw material/component r in production center i at time-period t
	C_{rnt}^{FS}	Fixed cost to make a contract with supplier n for raw material/component r at time-period t
	C_{rnt}^{RS}	Purchasing cost of one unit of raw material/component r from supplier n at time-period t
	C_{pkt}^{ID}	Inventory cost of product p in distribution center k at time-period t

Continue of Table 2

		Description
	C^{DC}_{pkt}	Variable handling cost of product p in distribution center k at time-period t
	C^{IS}_{plt}	Processing cost of usable portion of returned product p in collection center l at time-period t
	C^{IPC}_{plt}	Inventory cost of returned product p in collection center l at time-period t
	C^{DSC}	Disposal cost of returned products in collection centers
	C^{IZC}_{zlt}	Inventory cost of recoverable material/component z in collection center l at time-period t
	C^{RC}_{zmt}	Processing cost of usable portion of recoverable material/component z in recovery center m at time-period t
	C^{DSR}	Disposal cost of recoverable materials/components in collection centers
	C^{IZR}_{zmt}	Inventory cost of recoverable material/component z in recovery center m at time-period t
	C^{IRR}_{rmt}	Inventory cost of raw material/component r in recovery center m at time-period t
	P^{G}_{g}	Selling price of one unit of recycled material g
	C^{TR}_{r}	Distance-based transportation cost of one unit of raw material/component r
	C^{TP}_{p}	Distance-based transportation cost of one unit of product p
Parameters	C^{TZ}_{z}	Distance-based transportation cost of one unit of recoverable material/component z
	D^{ASP}_{nj}	Distance between supplier n and potential location $j \in LC^{P}$
	$D^{APD}_{jj'}$	Distance between potential location $j \in LC^{P}$ and potential location $j' \in LC^{D}$
	D^{ADC}_{jq}	Distance between potential location $j \in LC^{D}$ and customer q
	$D^{ACR}_{jj'}$	Distance between potential location $j \in LC^{C}$ and potential location $j' \in LC^{R}$
	$D^{ARP}_{jj'}$	Distance between potential location $j \in LC^{R}$ and potential location $j' \in LC^{P}$
	$\widetilde{CP}^{S}_{rnt}$	Fuzzy capacity of supplier n for raw material/component r at time-period t
	CP^{P}_{pit}	Capacity of production center i for manufacturing product p at time-period t
	INV^{PP*}_{pit}	Inventory capacity for product p in production center i at time-period t
	INV^{RP*}_{rit}	Inventory capacity for raw material/component r in production center i at time-period t
	CP^{DC}_{pkt}	Capacity of distribution center k for distributing product p at time-period t
	INV^{D*}_{pkt}	Inventory capacity for product p in distribution center k at time-period t

Continue of Table 2

		Description
Parameters	$\widetilde{DEM}_{pqt}^{C}$	Fuzzy demand of product *p* for customer *q* at time-period *t*
	INV_{plt}^{PC*}	Inventory capacity for returned product *p* in collection center *l* at time-period *t*
	INV_{zlt}^{ZC*}	Inventory capacity for recoverable material/component *z* in collection center *l* at time-period *t*
	INV_{zmt}^{ZR*}	Inventory capacity for recoverable material/component *z* in recovery center *m* at time-period *t*
	INV_{rmt}^{RR*}	Inventory capacity for raw material/component *r* in recovery center *m* at time-period *t*
	X_{nit}^{FSP*}	Capacity of transportation between supplier *n* and production center *i* at time-period *t*
	X_{mit}^{FRP*}	Capacity of transportation between recovery center *m* and production center *i* at time-period *t*
	X_{ikt}^{FPD*}	Capacity of transportation between production center *i* and distribution center *k* at time-period *t*
	X_{kt}^{FDC*}	Capacity of transportation for distribution center *k* at time-period *t*
	X_{lmt}^{FCR*}	Capacity of transportation between collection center *l* and recovery center *m* at time-period *t*
	φ_{p}^{D}	Disposal rate of returned product *p*
	λ_{z}^{D}	Disposal rate of recoverable material/component *z*
	τ^{D}	Distance factor of transportation cost
	τ_{rp}^{A}	Utilization factor of raw material/component *r* in manufacturing product *p*
	σ_{pt}^{RU}	Return rate target for product *p* at time-period *t*
	φ_{pz}^{A}	Conversion factor of returned product *p* to recoverable material/component *z*
	λ_{zr}^{A}	Conversion factor of recoverable material/component *z* to raw material/component *r*
	β_{zg}^{A}	Conversion factor of recoverable material/component *z* to recycled material *g*
Variables	x_{pit}^{QP}	Quantity of product *p* manufactured in production center *i* at time-period *t*
	x_{zlt}^{QZ}	Quantity of recoverable material/component *z* produced in collection center *l* at time-period *t*
	x_{rmt}^{QR}	Quantity of raw material/component *r* produced in recovery center *m* at time-period *t*
	x_{gmt}^{QG}	Quantity of recycled material *g* produced in recovery center *m* at time-period *t*
	x_{rnit}^{FSP}	Quantity of raw material/component *r* transported from supplier *n* to production center *i* at time-period *t*
	x_{pikt}^{FPD}	Quantity of product *p* transported from production center *i* to distribution center *k* at time-period *t*
	x_{pkqt}^{FDC}	Quantity of product *p* transported from distribution center *k* to customer *q* at time-period *t*

End of Table 2

		Description
Variables	x_{plt}^{FCC}	Quantity of product p returned from customers to collection center l at time-period t
	x_{zlmt}^{FCR}	Quantity of recoverable material/component z transported from collection center l to recovery center m at time-period t
	x_{rmit}^{FRP}	Quantity of raw material/component r transported from recovery center m to production center i at time-period t
	x_{plt}^{TCC}	Quantity of returned product p processed in collection center l at time-period t
	x_{zmt}^{TCR}	Quantity of recoverable material/component z processed in recovery center m at time-period t
	y_{ij}^{LP}	Binary variable takes a value of 1 if production center i is established at potential location $j \in LC^P$
	y_{kj}^{LD}	Binary variable takes a value of 1 if distribution center k is established at potential location $j \in LC^D$
	y_{lj}^{LC}	Binary variable takes a value of 1 if collection center l is established at potential location $j \in LC^C$
	y_{mj}^{LR}	Binary variable takes a value of 1 if recovery center m is established at potential location $j \in LC^C$
	y_{pit}^{FP}	Binary variable takes a value of 1 if production line of product p is set up in production center i at time-period t
	y_{rnt}^{S}	Binary variable takes a value of 1 if raw material/component r is purchased from supplier n at time-period t
	inv_{pit}^{PP}	Inventory level of product p in production center i at time-period t
	inv_{rit}^{RP}	Inventory level of raw material/component r in production center i at time-period t
	inv_{pkt}^{D}	Inventory level of product p in distribution center k at time-period t
	inv_{plt}^{PC}	Inventory level of returned product p in collection center l at time-period t
	inv_{zlt}^{ZC}	Inventory level of recoverable material/component z in collection center l at time-period t
	inv_{zmt}^{ZR}	Inventory level of recoverable material/component z in recovery center m at time-period t
	inv_{rmt}^{RR}	Inventory level of raw material/component r in recovery center m at time-period t
	c_{rni}^{TSP}	Transportation cost of one unit of raw material/component r between supplier n and production center i
	c_{pik}^{TPD}	Transportation cost of one unit of product p between production center i and distribution center k
	c_{pkq}^{TDC}	Transportation cost of one unit of product p between distribution center k and customer q
	c_{zlm}^{TCR}	Transportation cost of one unit of recoverable material/component z between collection center l and recovery center m
	c_{rmi}^{TRP}	Transportation cost of one unit of raw material/component r between recovery center m and production center i

The economical objective (f^c) function includes total production cost (TPC), total distribution cost (TDC), total collection cost (TCC), total recovery cost (TRC) and total transportation cost (TTC). These costs are defined in Eqs. (1) to (5):

$$TPC = \sum_{i\in I}\sum_{j\in LC^P} C_j^{LP} y_{ij}^{LP} + \sum_{p\in P}\sum_{i\in I}\sum_{t\in T}\left(C_{pit}^{FP} y_{pit}^{FP} + C_{pit}^{VP} x_{pit}^{QP} + C_{pit}^{IPP} inv_{pit}^{PP}\right) + \sum_{r\in R}\sum_{i\in I}\sum_{t\in T} C_{rit}^{IRP} inv_{rit}^{RP} + \sum_{r\in R}\sum_{n\in N}\sum_{t\in T} C_{rnt}^{FS} y_{rnt}^{S} + \sum_{r\in R}\sum_{n\in N}\sum_{i\in I}\sum_{t\in T} C_{rnt}^{RS} x_{rnit}^{FSP}; \quad (1)$$

$$TDC = \sum_{k\in K}\sum_{j\in LC^D} C_j^{LD} y_{kj}^{LD} + \sum_{p\in P}\sum_{k\in K}\sum_{t\in T} C_{pkt}^{ID} inv_{pkt}^{D} + \sum_{p\in P}\sum_{k\in K}\sum_{q\in Q}\sum_{t\in T} C_{pkt}^{DC} x_{pkqt}^{FDC}; \quad (2)$$

$$TCC = \sum_{l\in L}\sum_{j\in LC^R} C_j^{LC} y_{lj}^{LC} + \sum_{p\in P}\sum_{l\in L}\sum_{t\in T}\left(C_{plt}^{IS}\left(\left(1-\varphi_p^D\right) x_{plt}^{TCC}\right) + C_{plt}^{IPC} inv_{plt}^{PC} + C^{DSC}\varphi_p^D x_{plt}^{TCC}\right) + \sum_{z\in Z}\sum_{l\in L}\sum_{t\in T} C_{zlt}^{IZC} inv_{zlt}^{ZC}; \quad (3)$$

$$TRC = \sum_{m\in M}\sum_{j\in LC^R} C_j^{LR} y_{mj}^{LR} + \sum_{z\in Z}\sum_{m}\sum_{t\in T}\left(C_{zmt}^{RC}\left(\left(1-\lambda_z^D\right) x_{zmt}^{TCR}\right) + C^{DSR}\lambda_z^D x_{zmt}^{TCR} + C_{zmt}^{IZR} inv_{zmt}^{ZR}\right) + \sum_{r\in R}\sum_{m\in M}\sum_{t\in T} C_{rmt}^{IRR} inv_{rmt}^{RR} - \sum_{g\in G}\sum_{m\in M}\sum_{t\in T} P_g^G x_{gmt}^{QG}; \quad (4)$$

$$TTC = \sum_{r\in R}\sum_{n\in N}\sum_{i\in I}\sum_{t\in T} c_{rni}^{TSP} x_{rnit}^{FSP} + \sum_{p\in P}\sum_{i\in I}\sum_{k\in K}\sum_{t\in T} c_{pik}^{TPD} x_{pikt}^{FPD} + \sum_{p\in P}\sum_{k\in K}\sum_{q\in Q}\sum_{t\in T} c_{pkq}^{TDC} x_{pkqt}^{FDC} + \sum_{z\in Z}\sum_{l\in L}\sum_{m\in M}\sum_{t\in T} c_{zlm}^{TCR} x_{zlmt}^{FCR} + \sum_{r\in R}\sum_{m\in M}\sum_{i\in I}\sum_{t\in T} c_{rmi}^{TRP} x_{rmit}^{FRP}. \quad (5)$$

In TRC Equation (Eq. (4)), the last expression is subtracted from the other costs because it is a benefit expression and should be maximized.

In summary, Eq. (6) shows the economical objective function that should be minimized.

$$\text{Min } f^c = TPC + TDC + TCC + TRC + TTC. \quad (6)$$

Moreover, the environmental objective of the proposed model, which is related to maximization of total greenness score of purchased raw materials/components from suppliers, is shown in Eq. (7).

$$\text{Max } f^g = \sum_{r\in R}\sum_{n\in N}\sum_{i\in I}\sum_{t\in T} S_{rn}^{SUP} x_{rnit}^{FSP}. \quad (7)$$

In Eq. (5) the transportation cost coefficients in different stages of the network are dependent on the distances between established facilities and defined in Eqs. (8) to (12).

$$c_{rni}^{TSP} = \tau^D C_r^{TR} \sum_{j\in LC^P} D_{nj}^{ASP} y_{ij}^{LP}, \qquad \forall r\in R, \forall n\in N, \forall i\in I; \quad (8)$$

$$c_{pik}^{TPD} = \tau^D C_p^{TP} \sum_{j\in LC^P}\sum_{j'\in LC^D} D_{jj'}^{APD} y_{ij}^{LP} y_{kj'}^{LD}, \qquad \forall p\in P, \forall i\in I, \forall k\in K; \quad (9)$$

$$c_{pkq}^{TDC} = \tau^D C_p^{TP} \sum_{j \in LC^D} D_{jq}^{ADC} y_{kj}^{LD} , \qquad \forall p \in P, \forall k \in K, \forall q \in Q ; \tag{10}$$

$$c_{zlm}^{TCR} = \tau^D C_z^{TZ} \sum_{j \in LC^C} \sum_{j' \in LC^R} D_{jj'}^{ACR} y_{lj}^{LC} y_{mj'}^{LR} , \qquad \forall z \in Z, \forall l \in L, \forall m \in M ; \tag{11}$$

$$c_{rmi}^{TRP} = \tau^D C_r^{TR} \sum_{j \in LC^R} \sum_{j' \in LC^P} D_{jj'}^{ARP} y_{mj}^{LR} y_{ij'}^{LP} , \qquad \forall r \in R, \forall m \in M, \forall i \in I . \tag{12}$$

The constraints of the production centers (purchasing and manufacturing) are defined in the following equations. Eqs. (13) and (14) shows the capacity constraints of suppliers and production centers, respectively. The maximum capacity of suppliers is considered as an uncertain (fuzzy) parameter. Eqs. (15) to (18) are the inventory constraints of products and raw materials/components in production centers. Eq. (19) states that if a production line is set up in a time-period, it can be operational after that time-period.

$$\sum_{i \in I} x_{rnit}^{FSP} \le \widetilde{CP}_{rnt}^{S} y_{rnt}^{S} , \qquad \forall r \in R, \forall n \in N, \forall t \in T ; \tag{13}$$

$$x_{pit}^{QP} \le CP_{pit}^{P} y_{pit}^{FP} , \qquad \forall p \in P, \forall i \in I, \forall t \in T ; \tag{14}$$

$$inv_{pit}^{PP} = inv_{pi(t-1)}^{PP} + x_{pit}^{QP} - \sum_{k \in K} x_{pikt}^{FPD} , \qquad \forall p \in P, \forall i \in I, \forall t \in T ; \tag{15}$$

$$inv_{rit}^{RP} = inv_{ri(t-1)}^{RP} + \sum_{n \in N} x_{rnit}^{FSP} + \sum_{m \in M} x_{rmit}^{FRP} - \sum_{p \in P} \tau_{rp}^{A} x_{pit}^{QP} , \qquad \forall r \in R, \forall i \in I, \forall t \in T ; \tag{16}$$

$$inv_{pit}^{PP} \le INV_{pit}^{PP*} , \qquad \forall p \in P, \forall i \in I, \forall t \in T ; \tag{17}$$

$$inv_{rit}^{RP} \le INV_{rit}^{RP*} , \qquad \forall r \in R, \forall i \in I, \forall t \in T ; \tag{18}$$

$$y_{pit}^{FP} \ge y_{pi(t-1)}^{FP} , \qquad \forall p \in P, \forall i \in I, \forall t \in T . \tag{19}$$

Eqs. (20) to (23) show the constraints related to distribution of products. Eq. (20) is the capacity constraint of distribution centers on each product. Eqs. (21) and (22) are the constraints of inventory of products in distribution centers, and Eq. (23) is the constraint to meet the demand of customers. In Eq. (23), the demand of customers is considered as an uncertain (fuzzy) parameter.

$$\sum_{q \in Q} x_{pkqt}^{FDC} \le CP_{pkt}^{DC} , \qquad \forall p \in P, \forall k \in K, \forall t \in T ; \tag{20}$$

$$inv_{pkt}^{D} = inv_{pk(t-1)}^{D} + \sum_{i \in I} x_{pikt}^{FPD} - \sum_{q \in Q} x_{pkqt}^{FDC} , \qquad \forall p \in P, \forall k \in K, \forall t \in T ; \tag{21}$$

$$inv_{pkt}^{D} \le INV_{pkt}^{D*} , \qquad \forall p \in P, \forall k \in K, \forall t \in T ; \tag{22}$$

$$\sum_{k \in K} x_{pkqt}^{FDC} = \widetilde{DEM}_{pqt}^{C} , \qquad \forall p \in P, \forall q \in Q, \forall t \in T . \tag{23}$$

The following equations describe the constraints related to collection activities. Eq. (24) shows the constraint of returned product in each time-period. It's clear that total returned product in the first time-period is equal to zero ($\sum_{l\in L} x_{pl1}^{FCC} = 0$). Eq. (25) is related to transformation of returned product to the recoverable materials/components. Eqs. (26) to (29) show the inventory constraints in the collection centers.

$$\sum_{l\in L} x_{plt}^{FCC} = \frac{\sigma_{pt}^{RU}}{t-1} \sum_{t'=2}^{t-1} \sum_{q\in Q} \widetilde{DEM}_{pqt'}^{C}, \qquad \forall p \in P, \forall t \in T - \{1\}; \tag{24}$$

$$x_{zlt}^{QZ} = \sum_{p\in P} \varphi_{pz}^{A} \left(\left(1 - \varphi_p^D\right) x_{plt}^{TCC} \right), \qquad \forall z \in Z, \forall l \in L, \forall t \in T; \tag{25}$$

$$inv_{plt}^{PC} = inv_{pl(t-1)}^{PC} + x_{plt}^{FCC} - x_{plt}^{TCC}, \qquad \forall p \in P, \forall l \in L, \forall t \in T; \tag{26}$$

$$inv_{zlt}^{ZC} = inv_{zl(t-1)}^{ZC} + x_{zlt}^{QZ} - \sum_{m\in M} x_{zlmt}^{FCR}, \qquad \forall z \in Z, \forall l \in L, \forall t \in T; \tag{27}$$

$$inv_{plt}^{PC} \le INV_{plt}^{PC*}, \qquad \forall p \in P, \forall l \in L, \forall t \in T; \tag{28}$$

$$inv_{zlt}^{ZC} \le INV_{zlt}^{ZC*}, \qquad \forall z \in Z, \forall l \in L, \forall t \in T. \tag{29}$$

Constrains of recovery activities are defined in Eqs. (30) to (36). Eq. (30) is the constraint of converting recoverable materials/components to the raw materials/components that can be used in the production centers, and Eq. (31) shows the constraint of transforming the recoverable materials/components to the recycled materials for selling in markets. Eqs. (32) to (35) indicate the inventory constraints of recovery centers.

$$x_{rmt}^{QR} = \sum_{z\in Z} \lambda_{zr}^{A} \left(\left(1 - \lambda_z^D\right) x_{zmt}^{TCR} \right), \qquad \forall r \in R, \forall m \in M, \forall t \in T; \tag{30}$$

$$x_{gmt}^{QG} = \sum_{z\in Z} \beta_{zg}^{A} \left(\left(1 - \lambda_z^D\right) x_{zmt}^{TCR} \right), \qquad \forall g, \forall m \in M, \forall t \in T; \tag{31}$$

$$inv_{zmt}^{ZR} = inv_{zm(t-1)}^{ZR} + \sum_{l\in L} x_{zlmt}^{FCR} - x_{zmt}^{TCR}, \qquad \forall z \in Z, \forall m \in M, \forall t \in T; \tag{32}$$

$$inv_{rmt}^{RR} = inv_{rm(t-1)}^{RR} + x_{rmt}^{QR} - \sum_{i\in I} x_{rmit}^{FRP}, \qquad \forall r \in R, \forall m \in M, \forall t \in T; \tag{33}$$

$$inv_{zmt}^{ZR} \le INV_{zmt}^{ZR*}, \qquad \forall z \in Z, \forall m \in M, \forall t \in T; \tag{34}$$

$$inv_{rmt}^{RR} \le INV_{rmt}^{RR*}, \qquad \forall r \in R, \forall m \in M, \forall t \in T. \tag{35}$$

Constraints of transportation flow between different stages of the supply chain network are defined in Eqs. (36) to (40).

$$\sum_{r\in R} x_{rnit}^{FSP} \le X_{nit}^{FSP*}, \qquad \forall n \in N, \forall i \in I, \forall t \in T; \tag{36}$$

$$\sum_{r\in R} x_{rmit}^{FRP} \le X_{mit}^{FRP*}, \qquad \forall m \in M, \forall i \in I, \forall t \in T; \tag{37}$$

$$\sum_{p\in P} x_{pikt}^{FPD} \le X_{ikt}^{FPD*}, \qquad \forall i\in I, \forall k\in K, \forall t\in T; \tag{38}$$

$$\sum_{p\in P}\sum_{q\in Q} x_{pkqt}^{FDC} \le X_{kt}^{FDC*}, \qquad \forall k\in K, \forall t\in T; \tag{39}$$

$$\sum_{z\in Z} x_{zlmt}^{FCR} \le X_{lmt}^{FCR*}, \qquad \forall l\in L, \forall m\in M, \forall t\in T. \tag{40}$$

Eqs. (41) to (48) state the constraints of assigning the potential locations for establishing the required centers in different stages.

$$\sum_{i\in I} y_{ij}^{LP} \le 1, \qquad \forall j\in LC^P; \tag{41}$$

$$\sum_{j\in LC^P} y_{ij}^{LP} = 1, \qquad \forall i\in I; \tag{42}$$

$$\sum_{k\in K} y_{kj}^{LD} \le 1, \qquad \forall j\in LC^D; \tag{43}$$

$$\sum_{j\in LC^D} y_{kj}^{LD} = 1, \qquad \forall k\in K; \tag{44}$$

$$\sum_{l\in L} y_{lj}^{LC} \le 1, \qquad \forall j\in LC^C; \tag{45}$$

$$\sum_{j\in LC^C} y_{lj}^{LC} = 1, \qquad \forall l\in L; \tag{46}$$

$$\sum_{m\in M} y_{mj}^{LR} \le 1, \qquad \forall j\in LC^R; \tag{47}$$

$$\sum_{j\in LC^R} y_{mj}^{LR} = 1, \qquad \forall m\in M. \tag{48}$$

It should be noted that there is no initial inventory in all stages (i.e. $inv_{pi0}^{PP} = 0$, $inv_{ri0}^{RP} = 0$, $inv_{pk0}^{D} = 0$, $inv_{pl0}^{PC} = 0$, $inv_{zl0}^{ZC} = 0$, $inv_{zm0}^{ZR} = 0$ and $inv_{rm0}^{RR} = 0$).

3. Solution approach

In this section, a solution approach is described for optimization of the proposed multi-objective mathematical model. The framework of the proposed approach is depicted in Figure 2. In the following sub-sections, this framework is explained.

3.1. Reformulation of uncertain constraints

As can be seen in Figure 2, after definition of problem and formulation of model, it's needed to reformulate the constraints of the model that include uncertain (fuzzy) parameters. By using α-cuts approach, fuzzy right hand sides of the constraints are converted to interval values. According to the proposed model, Eqs. (13) and (23) are two constrains with fuzzy

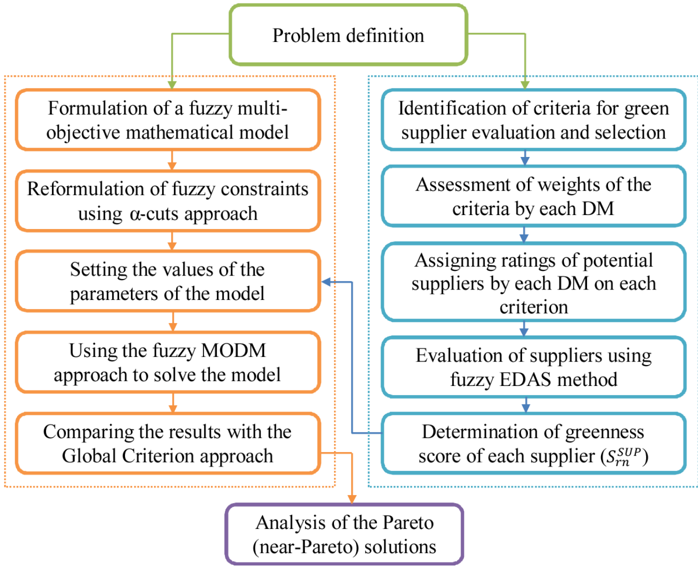

Fig. 2. The framework of the solution approach

right hand sides. Suppose that the values of $\widetilde{CP}_{rnt}^{S}$ and $\widetilde{DEM}_{pqt}^{C}$ are triangular fuzzy numbers, i.e. $\widetilde{CP}_{rnt}^{S}=\left(CP_{rnt}^{S1},CP_{rnt}^{S2},CP_{rnt}^{S3}\right)$ and $\widetilde{DEM}_{pqt}^{C}=\left(DEM_{pqt}^{C1},DEM_{pqt}^{C2},DEM_{pqt}^{C3}\right)$. Then α-cuts of these values are defined as follows:

$$\widetilde{CP}_{rnt}^{S\alpha}=\left[CP_{rnt}^{S\alpha L},CP_{rnt}^{S\alpha U}\right]; \tag{49}$$

$$\widetilde{DEM}_{pqt}^{C\alpha}=\left[DEM_{pqt}^{C\alpha L},DEM_{pqt}^{C\alpha U}\right], \tag{50}$$

where,

$$CP_{rnt}^{S\alpha L}=CP_{rnt}^{S1}+\alpha\left(CP_{rnt}^{S2}-CP_{rnt}^{S1}\right); \tag{51}$$

$$CP_{rnt}^{S\alpha U}=CP_{rnt}^{S3}-\alpha\left(CP_{rnt}^{S3}-CP_{rnt}^{S2}\right); \tag{52}$$

$$DEM_{pqt}^{C\alpha L}=DEM_{pqt}^{C1}+\alpha\left(DEM_{pqt}^{C2}-DEM_{pqt}^{C1}\right); \tag{53}$$

$$DEM_{pqt}^{C\alpha U}=DEM_{pqt}^{C3}-\alpha\left(DEM_{pqt}^{C3}-DEM_{pqt}^{C2}\right). \tag{54}$$

To reformulate the considered constraints, the approach of Gabrel *et al.* (2010) is used and two groups of variables (cp_{rnt}^{SV} and dem_{pqt}^{CV}) are defined according to the right hand sides. Then Eq. (13) is replaced with Eqs. (55) to (57), and Eq. (23) is transformed to Eqs. (58) to (60) shown as follows:

$$\sum_{i\in I}x_{rnit}^{FSP}\le cp_{rnt}^{SV}\,y_{rnt}^{S}, \qquad \forall r\in R,\forall n\in N,\forall t\in T; \tag{55}$$

$$cp_{rnt}^{SV}\le CP_{rnt}^{S\alpha U}, \qquad \forall r\in R,\forall n\in N,\forall t\in T; \tag{56}$$

$$cp_{rnt}^{SV} \geq CP_{rnt}^{S\alpha L}, \qquad \forall r \in R, \forall n \in N, \forall t \in T; \tag{57}$$

$$\sum_{k \in K} x_{pkqt}^{FDC} = dem_{pqt}^{CV}, \qquad \forall p \in P, \forall q \in Q, \forall t \in T; \tag{58}$$

$$dem_{pqt}^{CV} \leq DEM_{pqt}^{C\alpha U}, \qquad \forall p \in P, \forall q \in Q, \forall t \in T; \tag{59}$$

$$dem_{pqt}^{CV} \geq DEM_{pqt}^{C\alpha L}, \qquad \forall p \in P, \forall q \in Q, \forall t \in T. \tag{60}$$

Using this reformulation, we can optimize the model with different values of α.

3.2. Using fuzzy EDAS to determine greenness scores

After reformulation of the uncertain constraints, we need to set parameters of the model. One of these parameters is the greenness score of each supplier on each raw material/component. To determine this parameter, the fuzzy EDAS method is used. The EDAS method is a new and efficient method which was proposed by Keshavarz Ghorabaee *et al.* (2015) for inventory classification. This method has been used and extended by some researchers (Turskis, Juodagalvienė 2016; Kahraman *et al.* 2017; Peng, Liu 2017). The fuzzy EDAS method was proposed to deal with MCDM problems under uncertainty (Keshavarz Ghorabaee *et al.* 2016b). For using this method, first, evaluation criteria should be identified and then weights of criteria and ratings of alternatives (suppliers) on each criterion should be assessed by decision-makers. In this study, linguistic variables with trapezoidal fuzzy numbers, which are presented in Table 3, are used by decision-makers to evaluate suppliers. Interested readers are referred to the research of Keshavarz Ghorabaee *et al.* (2016b) for detailed information about the fuzzy EDAS method and the computational steps of it.

Table 3. Linguistic variables with fuzzy numbers

Usage	Linguistic variable	Trapezoidal fuzzy number
For weighting criteria	Very low (VL)	(0,0, 0.1,0.2)
	Low (L)	(0.1,0.2,0.2,0.3)
	Medium low (ML)	(0.2,0.3,0.4,0.5)
	Medium (M)	(0.4,0.5,0.5,0.6)
	Medium high (MH)	(0.5,0.6,0.7,0.8)
	High (H)	(0.7,0.8,0.8,0.9)
	Very high (VH)	(0.8,0.9,1,1)
For ratings	Very poor (VP)	(0,0,1,2)
	Poor (P)	(1,2,2,3)
	Medium poor (MP)	(2,3,4,5)
	Fair (F)	(4,5,5,6)
	Medium good (MG)	(5,6,7,8)
	Good (G)	(7,8,8,9)
	Very good (VG)	(8,9,10,10)

3.3. Fuzzy MODM to solve the model

A fuzzy multi-objective approach based on the method of Zimmermann (1978) is used in this study for optimization of the proposed model. To solve the model by this approach, objective functions of the original mathematical model, which are defined in Eqs. (6) and (7), are replaced with one objective function (Eq. (61)) and two new constraints (Eqs. (62) and (63)) shown as follows:

$$\text{Max} f = w^c \lambda^c + w^g \lambda^g ; \tag{61}$$

$$\lambda^c \le 1 - \frac{f^c - f^c_{min}}{f^c_{max} - f^c_{min}} ; \tag{62}$$

$$\lambda^g \le 1 + \frac{f^g - f^g_{max}}{f^g_{max} - f^g_{min}} , \tag{63}$$

where λ^c denotes the satisfaction degree of the minimization function (f^c) and λ^g shows the satisfaction degree of the maximization function (f^g). Moreover, w^c and w^g are used for weighting objectives ($w^c + w^g = 1$). By changing these weights, we can obtain the Pareto-optimal solutions of the multi-objective model.

3.4. Comparing the results

Global criterion method is used in this study to compare the results of the fuzzy MODM approach and validate them. For using this approach the objectives of the proposed model (Eqs. (6) and (7)) should be merged to one objective function as follows:

$$\text{Min} f = \left(w^c \left(\frac{f^c - f^c_{min}}{f^c_{max} - f^c_{min}} \right) \right)^{\rho} + \left(w^g \left(\frac{f^g_{max} - f^g}{f^g_{max} - f^g_{min}} \right) \right)^{\rho} . \tag{64}$$

Using different values of w^c and w^g in Eq. (63), Pareto-optimal solutions can be determined. Then we can compare them with the corresponding solutions of the fuzzy MODM approach.

4. Numerical example

In this section, a numerical example is used to illustrate the propose model and solution procedure. The example is related to a home appliance company which decides to design and optimize its supply chain with reverse logistics. The company has a plan to establish some facilities in some potential locations to manufacture and distribute its products and recover the returned products. The basic data about the problem is presented in Table 4 and the detailed data is provided as Supplementary information (Data 1.xlsx).

As can be seen in Table 4, there are nine suppliers (n_1 to n_9) for six raw materials/components (r_1 to r_6). It should be noted that, in this problem, each supplier has its own characteristics and can supply specific raw materials/components. n_1 and n_2 are the suppliers of r_1, n_3 to n_6 can only supply r_2 to r_4, and n_7 to n_9 are the suppliers of r_5 and r_6. The

Table 4. Basic data of the example

Item	Number
Potential locations for production centers	7
Potential locations for distribution centers	6
Potential locations for collection centers	5
Potential locations for recovery centers	5
Required production centers	2
Required distribution centers	2
Required collection centers	2
Required recovery centers	2
Suppliers	9
Customers	10
Products	4
Raw materials/components	6
Recoverable materials/components	4
Salable recycled material	2
Time-periods	4

company formed a group of ten experts (decision-makers) to evaluate these suppliers and determine the greenness score of them (S_{rn}^{SUP}). First the experts defined some criteria with respect to the review article of Nielsen *et al.* (2014) and evaluate their importance. Then the ratings of suppliers were assigned on each criterion by each decision-maker, and finally the greenness scores were determined using the fuzzy EDAS method. The detailed data of experts' evaluations is provided as Supplementary information (Data 2.xlsx). Table 5 shows the defined criteria and their average importance, and Table 6 presents the greenness score of each supplier. It is assumed that the greenness scores of a supplier are equal in different raw materials/components.

Table 5. Evaluation criteria and their average fuzzy weights

Criteria	Fuzzy weights
Environmental management systems	(0.75,0.85,0.9,0.95)
Green image	(0.64,0.74,0.83,0.89)
Environmental competences	(0.56,0.66,0.7,0.8)
Design for environment	(0.75,0.85,0.9,0.95)
Environmental improvement costs	(0.29,0.39,0.4,0.5)
Delivery	(0.65,0.75,0.82,0.89)
Quality	(0.74,0.84,0.88,0.94)
Technical capability	(0.21,0.31,0.36,0.46)
Management and organization	(0.26,0.36,0.4,0.5)
Financial position	(0.52,0.62,0.65,0.75)

Table 6. The greenness score of suppliers

Supplier (n)	Fuzzy score	S_{rn}^{SUP}
1	(–2.16,0.26,1.32,3.81)	0.8135
2	(–2.52,–0.32,0.75,2.86)	0.1867
3	(–0.16,0.57,0.93,1.69)	0.7584
4	(–0.67,0.09,0.45,1.19)	0.2649
5	(0.06,0.78,1.13,1.92)	0.9741
6	(–0.82,–0.08,0.27,0.98)	0.0836
7	(–0.98,0.22,0.83,2.01)	0.5182
8	(–0.63,0.55,1.12,2.31)	0.8397
9	(–1.32,–0.12,0.49,1.71)	0.1897

Figure 3 depicts the potential locations for required facilities, location of suppliers and location of customers. With respect to the parameters of the problem, the mathematical model is solved using the fuzzy MODM approach described in the previous section with different α-cuts and different weights of objectives. The values of objective functions are presented in Table 7. The global criterion results (with ρ = 1) are also included in this table for comparison. We used an educational unlimited version of Lingo 16.0×64 to solve the model.

According to Table 7, the results of the fuzzy MODM and global criterion approaches are very close together. The estimated Pareto (near-Pareto) front is shown in Figure 4 (M1 = fuzzy MODM and M2 = global criterion). As can be seen in this figure, there is a good trade-off between the values of objectives in different weights, and so the proposed

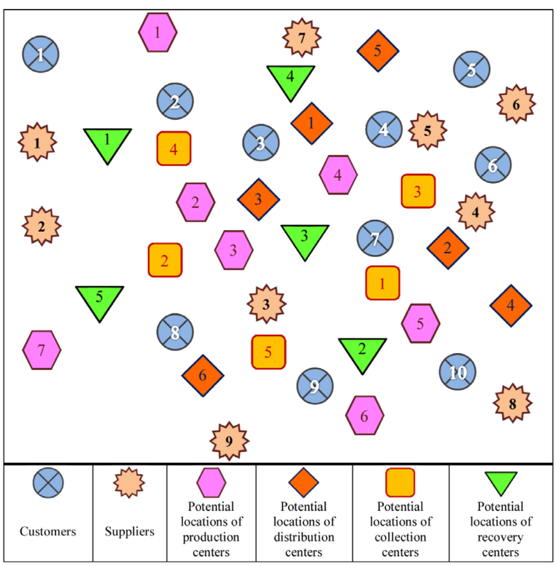

Fig. 3. The location of different elements of the network

Table 7. The results of model in different α-cuts and different weights

	Objectives bounds				Weights		Fuzzy MODM		Global criterion	
α	f^c_{max}	f^c_{min}	f^g_{max}	f^g_{min}	w^c	w^g	f^c	f^g	f^c	f^g
0	1.10E+07	7565890	129517	64907.06	0.9	0.1	7646035	91283.06	7633237	85387.79
	1.10E+07	7565890	129517	64907.06	0.7	0.3	7768330	101668.1	7766399	101613.4
	1.10E+07	7565890	129517	64907.06	0.5	0.5	8121455	111463.4	8124719	111459.1
	1.10E+07	7565890	129517	64907.06	0.3	0.7	9016905	123418.8	9007653	123418.8
	1.10E+07	7565890	129517	64907.06	0.1	0.9	1.04E+07	129517	1.04E+07	129517
0.25	1.10E+07	7703513	127101	64907.06	0.9	0.1	7775431	91229.3	7759977	89490.27
	1.10E+07	7703513	127101	64907.06	0.7	0.3	7905716	102485.8	7907310	102525.3
	1.10E+07	7703513	127101	64907.06	0.5	0.5	8163772	109844.5	8165207	109855.3
	1.10E+07	7703513	127101	64907.06	0.3	0.7	9030399	121423.7	9031007	121423.7
	1.10E+07	7703513	127101	64907.06	0.1	0.9	1.03E+07	127101	1.03E+07	127101
0.5	1.10E+07	7814672	124622.9	64907.06	0.9	0.1	7889123	91770.88	7887453	91502.5
	1.10E+07	7814672	124622.9	64907.06	0.7	0.3	8022493	103462.4	8013425	103072.9
	1.10E+07	7814672	124622.9	64907.06	0.5	0.5	8180710	108059.9	8197290	108083.3
	1.10E+07	7814672	124622.9	64907.06	0.3	0.7	8976226	118921.6	8973290	118902.8
	1.10E+07	7814672	124622.9	64907.06	0.1	0.9	1.03E+07	124622.9	1.03E+07	124622.9
0.75	1.10E+07	7960902	122117.4	64907.06	0.9	0.1	8056074	93709.23	8068412	94407.52
	1.10E+07	7960902	122117.4	64907.06	0.7	0.3	8156360	103903.9	8169726	103957
	1.10E+07	7960902	122117.4	64907.06	0.5	0.5	8228325	106246.8	8239931	106255.4
	1.10E+07	7960902	122117.4	64907.06	0.3	0.7	9023399	117180.4	9034558	117184.2
	1.10E+07	7960902	122117.4	64907.06	0.1	0.9	1.03E+07	122117.4	1.03E+07	122117.4
1	1.10E+07	8103978	119611.8	64907.06	0.9	0.1	8174834	93746.32	8190538	93630.9
	1.10E+07	8103978	119611.8	64907.06	0.7	0.3	8291746	104031.8	8305633	104031.8
	1.10E+07	8103978	119611.8	64907.06	0.5	0.5	8340980	105680.5	8355978	105680.1
	1.10E+07	8103978	119611.8	64907.06	0.3	0.7	8982413	114194.8	8980628	114224.6
	1.10E+07	8103978	119611.8	64907.06	0.1	0.9	1.03E+07	119611.8	1.03E+07	119611.8

approach is efficient to obtain Pareto (near-Pareto) optimal solutions for the mathematical model.

Here, one of these solutions (with α = 0.5 and $w^c = w^g = 0.5$) is considered to show the optimal design of the network. Figure 5 represent a graphical view of the optimum location of facilities in different stages and the flow of materials and product over the whole planning horizon.

We can see that n_2 and n_9 are not selected for purchasing raw materials/components in all time-periods. It should be noted that the detailed results for this network configuration is provided as a Lingo report file in Supplementary information (Report.pdf). However, as an example, the values of the flow of raw materials/components from suppliers to production centers in each time-period (x^{FSP}_{rnit}) are presented in Table 8.

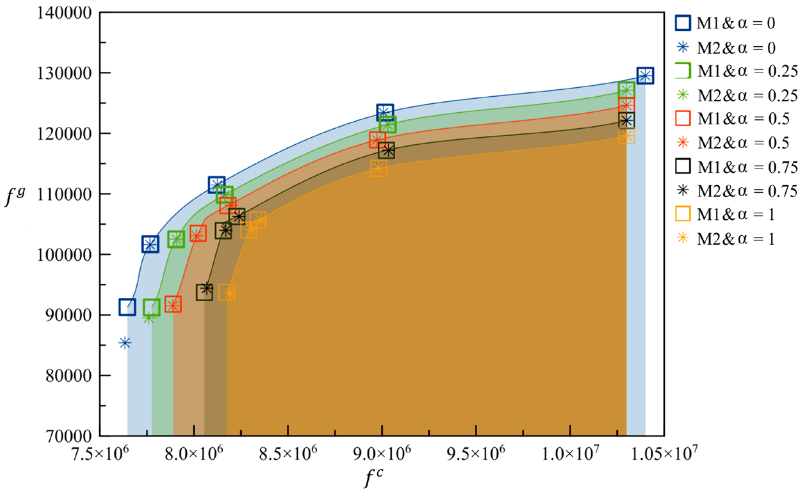

Fig. 4. The estimated Pareto (near-Pareto) front

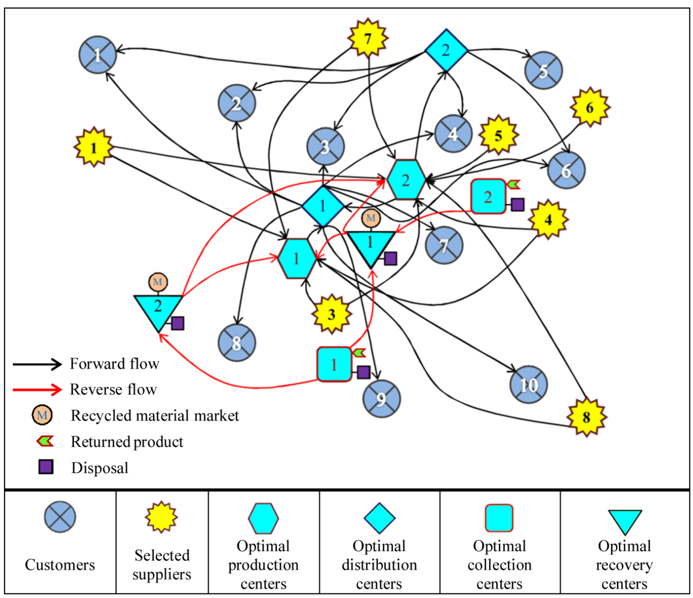

Fig 5. The optimal network design with α = 0.5 and $w^c = w^g = 0.5$

According to this table, there is no flow between n_2 and n_9 and production centers which shows that these suppliers are not selected in all time-periods. Also, it can be seen that n_6 only supplies r_2 for the second production center in one of the time-periods. Moreover, raw materials/components of n_5 only transport to the second production center, and there is no connection between n_5 and the first production center.

Table 8. The flow of raw materials/components from suppliers to production centers (x_{rnit}^{FSP})

i		1				2			
t		1	2	3	4	1	2	3	4
r	*n*								
1	1	2849.5	2350.7	1818	2591.8	3555.5	5104.3	4223.7	2703.8
	2	0	0	0	0	0	0	0	0
2	3	1890	2520	2835	2835	0	0	0	0
	4	250	0	0	0	1640	1271.6	0	0
	5	0	0	0	0	1890	2100	2415	2520
	6	0	0	0	0	191.5	0	0	0
3	3	0	520.3	1365	1470	1050	739.7	0	0
	4	0	0	0	0	1365	1365	1470	1470
	5	0	0	0	0	840	840	1050	1260
	6	0	0	0	0	0	0	0	0
4	3	375	1365	1449	0	885	0	21	1470
	4	0	0	0	0	1365	1365	1470	1680
	5	0	0	0	0	1050	1050	1050	1365
	6	0	0	0	0	0	0	0	0
5	7	0	0	0	0	3892.3	4116.7	0	3104.6
	8	2602	2016.1	0	3812.2	1913	2708.8	4935	1122.8
	9	0	0	0	0	0	0	0	0
6	7	0	0	0	386.3	4725	4935	4935	4758.7
	8	2832	5565	5775	5775	2523	0	0	0
	9	0	0	0	0	0	0	0	0

Conclusions

In recent years, using reverse logistics in designing supply chain networks has received more and more attentions from both academics and practitioners because of its consequential effect on environmental aspects of supply chains. In this study, a new general problem has been considered to design a multi-product, multi-period supply chain network with reverse logistics. The reverse logistics which has been presented in the problem includes both closed-loop and open-loop modes. Therefore the recovered products of the network can be either used in the production centers of the supply chain or sold to the recycled material markets. We have also integrated the process of green supplier evaluation in designing the network. A multi-objective mathematical model has been developed for minimization of the total cost of the supply chain and maximization of total greenness score of purchased raw materials/components from the suppliers. The uncertainty in the demand of customers and capacity of suppliers has been dealt with using fuzzy numbers in the proposed model.

A framework based on fuzzy EDAS, fuzzy MODM and global criterion methods has been presented to evaluate suppliers and determine the greenness score of them, optimization of the mathematical model, obtain the Pareto (near-Pareto) solutions and comparison of the results.

A numerical example of a home appliance company has been utilized to describe the procedure of the proposed approach. By evaluation of suppliers with respect to green criteria in a fuzzy environment, we have incorporated the experts' opinions about suppliers into the optimal design of the network. The fuzzy EDAS method has provided us with an efficient way to determine the greenness score of suppliers. In addition, the proposed framework helps us to examine the effect of changing degree of uncertainty of the supply and demand by varying the values of α in the model. Using lower values of α, which are closer to zero, leads to network configurations associated with higher degree of uncertainty. The results of this study confirmed that the estimated Pareto (near-Pareto) front is wider in lower values of α. Moreover, because the transportation costs have been considered as dependent variables of distances between potential locations of stages, in the optimal solution of the network, minimization of distances between optimal locations has been involved by minimizing the total transportation cost. The results show that the proposed framework is efficient and feasible to solve the considered supply chain network problem and can determine optimal configurations with different weights of objective functions.

Because the supply chain network design is an NP-hard (non-deterministic polynomial-time hard) problem, the computational time of solving the model increases with the size of the problem. Therefore, it is suggested for future research to develop multi-objective metaheuristic algorithms for solving the proposed model. Also, the uncertainty of the other parameters of the model like the return rate of products can be considered in future research. Furthermore, locations of the recycled material markets and disposal sites have not been included in the model of this research which can be considered as variables in future research.

References

Alshamsi, A.; Diabat, A. 2015. A reverse logistics network design, *Journal of Manufacturing Systems* 37(Part 3): 589–598. https://doi.org/10.1016/j.jmsy.2015.02.006

Beamon, B. M. 1999. Designing the green supply chain, *Logistics information management* 12(4): 332–342. https://doi.org/10.1108/09576059910284159

Dai, Z. 2016. Multi-objective fuzzy design of closed-loop supply chain network considering risks and environmental impact, *Human and Ecological Risk Assessment: An International Journal* 22(4): 845–873. https://doi.org/10.1080/10807039.2015.1113852

Diabat, A.; Kannan, D.; Kaliyan, M.; Svetinovic, D. 2013. An optimization model for product returns using genetic algorithms and artificial immune system, *Resources, Conservation and Recycling* 74: 156–169. https://doi.org/10.1016/j.resconrec.2012.12.010

Eskandarpour, M.; Masehian, E.; Soltani, R.; Khosrojerdi, A. 2014. A reverse logistics network for recovery systems and a robust metaheuristic solution approach, *The International Journal of Advanced Manufacturing Technology* 74(9): 1393–1406. https://doi.org/10.1007/s00170-014-6045-7

Fleischmann, M.; Bloemhof-Ruwaard, J. M.; Dekker, R.; van der Laan, E.; van Nunen, J. A. E. E.; Van Wassenhove, L. N. 1997. Quantitative models for reverse logistics: a review, *European Journal of Operational Research* 103(1): 1–17. https://doi.org/10.1016/S0377-2217(97)00230-0

Gabrel, V.; Murat, C.; Remli, N. 2010. Linear programming with interval right hand sides, *International Transactions in Operational Research* 17(3): 397–408. https://doi.org/10.1111/j.1475-3995.2009.00737.x

Garg, K.; Kannan, D.; Diabat, A.; Jha, P. C. 2015. A multi-criteria optimization approach to manage environmental issues in closed loop supply chain network design, *Journal of Cleaner Production* 100: 297–314. ttps://doi.org/10.1016/j.jclepro.2015.02.075

Geyer, R.; Jackson, T. 2004. Supply loops and their constraints: the industrial ecology of recycling and reuse, *California Management Review* 46(2): 55–73. https://doi.org/10.2307/41166210

Govindan, K.; Rajendran, S.; Sarkis, J.; Murugesan, P. 2015. Multi criteria decision making approaches for green supplier evaluation and selection: a literature review, *Journal of Cleaner Production* 98: 66–83. https://doi.org/10.1016/j.jclepro.2013.06.046

Govindan, K.; Sivakumar, R. 2016. Green supplier selection and order allocation in a low-carbon paper industry: integrated multi-criteria heterogeneous decision-making and multi-objective linear programming approaches, *Annals of Operations Research* 238(1): 243–276. https://doi.org/10.1007/s10479-015-2004-4

Güleş, H. K.; Ergen, Z.; Karaboğa, K. 2013. A mixed integer linear programming model proposal for network design of a multi-phase, environmental and flexible closed loop supply chain, *Mediterranean Journal of Social Sciences* 4(10): 586–593. https://doi.org/10.5901/mjss.2013.v4n10p586

Hugos, M. H. 2010. *Essentials of supply chain management.* New York: Wiley.

Jayaraman, V.; Patterson, R. A.; Rolland, E. 2003. The design of reverse distribution networks: models and solution procedures, *European Journal of Operational Research* 150(1): 128–149. https://doi.org/10.1016/S0377-2217(02)00497-6

Jindal, A.; Sangwan, K. S. 2014. Closed loop supply chain network design and optimisation using fuzzy mixed integer linear programming model, *International Journal of Production Research* 52(14): 4156–4173. https://doi.org/10.1080/00207543.2013.861948

Kahraman, C.; Keshavarz Ghorabaee, M.; Zavadskas, E. K.; Cevik Onar, S.; Yazdani, M.; Oztaysi, B. 2017. Intuitionistic fuzzy EDAS method: an application to solid waste disposal site selection, *Journal of Environmental Engineering and Landscape Management* 25(1): 1–12. https://doi.org/10.3846/16486897.2017.1281139

Kalaitzidou, M. A.; Longinidis, P.; Georgiadis, M. C. 2015. Optimal design of closed-loop supply chain networks with multifunctional nodes, *Computers & Chemical Engineering* 80: 73–91. https://doi.org/10.1016/j.compchemeng.2015.05.009

Kannan, D.; Khodaverdi, R.; Olfat, L.; Jafarian, A.; Diabat, A. 2013. Integrated fuzzy multi criteria decision making method and multi-objective programming approach for supplier selection and order allocation in a green supply chain, *Journal of Cleaner Production* 47: 355–367. https://doi.org/10.1016/j.jclepro.2013.02.010

Keshavarz Ghorabaee, M.; Zavadskas, E. K.; Amiri, M.; Esmaeili, A. 2016a. Multi-criteria evaluation of green suppliers using an extended WASPAS method with interval type-2 fuzzy sets, *Journal of Cleaner Production* 137: 213–229. https://doi.org/10.1016/j.jclepro.2016.07.031

Keshavarz Ghorabaee, M.; Zavadskas, E. K.; Amiri, M.; Turskis, Z. 2016b. Extended EDAS method for fuzzy multi-criteria decision-making: an application to supplier selection, *International Journal of Computers Communications & Control* 11(3): 358–371. h https://doi.org/10.15837/ijccc.2016.3.2557

Keshavarz Ghorabaee, M.; Zavadskas, E. K.; Olfat, L.; Turskis, Z. 2015. Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS), *Informatica* 26(3): 435–451. https://doi.org/10.15388/informatica.2015.57

Khaksar, E.; Abbasnejad, T.; Esmaeili, A.; Tamošaitienė, J. 2016. The effect of green supply chain management practices on environmental performance and competitive advantage: a case study of the cement industry, *Technological and Economic Development of Economy* 22(2): 293–308. https://doi.org/10.3846/20294913.2015.1065521

Krikke, H.; van Nunen, J. A. E. E.; Zuidwijk, R.; Kuik, R., 2005. E-business and circular supply chains: increased business opportunities by IT-based customer oriented return-flow management, in B. Fleischmann, A. Klose (Eds.). *Distribution logistics: advanced solutions to practical problems.* Berlin, Heidelberg: Springer Berlin Heidelberg, 221–239. https://doi.org/10.1007/978-3-642-17020-1_12

Liao, C.-N.; Fu, Y.-K.; Wu, L.-C. 2016. Integrated FAHP, ARAS-F and MSGP methods for green supplier evaluation and selection, *Technological and Economic Development of Economy* 22(5): 651–669. https://doi.org/10.3846/20294913.2015.1072750

Ma, R.; Yao, L.; Jin, M.; Ren, P.; Lv, Z. 2016. Robust environmental closed-loop supply chain design under uncertainty, *Chaos, Solitons & Fractals* 89: 195–202. https://doi.org/10.1016/j.chaos.2015.10.028

Mirakhorli, A. 2014. Fuzzy multi-objective optimization for closed loop logistics network design in bread-producing industries, *The International Journal of Advanced Manufacturing Technology* 70(1): 349–362. https://doi.org/10.1007/s00170-013-5264-7

Moghaddam, K. S. 2015. Supplier selection and order allocation in closed-loop supply chain systems using hybrid Monte Carlo simulation and goal programming, *International Journal of Production Research* 53(20): 6320–6338. https://doi.org/10.1080/00207543.2015.1054452

Mohajeri, A.; Fallah, M. 2016. A carbon footprint-based closed-loop supply chain model under uncertainty with risk analysis: a case study, *Transportation Research Part D: Transport and Environment* 48: 425–450. https://doi.org/10.1016/j.trd.2015.09.001

Moncayo–Martínez, L. A.; Mastrocinque, E. 2016. A multi-objective intelligent water drop algorithm to minimise cost of goods sold and time to market in logistics networks, *Expert Systems with Applications* 64: 455–466. https://doi.org/10.1016/j.eswa.2016.08.003

Nielsen, I.; Banaeian, N.; Golińska, P.; Mobli, H.; Omid, M., 2014. Green supplier selection criteria: from a literature review to a flexible framework for determination of suitable criteria, in P. Golinska (Ed.). *Logistics operations, supply chain management and sustainability.* Springer International Publishing, 79–99. https://doi.org/10.1007/978-3-319-07287-6_6

Pati, R. K.; Vrat, P.; Kumar, P. 2008. A goal programming model for paper recycling system, *Omega* 36(3): 405–417. https://doi.org/10.1016/j.omega.2006.04.014

Pazhani, S.; Ramkumar, N.; Narendran, T. T.; Ganesh, K. 2013. A bi-objective network design model for multi-period, multi-product closed-loop supply chain, *Journal of Industrial and Production Engineering* 30(4): 264–280. https://doi.org/10.1080/21681015.2013.830648

Peng, X.; Liu, C. 2017. Algorithms for neutrosophic soft decision making based on EDAS, new similarity measure and level soft set, *Journal of Intelligent & Fuzzy Systems* 32: 955–968. https://doi.org/10.3233/JIFS-161548

Pishvaee, M. S.; Kianfar, K.; Karimi, B. 2010. Reverse logistics network design using simulated annealing, *The International Journal of Advanced Manufacturing Technology* 47(1): 269–281. https://doi.org/10.1007/s00170-009-2194-5

Qin, Z.; Ji, X. 2010. Logistics network design for product recovery in fuzzy environment, *European Journal of Operational Research* 202(2): 479–490. https://doi.org/10.1016/j.ejor.2009.05.036

Ramezani, M.; Kimiagari, A. M.; Karimi, B.; Hejazi, T. H. 2014. Closed-loop supply chain network design under a fuzzy environment, *Knowledge-Based Systems* 59: 108–120. https://doi.org/10.1016/j.knosys.2014.01.016

Shahryari Nia, A.; Olfat, L.; Esmaeili, A.; Rostamzadeh, R.; Antuchevičienė, J. 2016. Using fuzzy Choquet Integral operator for supplier selection with environmental considerations, *Journal of Business Economics and Management* 17(4): 503–526. https://doi.org/10.3846/16111699.2016.1194315

Soleimani, H.; Govindan, K. 2014. Reverse logistics network design and planning utilizing conditional value at risk, *European Journal of Operational Research* 237(2): 487–497. https://doi.org/10.1016/j.ejor.2014.02.030

Subulan, K.; Baykasoğlu, A.; Özsoydan, F. B.; Taşan, A. S.; Selim, H. 2015. A case-oriented approach to a lead/acid battery closed-loop supply chain network design under risk and uncertainty, *Journal of Manufacturing Systems* 37(Part 1): 340–361. https://doi.org/10.1016/j.jmsy.2014.07.013

Talaei, M.; Farhang Moghaddam, B.; Pishvaee, M. S.; Bozorgi-Amiri, A.; Gholamnejad, S. 2016. A robust fuzzy optimization model for carbon-efficient closed-loop supply chain network design problem: a numerical illustration in electronics industry, *Journal of Cleaner Production* 113: 662–673. https://doi.org/10.1016/j.jclepro.2015.10.074

Tavakkoli-Moghaddam, R.; Sadri, S.; Pourmohammad-Zia, N.; Mohammadi, M. 2015. A hybrid fuzzy approach for the closed-loop supply chain network design under uncertainty, *Journal of Intelligent & Fuzzy Systems* 28(6): 2811–2826. https://doi.org/10.3233/IFS-151561

Turskis, Z.; Juodagalvienė, B. 2016. A novel hybrid multi-criteria decision-making model to assess a stairs shape for dwelling houses, *Journal of Civil Engineering and Management* 22(8): 1078–1087. https://doi.org/10.3846/13923730.2016.1259179

Vahdani, B.; Mohammadi, M. 2015. A bi-objective interval-stochastic robust optimization model for designing closed loop supply chain network with multi-priority queuing system, *International Journal of Production Economics* 170(Part A): 67–87. https://doi.org/10.1016/j.ijpe.2015.08.020

Yu, H.; Solvang, W. D. 2016. A general reverse logistics network design model for product reuse and recycling with environmental considerations, *The International Journal of Advanced Manufacturing Technology* 87(9): 2693–2711. https://doi.org/10.1007/s00170-016-8612-6

Zandieh, M.; Chensebli, A. 2016. Reverse logistics network design: a water flow-like algorithm approach, *OPSEARCH* 53(4): 667–692. https://doi.org/10.1007/s12597-016-0250-0

Zeballos, L. J.; Méndez, C. A.; Barbosa-Povoa, A. P.; Novais, A. Q. 2014. Multi-period design and planning of closed-loop supply chains with uncertain supply and demand, *Computers & Chemical Engineering* 66: 151–164. https://doi.org/10.1016/j.compchemeng.2014.02.027

Zimmermann, H. J. 1978. Fuzzy programming and linear programming with several objective functions, *Fuzzy Sets and Systems* 1(1): 45–55. https://doi.org/10.1016/0165-0114(78)90031-3

Mehdi KESHAVARZ GHORABAEE received the B.S. degree in electrical engineering from University of Guilan, Rasht, Iran in 2010 and the M.S. degree in production management from Allameh Tabataba'i University, Tehran, Iran in 2013. He is currently working toward the PhD degree in Operations Research at Allameh Tabataba'i University. He has published some papers in leading international journals such as *Robotics and Computer-Integrated Manufacturing, The International Journal of Advanced Manufacturing Technology, Journal of Cleaner Production* and *Applied Mathematical Modelling*. His research interests include multi-criteria decision making (MCDM), multi-objective evolutionary algorithms, genetic algorithm, fuzzy MCDM, inventory control, supply chain management, scheduling and reliability engineering.

Maghsoud AMIRI is Professor at the Department of Industrial Management of Allameh Tabataba'i University, Tehran, Iran. He received PhD degree in industrial engineering from Sharif University of Technology, Tehran, Iran. He has published many papers in leading international journals. His research interests include multi-criteria decision-making (MCDM), data envelopment analysis (DEA), design of experiments (DOE), response surface methodology (RSM), fuzzy MCDM, inventory control, supply chain management, simulation and reliability engineering.

Laya OLFAT is an Associate Professor with the Department of Industrial Management of Allameh Tabataba'i University, Tehran, Iran. She received the M.S. degree in industrial engineering from the University of Birmingham, UK and the PhD degree in management (Operations Research) from the University of Tehran, Iran. She is currently Dean of the Management and Accounting Faculty of Allame Tabataba'i University. Her research interests include supply chain management (SCM), production planning, inventory control, scheduling, green SCM, optimization, multi-criteria decision making, project management and manufacturing systems.

S. M. Ali KHATAMI FIROUZABADI is an Associate Professor with the Department of Industrial Management of Allameh Tabataba'i University, Tehran, Iran. He received his PhD degree in industrial engineering from University of Leeds, UK in 2005. His main research interests are operations research, mathematical programming, production planning, inventory control, multi-criteria decision-making (MCDM) and fuzzy MCDM.