Research Article

An integrated open-loop supply chain network configuration model with sustainable supplier selection: fuzzy multi-objective approach

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Abstract
Supply chain management is an essential part of most companies to reduce costs and increase the profit for a competitive business environment. The success of companies is directly connected to the performance of the supply chain. The sustainability of businesses broadly depends on the purchasing decision, and the process becomes more complex with resource limitations. In addition, relationships with suppliers are considered for optimal production and risk minimization in the supply chain network. This research aims to design and optimize a multi-echelon, multi-period, and multi-objective open-loop supply chain (OLSC) network design. The objectives are deemed to be the total costs, the minimization of environmental costs, and the maximization of the importance level of suppliers. Furthermore, a fuzzy approach based on interval type-2 fuzzy sets is designed to evaluate the supplier performance according to sustainable qualitative criteria. After determination of the weights of criteria and evaluation of suppliers by interval type-2 fuzzy numbers, the final score of suppliers is calculated based on the weights of criteria and evaluation scores. Three fuzzy programming approaches are utilized to solve the developed OLSC model. A numerical example is provided to validate the model and effectiveness of the proposed evaluation procedure. The results demonstrate the feasibility of the proposed evaluation procedure and the achievement of a compromise in the developed model.

Keywords Interval type-2 fuzzy sets · Multi-objective optimization · Open-loop supply chain · Sustainable supplier selection

Mathematical Subject Classification 03E72 · 90B10 · 90B50 · 90C29 · 90C70

JEL Classification C44 · C61 · D81 · R41

1 Introduction

In recent years, interest in reverse logistics and closed-loop supply chains (CLSCs) has increased significantly by researchers and practitioners [1]. If end-of-life (EOL) products are collected from the end-use point through applying recovery processes to regain value, returning to the first production point and re-launching them to the market is defined as CLSC [2]. However, in an open-loop supply chain (OLSC) network, the products are not returned to the original manufacturers. Generally, the products or materials that have been processed under various operations are recovered by the parties who wish to reuse them [3]. Due to increased environmental awareness and legal requirements, both the public and private sectors are required to consider environmental issues in managing their operations and supply chains [4, 5].

CLSC network design is one of the most important long-term strategic decisions for businesses due to the activities of increasing globalization and the change in technology

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levels [6]. In recent years, the importance of reverse logistics, including reuse, repair, refurbishing, remanufacturing, and recycling of EOL, has been highlighted by researchers and businesses due to the changes that have taken place and the economic benefits of used products [7]. A comprehensive plan for collecting EOL is required if minimal environmental damage is desired [8]. Therefore, the CLSC network design can be the best solution for businesses that want to collect the EOL and add them to the re-evaluation process [9].

In supply chain management, many businesses have resorted to outsourcing and supplier selection in recent years because they seem more profitable and want to focus on their strategic activities [2]. Choosing the right supplier is a key issue in SCM, but it also has a major impact on the strategic and operational performance of a firm [10]. Considering that more than 50% of the production cost of enterprises consists of purchasing activities [11, 12], it is more coherent for businesses to purchase from many suppliers instead of linking them to the capacity and flexibility of a single supplier. In addition, suppliers should be evaluated by taking into consideration the cost of purchase as well as criteria such as late delivery, energy consumption and respect for human rights. For this reason, many organizations have recently started to incorporate environmental, social, and economic aspects of sustainability into their supplier selection processes [13].

Integrating sustainability into this selection process rather than the classical supplier selection has been the focus for businesses that provide a more competitive edge in global markets [14, 15]. Choosing the most appropriate one among the suppliers with different levels of capability and potential is a very demanding task that requires various criteria and different solution approaches [16]. In this context, multi-criteria decision-making (MCDM) methods can help solve the problem of supplier selection and find the optimal product quantity [17]. In the real world, linguistic terms may need to be used to evaluate alternatives and criteria, and words contain uncertainty [18]. To deal with linguistic uncertainty, it has been shown that deciding interval type-2 fuzzy sets (IT2FSs) are more effective than traditional decision-making tools [19].

Based on the discussions above, this paper presents a multi-objective model for OLSC network design and sustainable supplier selection problem. A new approach based on IT2FSs is proposed to find the best suppliers from a sustainability perspective. In the proposed approach, uncertain judgments of multiple decision-makers are captured by the IT2Fs; the importance levels of the evaluation criteria are determined by the interval type-2 analytic hierarchy process (AHP) method to take into account various and conflicting criteria. An integrated OLSC model is developed in a multi-period environment to address the importance of suppliers and to determine the number of products to be processed in each echelon. Finally, based on the opinions of experts, three fuzzy approaches are utilized in this paper to solve the multi-objective optimization problem in hand.

The rest of the study is organized as follows: In the second chapter, the related literature is reviewed, and the research is described. In the third chapter, the definition and formulation of the developed mathematical model are presented. The fourth section describes the proposed assessment procedure. The fifth section includes the analysis and interpretation of the numerical results obtained from the solution of the model. In the last section, the results of the article are presented, and future research suggestions are presented.

2 Literature review

Although CLSC and reverse logistics network designs have been a prevalent research topic of academic interest in recent years, OLSC network designs have not attracted much attention from researchers and practitioners. Gou et al. [20] presented a stochastic inventory model for an open-loop reverse supply chain to find the optimal economic delivery batch size for collection points. Ene and Öztürk [21] developed an open-loop reverse supply chain network design with a mixed-integer linear programming model. Özceylan [3] handled the CLSC and OLSC network simultaneously by developing a mixed-integer linear programming model. The model simulated with randomly using data and results showed that cost savings may be achieved by solving the integrated objective function instead of solving the individual objective functions. Kalverkamp and Young [22] tested three research questions by using three case examples and indicated that OLSCs may offer sustainable advantages to actors in supply chains.

To illustrate the difference of this study from others, a summary of the relevant literature is presented in Table 1 where the features of the proposed problem are presented in the last row. According to Table 1, although most of the studies have been discussed in economic and environmental objectives in CLSC objectives, the assessment of suppliers of OLSC is still in need of further research. Most publications have ignored the problem of supplier selection at the same time with the OLSC network design and

Table 1 Review of some articles

	Network type		Objectives			Solution method		Uncertain approach	Number of periods		Application field	
	CLSC	OLSC	Economic	Environmental	Assessment of suppliers	MCDM	Optimization technique		Single	Multi	Hypothetical	Case study
Gou et al. [20]		•	•				•	Randomness	•		•	
Ene and Öztürk [21]		•	•				•			•	•	
Özceylan [3]	•	•	•				•	Type-1 fuzzy sets		•	•	
Zandkarimkhani et al. [22]		•	•				•		•			•
Amin and Zhang [24]	•		•	•	•	•	•	Type-1 fuzzy sets	•		•	
Moghaddam [25]	•		•	•	•	•	•	Type-1 fuzzy sets		•	•	
Ghayebloo et al. [2]	•		•	•			•		•		•	
Shakourloo et al. [1]	•		•	•		•	•	Type-1 fuzzy sets	•		•	
Shafiei Kisomi et al. [26]	•		•				•	Type-1 fuzzy sets	•		•	
Soleimani et al. [27]	•		•				•			•	•	
Jahangoshai Rezaee et al. [28]	•		•	•			•		•		•	
Govindan et al. [29]	•		•	•	•	•	•			•		•
Mota et al. [30]			•	•			•			•		•
Sadeghi Rad and Nahavandi [31]	•		•	•			•			•	•	
Ebrahimi [32]	•		•	•			•		•			•
Alikhani et al. [34]			•	•		•						•
Ahmadi and Amin [25]	•		•		•	•	•	Type-1 fuzzy sets		•		•
Papen and Amin [24]	•		•				•		•			•
Darbari et al. [35]	•		•	•		•	•		•			•
Taleizadeh et al. [9]	•		•	•			•			•		•
Hamdan and Cheaitou [4]			•		•	•	•	Type-1 fuzzy sets		•	•	
Ghahremani-Nahr et al. [23]	•		•				•			•	•	
This paper		•	•	•	•	•	•	Type-2 fuzzy sets		•	•	

with the identification of decision variables in a single period. Moreover, a limited number of studies have been performed with fuzzy sets in the OLSC network design, but the interval type-2 fuzzy sets have not been used yet. Thereby, the contributions of our study which aim to fill these gaps are explained in the following sections.

3 Problem definition

The structure of the OLSC discussed in this study is represented in Fig. 1. In the model, the forward supply chain consists of four levels: suppliers (*i*), plants (*j*), distribution centers (*k*), and customers (*l*). Similarly, the reverse supply chain includes six levels: collection centers (*m*), refurbishing centers (*n*), recycling centers (*r*), remanufacturing centers (*q*), secondary markets (*s*), and disposal.

Forward flow begins with suppliers who are responsible for the procurement of parts of the plants for each period, parts are transformed to final products in the plants, and the products are sent to the customers through distribution centers to meet the fixed customer demands. The flow of the final products does not end after the products are delivered to the customers. The reverse flow starts with the collection of the used products by the customers at a certain rate after a period of usage. In the next step, used products are shipped to collection/inspections centers. Used products are inspected at collection centers and transferred to refurbishing, recycling, remanufacturing, and disposal according to quality classification. The high quality of the products processed in these facilities can be sold as a second-hand product at a cheaper price in the secondary markets.

3.1 Model formulation

The OLSC network design considered in this study is a multi-echelon network consisting of ten layers: suppliers, plants, distribution centers, customers, collection centers, refurbishing centers, recycling centers, remanufacturing centers, secondary markets, and disposal. The indices, parameters, decision variables, objective functions, and constraints used in the formulation to solve the problem are presented below:

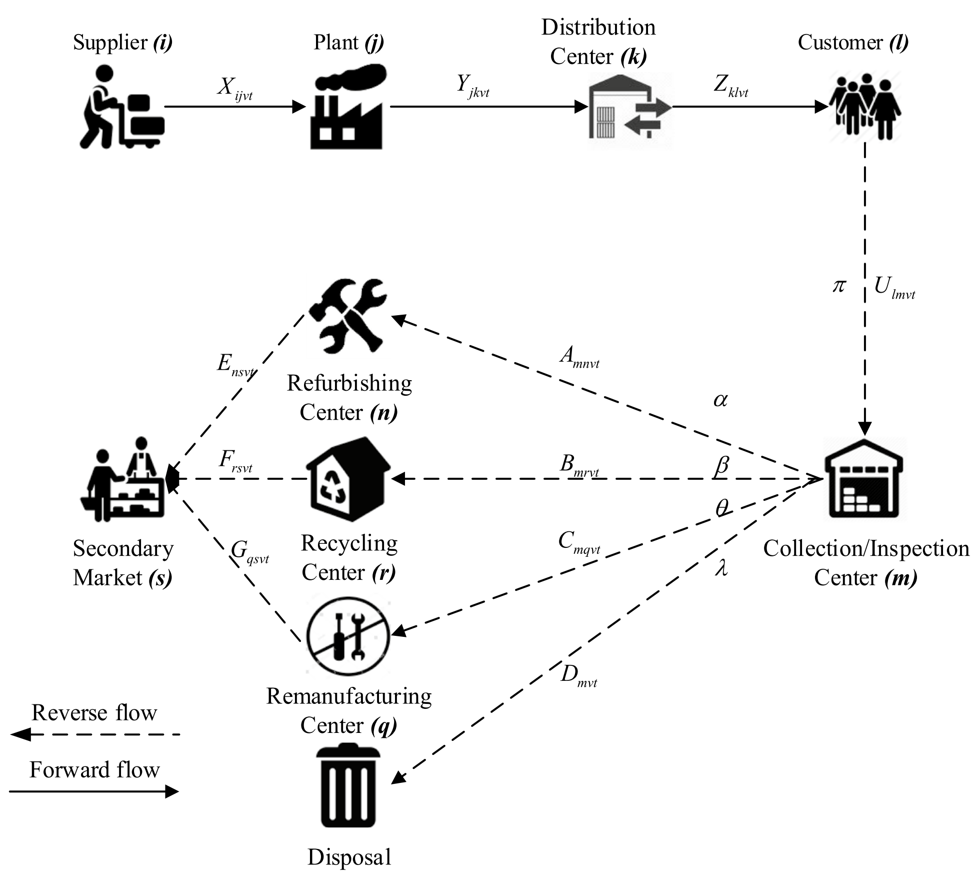

Fig. 1 General structure of the OLSC network

3.2 Indices

Symbol	Description
i	Set of suppliers, $i = 1, 2 \ldots I$
j	Set of plants, $j = 1, 2 \ldots J$
k	Set of distribution centers, $k = 1, 2 \ldots K$
l	Set of customers, $l = 1, 2 \ldots L$
m	Set of collection centers, $m = 1, 2 \ldots M$
n	Set of refurbishing centers, $n = 1, 2 \ldots N$
r	Set of recycling centers, $r = 1, 2 \ldots R$
q	Set of remanufacturing centers, $q = 1, 2 \ldots Q$
s	Set of secondary markets, $s = 1, 2 \ldots S$
v	Set of type of vehicles, $v = 1, 2 \ldots V$
t	Set of periods, $t = 1, 2 \ldots T$

3.3 Parameters

Symbol	Description
$d_{\mu\sigma}$	Distance from origin μ to destination σ; $\mu, \sigma \in \{I, J, K, L, M, N, R, Q, S\}$ (km)
c_v	Unit transportation cost by vehicle v (\$/ton km)
$capt_{\vartheta t}$	Capacity of facility ϑ in period t; $\vartheta \in \{I, J, K, M, N, R, Q\}$ (ton)
tal_{lt}	Demand of customer l in period t (ton)
smf_τ	Fixed cost of facility τ; $\tau \in \{J, M, N, R, Q\}$ (\$)
$samt_i, um_j, top_{lm}, yen_n, grm_r, yum_q, dc$	Unit purchasing, production, collection, refurbishing, recycling, remanufacturing, disposal cost (\$/ton)
$tasyen_n, tasgr_r, tasyu_q$	Unit cost saving at refurbishing, recycling, remanufacturing center (\$/ton)
cep_j	The amount of CO_2 emission caused by the production of one ton of product at plant j (gr/ton)
C_{CO_2}	Unit cost of CO_2 emission (\$/gr)
cet_v	Amount of CO_2 emission of one-ton load transported by vehicle v through one kilometer (gr/ton km)
u_v	The maximum capacity of vehicle v (ton)
$\pi, \alpha, \beta, \theta, \lambda$	Percentage of products collected by centers (%)
w_i	Level of importance weight of supplier i for procured parts

3.4 Decision variables

Symbol	Description
$X_{ijvt}, Y_{jkvt}, Z_{klvt}, U_{lmvt}, A_{mnvt}, B_{mrvt}, C_{mqvt}, D_{mvt}, E_{nsvt}, F_{rsvt}, G_{qsvt}$	Quantity of parts/products between pair of nodes by vehicle v at time period t (ton)
$XX_{ijvt}, YY_{jkvt}, ZZ_{klvt}, UU_{lmvt}, AA_{mnvt}, BB_{mrvt}, CC_{mqvt}, DD_{mvt}, EE_{nsvt}, FF_{rsvt}, GG_{qsvt}$	If parts are shipped between pair of nodes by vehicle v at time period t 1; otherwise, 0
$XINT_{ijvt}, YINT_{jkvt}, ZINT_{klvt}, UINT_{lmvt}, AINT_{mnvt}, BINT_{nvt}, CINT_{nrvt}, DINT_{rkvt}, EINT_{nsvt}, FINT_{rsvt}, GINT_{qsvt}$	Number of tours between pair of nodes by vehicle v at time period t
$OP_j, OC_m, OYEN_n, OGR_r, OYU_q$	If facility is opened at time period t, 1; otherwise, 0

3.5 Objective functions

The first objective function specifies the minimization of economic cost:

$$Min\, Z_1 = TC + POC + FOC \tag{1}$$

$$\begin{aligned} TC &= \sum_i \sum_j \sum_v \sum_t d_{ij} \cdot X_{ijvt} + \sum_j \sum_k \sum_v \sum_t d_{jk} \cdot Y_{jkvt} + \sum_k \sum_l \sum_v \sum_t d_{kl} \cdot Z_{klvt} + \sum_l \sum_m \sum_v \sum_t d_{lm} \cdot U_{lmvt} \\ &+ \sum_m \sum_n \sum_v \sum_t d_{mn} \cdot A_{mnvt} + \sum_m \sum_r \sum_v \sum_t d_{mr} \cdot B_{mrvt} + \sum_m \sum_q \sum_v \sum_t d_{mq} \cdot C_{mqvt} + \sum_n \sum_v \sum_t D_{mvt} \cdot d_m \\ &+ \sum_n \sum_s \sum_v \sum_t d_{ns} \cdot E_{nsvt} + \sum_r \sum_s \sum_v \sum_t d_{rs} \cdot F_{rsvt} + \sum_q \sum_s \sum_v \sum_t d_{qs} \cdot G_{qsvt} \end{aligned} \tag{2}$$

$$
\begin{aligned}
POC = & \sum_i \sum_j \sum_v \sum_t samt_i \cdot X_{ijvt} + \sum_j \sum_k \sum_v \sum_t um_j \cdot Y_{jkvt} + \sum_l \sum_m \sum_v \sum_t top_{lm} \cdot U_{lmvt} \\
& + \sum_m \sum_n \sum_v \sum_t yen_n \cdot A_{mnvt} + \sum_m \sum_r \sum_v \sum_t grm_r \cdot B_{mrvt} + \sum_m \sum_q \sum_v \sum_t yum_q \cdot C_{mqvt} \\
& + \sum_m \sum_v \sum_t dc \cdot D_{mvt} - \sum_n \sum_s \sum_v \sum_t tasm_r \cdot E_{nsvt} - \sum_r \sum_s \sum_v \sum_t tasgr_r \cdot F_{rsvt} - \sum_q \sum_s \sum_v \sum_t tasyu_q \cdot G_{qsvt}
\end{aligned} \tag{3}
$$

$$
\begin{aligned}
FOC = & \sum_j smf_j \cdot OP_j + \sum_m smto_m \cdot OC_m + \sum_n smyen_n \cdot OYEN_n + \sum_r smgr_r \cdot OGR_r \\
& + \sum_q smyu_q \cdot OYU_q.
\end{aligned} \tag{4}
$$

The first objective function has three components. The transportation cost between the facilities is the first component; the purchasing, production, collection, refurbishing, disposal costs, and cost saving owed to refurbished products are the second component; and the fixed-opening cost of facilities is the third component.

The second objective function (5) of the developed OLSC model minimizes the environmental impact. The generated CO_2 emission costs caused by transportation and manufacturing can be calculated as follows:

$$
\begin{aligned}
Min\, Z_2 = & C_{CO_2} \cdot \Bigg[cet_v \cdot \\
& \Bigg(\sum_i \sum_j \sum_v \sum_t d_{ij} \cdot X_{ijvt} + \sum_j \sum_k \sum_v \sum_t d_{jk} \cdot Y_{jkvt} + \sum_k \sum_l \sum_v \sum_t d_{kl} \cdot Z_{klvt} + \sum_l \sum_m \sum_v \sum_t d_{lm} \cdot U_{lmvt} \\
& + \sum_m \sum_n \sum_v \sum_t d_{mn} \cdot A_{mnvt} + \sum_m \sum_r \sum_v \sum_t d_{mr} \cdot B_{mrvt} + \sum_m \sum_q \sum_v \sum_t d_{mq} \cdot C_{mqvt} + \sum_n \sum_v \sum_t D_{mvt} \cdot d_m \\
& + \sum_n \sum_s \sum_v \sum_t d_{ns} \cdot E_{nsvt} + \sum_r \sum_s \sum_v \sum_t d_{rs} \cdot F_{rsvt} + \sum_q \sum_s \sum_v \sum_t d_{qs} \cdot G_{qsvt} \Bigg) \\
& + \sum_j \sum_k \sum_v \sum_t cep_j \cdot Y_{jkvt} \Bigg].
\end{aligned} \tag{5}
$$

The third objective function (6) expresses the maximum importance level of suppliers through the developed assessment approach:

$$
MaxZ_3 = \sum_i \sum_j \sum_v \sum_t w_i \cdot X_{ijvt}. \tag{6}
$$

3.6 Constraints

Constrains involved in the developed model are presented as follows:

$$
\sum_j \sum_v X_{ijvt} \le capt_{it} \quad \forall_{i,t} \tag{7}
$$

$$
\sum_k \sum_v Y_{jkvt} \le capf_{jt} \cdot OP_j \quad \forall_{j,t} \tag{8}
$$

$$
\sum_l \sum_v Z_{klvt} \le capdm_{kt} \quad \forall_{k,t} \tag{9}
$$

$$
\sum_l \sum_v U_{lmvt} \le kapto_{mt} \cdot OC_m \quad \forall_{m,t} \tag{10}
$$

$$
\sum_m \sum_v A_{mnvt} \le capym_{nt} \cdot OYEN_n \quad \forall_{n,t} \tag{11}
$$

$$
\sum_m \sum_v B_{mrvt} \le capgr_{rt} \cdot OGR_r \quad \forall_{r,t} \tag{12}
$$

$$
\sum_m \sum_v C_{mqvt} \le capyu_{qt} \cdot OYU_q \quad \forall_{q,t} \tag{13}
$$

$$\sum_{k}\sum_{v} Z_{klvt} \geq tal_{lt} \quad \forall_{l,t} \tag{14}$$

$$X_{ij1t} - M \cdot XX_{ij1t} \leq 0 \quad \forall_{i,j,t} \tag{15}$$

$$X_{ij1t} - M \cdot XX_{ij1t} \geq 0.001 - M \quad \forall_{i,j,t} \tag{16}$$

$$X_{ij2t} - M \cdot XX_{ij2t} \leq 0 \quad \forall_{i,j,t} \tag{17}$$

$$X_{ij2t} - M \cdot XX_{ij2t} \geq 10 - M \quad \forall_{i,j,t} \tag{18}$$

$$X_{ij3t} - M \cdot XX_{ij3t} \leq 0 \quad \forall_{i,j,t} \tag{19}$$

$$X_{ij3t} - M \cdot XX_{ij3t} \geq 20 - M \quad \forall_{i,j,t} \tag{20}$$

$$Y_{jk1t} - M \cdot YY_{jk1t} \leq 0 \quad \forall_{j,k,t} \tag{21}$$

$$Y_{jk1t} - M \cdot YY_{jk1t} \geq 0.001 - M \quad \forall_{j,k,t} \tag{22}$$

$$Y_{jk2t} - M \cdot YY_{jk2t} \leq 0 \quad \forall_{j,k,t} \tag{23}$$

$$Y_{jk2t} - M \cdot YY_{jk2t} \geq 10 - M \quad \forall_{j,k,t} \tag{24}$$

$$Y_{jk3t} - M \cdot YY_{jk3t} \leq 0 \quad \forall_{j,k,t} \tag{25}$$

$$Y_{jk3t} - M \cdot YY_{jk3t} \geq 20 - M \quad \forall_{j,k,t} \tag{26}$$

$$Z_{kl1t} - M \cdot ZZ_{kl1t} \leq 0 \quad \forall_{k,l,t} \tag{27}$$

$$Z_{kl1t} - M \cdot ZZ_{kl1t} \geq 0.001 - M \quad \forall_{k,l,t} \tag{28}$$

$$Z_{kl2t} - M \cdot ZZ_{kl2t} \leq 0 \quad \forall_{k,l,t} \tag{29}$$

$$Z_{kl2t} - M \cdot ZZ_{kl2t} \geq 10 - M \quad \forall_{k,l,t} \tag{30}$$

$$Z_{kl3t} - M \cdot ZZ_{kl3t} \leq 0 \quad \forall_{k,l,t} \tag{31}$$

$$Z_{kl3t} - M \cdot ZZ_{kl3t} \geq 20 - M \quad \forall_{k,l,t} \tag{32}$$

$$U_{lm1t} - M \cdot UU_{lm1t} \leq 0 \quad \forall_{l,m,t} \tag{33}$$

$$U_{lm1t} - M \cdot UU_{lm1t} \geq 0.001 - M \quad \forall_{l,m,t} \tag{34}$$

$$U_{lm2t} - M \cdot UU_{lm2t} \leq 0 \quad \forall_{l,m,t} \tag{35}$$

$$U_{lm2t} - M \cdot UU_{lm2t} \geq 10 - M \quad \forall_{l,m,t} \tag{36}$$

$$U_{lm3t} - M \cdot UU_{lm3t} \leq 0 \quad \forall_{l,m,t} \tag{37}$$

$$U_{lm3t} - M \cdot UU_{lm3t} \geq 20 - M \quad \forall_{l,m,t} \tag{38}$$

$$A_{mn1t} - M \cdot AA_{mn1t} \leq 0 \quad \forall_{m,n,t} \tag{39}$$

$$A_{mn1t} - M \cdot AA_{mn1t} \geq 0.001 - M \quad \forall_{m,n,t} \tag{40}$$

$$A_{mn2t} - M \cdot AA_{mn2t} \leq 0 \quad \forall_{m,n,t} \tag{41}$$

$$A_{mn2t} - M \cdot AA_{mn2t} \geq 10 - M \quad \forall_{m,n,t} \tag{42}$$

$$A_{mn3t} - M \cdot AA_{mn3t} \leq 0 \quad \forall_{m,n,t} \tag{43}$$

$$A_{mn3t} - M \cdot AA_{mn3t} \geq 20 - M \quad \forall_{m,n,t} \tag{44}$$

$$B_{mr1t} - M \cdot BB_{mr1t} \leq 0 \quad \forall_{m,r,t} \tag{45}$$

$$B_{mr1t} - M \cdot BB_{mr1t} \geq 0.001 - M \quad \forall_{m,r,t} \tag{46}$$

$$B_{mr2t} - M \cdot BB_{mr2t} \leq 0 \quad \forall_{m,r,t} \tag{47}$$

$$B_{mr2t} - M \cdot BB_{mr2t} \geq 10 - M \quad \forall_{m,r,t} \tag{48}$$

$$B_{mr3t} - M \cdot BB_{mr3t} \leq 0 \quad \forall_{m,r,t} \tag{49}$$

$$B_{mr3t} - M \cdot BB_{mr3t} \geq 20 - M \quad \forall_{m,r,t} \tag{50}$$

$$C_{mq1t} - M \cdot CC_{mq1t} \leq 0 \quad \forall_{m,q,t} \tag{51}$$

$$C_{mq1t} - M \cdot CC_{mq1t} \geq 0.001 - M \quad \forall_{m,q,t} \tag{52}$$

$$C_{mq2t} - M \cdot C_{mq2t} \leq 0 \quad \forall_{m,q,t} \tag{53}$$

$$C_{mq2t} - M \cdot CC_{mq2t} \geq 10 - M \quad \forall_{m,q,t} \tag{54}$$

$$C_{mq3t} - M \cdot CC_{mq3t} \leq 0 \quad \forall_{m,q,t} \tag{55}$$

$$C_{mq3t} - M \cdot CC_{mq3t} \geq 20 - M \quad \forall_{m,q,t} \tag{56}$$

$$D_{m1t} - M \cdot DD_{m1t} \leq 0 \quad \forall_{m,t} \tag{57}$$

$$D_{m1t} - M \cdot DD_{m1t} \geq 0.001 - M \quad \forall_{m,t} \tag{58}$$

$$D_{m2t} - M \cdot DD_{m2t} \leq 0 \quad \forall_{m,t} \tag{59}$$

$$D_{m2t} - M \cdot DD_{m2t} \geq 10 - M \quad \forall_{m,t} \tag{60}$$

$$D_{m3t} - M \cdot DD_{m3t} \leq 0 \quad \forall_{m,t} \tag{61}$$

$$D_{m3t} - M \cdot DD_{m3t} \geq 20 - M \quad \forall_{m,t} \tag{62}$$

$$E_{ns1t} - M \cdot EE_{ns1t} \leq 0 \quad \forall_{n,s,t} \tag{63}$$

$$E_{ns1t} - M \cdot EE_{ns1t} \geq 0.001 - M \quad \forall_{n,s,t} \tag{64}$$

$$E_{ns2t} - M \cdot EE_{ns2t} \leq 0 \quad \forall_{n,s,t} \tag{65}$$

$$E_{ns2t} - M \cdot EE_{ns2t} \geq 10 - M \quad \forall_{n,s,t} \tag{66}$$

$$E_{ns3t} - M \cdot EE_{ns3t} \leq 0 \quad \forall_{n,s,t} \tag{67}$$

$$E_{ns3t} - M \cdot EE_{ns3t} \geq 20 - M \quad \forall_{n,s,t} \tag{68}$$

$$F_{rs1t} - M \cdot FF_{rs1t} \leq 0 \quad \forall_{r,s,t} \tag{69}$$

$$F_{rs1t} - M \cdot FF_{rs1t} \geq 0.001 - M \quad \forall_{r,s,t} \tag{70}$$

$$F_{rs2t} - M \cdot FF_{rs2t} \leq 0 \quad \forall_{r,s,t} \tag{71}$$

$$F_{rs2t} - M \cdot FF_{rs2t} \geq 10 - M \quad \forall_{r,s,t} \tag{72}$$

$$F_{rs3t} - M \cdot FF_{rs3t} \leq 0 \quad \forall_{r,s,t} \tag{73}$$

$$F_{rs3t} - M \cdot FF_{rs3t} \geq 20 - M \quad \forall_{r,s,t} \tag{74}$$

$$G_{qs1t} - M \cdot GG_{qs1t} \leq 0 \quad \forall_{q,s,t} \tag{75}$$

$$G_{qs1t} - M \cdot GG_{qs1t} \geq 0.001 - M \quad \forall_{q,s,t} \tag{76}$$

$$G_{qs2t} - M \cdot GG_{qs2t} \leq 0 \quad \forall_{q,s,t} \tag{77}$$

$$G_{qs2t} - M \cdot GG_{qs2t} \geq 10 - M \quad \forall_{q,s,t} \tag{78}$$

$$G_{qs3t} - M \cdot GG_{qs3t} \leq 0 \quad \forall_{q,s,t} \tag{79}$$

$$G_{qqs3t} - M \cdot GG_{qs3t} \geq 20 - M \quad \forall_{q,s,t} \tag{80}$$

$$XINT_{ijvt} \geq \left(X_{ijvt}/u_v\right) \quad \forall_{i,j,v,t} \tag{81}$$

$$YINT_{jkvt} \geq \left(Y_{jkvt}/u_v\right) \quad \forall_{j,k,v,t} \tag{82}$$

$$ZINT_{klvt} \geq \left(Z_{klvt}/u_v\right) \quad \forall_{k,l,v,t} \tag{83}$$

$$UINT_{lmvt} \geq \left(U_{lmvt}/u_v\right) \quad \forall_{l,m,v,t} \tag{84}$$

$$AINT_{mnvt} \geq \left(A_{mnvt}/u_v\right) \quad \forall_{m,n,v,t} \tag{85}$$

$$BINT_{mrvt} \geq \left(B_{mrvt}/u_v\right) \quad \forall_{m,r,v,t} \tag{86}$$

$$CINT_{mqvt} \geq \left(C_{mqvt}/u_v\right) \quad \forall_{m,q,v,t} \tag{87}$$

$$DINT_{mvt} \geq \left(D_{mvt}/u_v\right) \quad \forall_{m,v,t} \tag{88}$$

$$EINT_{nsvt} \geq \left(E_{nsvt}/u_v\right) \quad \forall_{n,s,v,t} \tag{89}$$

$$FINT_{rsvt} \geq \left(F_{rsvt}/u_v\right) \quad \forall_{r,s,v,t} \tag{90}$$

$$GINT_{qsvt} \geq \left(G_{qsvt}/u_v\right) \quad \forall_{q,s,v,t} \tag{91}$$

$$\sum_i \sum_v X_{ijvt} - \sum_k \sum_v Y_{jkvt} = 0 \quad \forall_{j,t} \tag{92}$$

$$\sum_j \sum_v Y_{jkvt} - \sum_l \sum_v Z_{klvt} = 0 \quad \forall_{k,t} \tag{93}$$

$$\pi \cdot \left(\sum_k \sum_v Z_{klvt} \right) - \sum_m \sum_v U_{lmv(t+1)} = 0 \quad \forall_{l,t} \tag{94}$$

$$\sum_l \sum_v U_{lmvt} - \left(\sum_n \sum_v A_{mnvt} + \sum_r \sum_v B_{mrvt} + \sum_q \sum_v C_{mqvt} + \sum_v D_{mvt} \right) = 0 \quad \forall_{m,t} \tag{95}$$

$$\alpha \cdot \sum_{l} \sum_{v} U_{lmvt} - \sum_{n} \sum_{v} A_{mnvt} = 0 \quad \forall_{m,t} \tag{96}$$

$$\beta \cdot \sum_{l} \sum_{v} U_{lmvt} - \sum_{r} \sum_{v} B_{mrvt} = 0 \quad \forall_{m,t} \tag{97}$$

$$\theta \cdot \sum_{l} \sum_{v} U_{lmvt} - \sum_{q} \sum_{v} C_{mqvt} = 0 \quad \forall_{m,t} \tag{98}$$

$$\lambda \cdot \sum_{l} \sum_{v} U_{lmvt} - \sum_{v} D_{mvt} = 0 \quad \forall_{m,t} \tag{99}$$

$$\sum_{m} \sum_{v} A_{mnvt} - \sum_{s} \sum_{v} E_{nsvt} = 0 \quad \forall_{n,t} \tag{100}$$

$$\sum_{m} \sum_{v} B_{mrvt} - \sum_{s} \sum_{v} F_{rsvt} = 0 \quad \forall_{r,t} \tag{101}$$

$$\sum_{m} \sum_{v} C_{mqvt} - \sum_{s} \sum_{v} G_{qsvt} = 0 \quad \forall_{q,t} \tag{102}$$

$$X_{ijvt}, Y_{jkvt}, Z_{klvt}, U_{lmvt}, A_{mnvt}, B_{mrvt}, C_{mqvt}, D_{mvt}, E_{nsvt}, F_{rsvt}, G_{qsvt}, \geq 0 \quad \forall_{i,j,k,l,m,n,r,q,n,s,v,t} \tag{103}$$

$$OP_j, OC_m, OYEN_n, OGR_r, OYU_q, XX_{ijvt}, YY_{jkvt}, ZZ_{klvt}, UU_{lmvt}, AA_{mnvt}, BB_{mrvt}, CC_{mqvt}, DD_{mvt}, EE_{nsvt}, FF_{rsvt}, GG_{qsvt} = \{0,1\} \quad \forall_{i,j,k,l,m,n,r,q,n,s,v,t}. \tag{104}$$

Constraints (7)–(13) are the capacity constraints on facilities that the total amount of products sent from facilities to others should be equal to or less than the capacity of these facilities for any period. Constraint (14) ensures the demand of customers. Constraints (15)–(80) are the transportation constraints that provide the minimum level of load for each type of vehicle (M being a large number). Constraints (81)–(91) evaluate the number of tours at each arc regarding vehicle types. Constraints (92)–(102) are the balance equations for facilities. Constraint (103) preserves the nonnegativity restriction, and constraint (104) enforces the binary restriction of decision variables.

4 Proposed assessment procedure for sustainable supplier selection

In this study, a group decision-making approach based on IT2FSs is utilized which combines the judgments of the decision-makers according to the selected criteria [24–26]. To evaluate suppliers, a model based on triangular and/or trapezoidal fuzzy numbers and linguistic variables was developed in those studies. In this section, a method is suggested based on the proposed methods but using interval type-2 fuzzy numbers. The proposed method consists of three basic steps: (1) Determining the criteria and linguistic variables to be used in the model; (2) calculating the relative importance of the criteria; and (3) evaluating suppliers by decision-makers and calculating the evaluation scores. The decision-makers obtained the proposed solution by considering the following five steps:

Step 1 Qualitative and quantitative criteria to be used in the evaluation phase are determined.
Step 2 The weights of the criteria are calculated.
Step 3 Determine whether the opinions of the decision-makers are consistent.
Step 4 Under each criterion, suppliers are evaluated using interval type-2 fuzzy numbers and an assessment score is calculated for suppliers.
Step 5 The final scores of the suppliers are obtained by multiplying the weights obtained in the previous steps and the evaluation points.

The complexity of real-world problems and the optimization of multiple conflicting objectives that simultaneously under certain constraints have led to the development of multi-objective linear programming models. In order to solve the proposed multi-objective model, fuzzy programming approaches, such as Zimmermann [27], the ZIM method thereafter, Torabi and Hassini [28], the TH method thereafter, and F-WAMG approach [29], are utilized in this paper.

5 Computational experiment

5.1 Numerical example

To demonstrate the validity of the developed multi-objective linear programming model in supply chain network design and the effectiveness of the proposed solution methodology, a numerical experiment is performed in this section. It is assumed that there exist four suppliers, three plants, four distribution centers, four customers, three collection centers, two refurbishing centers, two recycling centers, two remanufacturing centers, two secondary markets, and three vehicles. All parameters for the proposed OLSC network are obtained through MATLAB software using a uniform distribution, and the relevant distributions are summarized in Table 2. In addition, three-period planning is considered in the OLSC. The other parameters defined are as follows: c_v 30, 20, and 10;

Table 2 Model parameters

Parameters	Rate or distribution
d_{ij}, d_{jk}	~ Uniform (100, 300)
$d_{kl}, d_{lm}, d_{mn}, d_{mr}, d_{mq}$	~ Uniform (100, 400)
$d_m, d_{ns}, d_{rs}, d_{qs}$	~ Uniform (50, 150)
$capt_{it}, capf_{jt}, capdm_{kt}, capto_{mt}, capym_{nt}, capgr_{rt}, capyu_{qt}$	~ Uniform (500, 10,000)
tal_{lt}	~ Uniform (50, 250)
smf_j	~ Uniform (50,000, 100,000)
$smto_m$	~ Uniform (10,000, 50,000)
$smyen_n, smgr_r, smyu_q$	~ Uniform (5000, 40,000)
$samt_i$	~ Uniform (100,500)
um_j	~ Uniform (350,750)
top_{lm}	~Uniform (50,150)
yen_n, grm_r, yum_q	~ Uniform (100,250)
cep_j	~ Uniform (5000,5500)
$tasyen_n, tasgr_r, tasyu_q$	~ Uniform (250,500)

$dc = 50$; $C_{CO_2} = 0.112$; cet_v 800, 1350, and 2450; u_v 10, 20, and 30; cep_j 60,331, 85,494, and 92,896; $\pi = 0.80$; $\alpha = 0.30$; $\beta = 0.30$; $\theta = 0.30$; $\lambda = 0.10$. CPLEX 12.6, commonly used in optimization software to solve the developed OLSC mixed-integer linear programming model, is implemented on a computer with Intel Core i3 3.30 GHz and 4.00 GB RAM to solve the test problem.

5.2 Results and analysis

To obtain the weights of suppliers in the third objective function, it aims to evaluate suppliers by considering the sustainability dimensions as well as the product flow in the network. With the help of the available literature [15, 30–32], an expert committee of three decision-makers is established for the evaluation of suppliers according to different criteria. The evaluation criteria are grouped under three dimensions as economic, social, and environmental and named as "main criteria." Sub-criteria are then placed into dimensions corresponding to the main criteria. The main and sub-criteria are shown in Table 3.

At first, criteria weights are determined using the interval type-2 AHP method. Three experts evaluated the criteria of sustainable supplier selection by considering the scale in Table 4, and as a result of the pairwise comparison of the criteria, the evaluations for the main criteria and sub-criteria are acquired as in Tables 5 and 6. The fuzzy weights of the criteria are calculated using the interval type-2 fuzzy AHP methodology, and the results are presented in Table 7.

After determining the weights of the criteria, suppliers are evaluated using interval type-2 fuzzy numbers. The linguistic terms used to rank suppliers are given in Table 8. The linguistic assessments given by the decision-makers to each of the four suppliers under each sub-criterion are shown in Table 9. According to experts' evaluation, the aggregated interval type-2 fuzzy numbers and assessment scores determined by gathering the opinions of the decision-makers are formed as in Table 10. The numerical data are then normalized and defuzzified using the center of area (CoA) method [33], and the crisp data are shown in Table 10. The weights obtained from the interval type-2 fuzzy AHP method are multiplied by the evaluation scores, and the final scores of the suppliers are calculated and indicated in Table 11.

When the developed multi-objective OLSC model is solved separately for each objective, it is seen that the highest cost among the objective functions is the transportation cost. For example, when economic costs are minimized, 54% of the total cost belongs to the transportation cost; besides, if the objective function is maximized, 72% of the total cost is actualized by this cost. When environmental costs are minimized, transportation costs decrease to 47%, and when if it is maximized, it decreases to 69%. Considering environmental costs, the total cost can be reduced. When environmental costs are minimized, the total cost is 34,963,605.8 $, a 9.87% reduction compared to the highest cost.

Table 3 Evaluation criteria

Main criteria	ECD: economic dimension	EVD: environmental dimension	SD: social dimension
Sub-criteria	C: cost Q: quality SP: service performance	EMS: environmental management systems PR: pollution reduction GI: green image	SH: safety and health EP: employment practices

Table 4 Linguistic variables for the importance level of weight for each criterion

Linguistic variables	Trapezoidal interval type-2 fuzzy scales
Absolutely strong (AS)	(7, 8, 9, 9; 1, 1) (7.2, 8.2, 8.8, 9; 0.8, 0.8)
Very strong (VS)	(5, 6, 8, 9; 1, 1) (5.2, 6.2, 7.8, 8.8; 0.8, 0.8)
Fairly strong (FS)	(3, 4, 6, 7; 1, 1) (3.2, 4.2, 5.8, 6.8; 0.8, 0.8)
Slightly strong (SS)	(1, 2, 4, 5; 1, 1) (1.2, 2.2, 3.8, 4.8; 0.8, 0.8)
Exactly equal (E)	(1, 1, 1, 1; 1, 1) (1, 1, 1, 1; 1, 1)
If factor *i* has one of the above linguistic variables assigned to it when compared with factor *j*, then *j* has the reciprocal value when compared with *i*.	Reciprocals of above

Table 5 Pairwise comparison matrix for main criteria

	ECD	EVD	SD
ECD	E, E, E	AS, 1/FS, FS	VS, 1/SS, 1/SS
EVD		E, E, E	1/SS, SS, 1/VS
SD			E, E, E

After the final scores of the suppliers are determined, the fuzzy approaches are applied to solve the proposed multi-objective OLSC model. First, the upper (Z^{+}) and the lower (Z^{-}) bounds of each objective function are determined (Table 12). Then, a linear membership function is created for the purpose functions, and finally the multi-objective OLSC model is transformed into a single-objective model.

$$\mu_1(Z_1(x)) = \begin{cases} 1, & Z_1(x) \le 17990123 \\ \frac{260743861 - Z_1(x)}{260743861 - 17990123}, & 17990123 \le Z_1(x) \le 260743861 \\ 0, & Z_1(x) \ge 260743861 \end{cases} \tag{105}$$

$$\mu_2(Z_2(x)) = \begin{cases} 1, & Z_2(x) \le 15693344.80 \\ \frac{101254381.76 - Z_2(x)}{101254381.76 - 15693344.80}, & 15693344.80 \le Z_2(x) \le 101254381.76 \\ 0, & Z_2(x) \ge 101254381.76 \end{cases} \tag{106}$$

$$\mu_3(Z_3(x)) = \begin{cases} 1, & Z_3(x) \ge 458.37 \\ \frac{Z_3(x) - 1861}{458.37 - 1861}, & 1861 \le Z_3(x) \le 458.37 \\ 0, & Z_3(x) \le 1861 \end{cases}. \tag{107}$$

The formulation of the ZIM approach is as follows:

$$Max\ \alpha$$

$$\alpha \le \mu_1(Z_1(x)) = \frac{260743861 - Z_1(x)}{260743861 - 17990123}$$

$$\alpha \le \mu_2(Z_2(x)) = \frac{101254381.76 - Z_2(x)}{101254381.76 - 15693344.80}$$

$$\alpha \le \mu_3(Z_3(x)) = \frac{Z_3(x) - 1861}{458.37 - 1861}.$$

C7-C104

$$0 \le \alpha \le 1. \tag{108}$$

Table 6 Pairwise comparison matrix for sub-criteria

	C	Q	SP	EMS	PR	GR	SH	EP
C	E, E, E	SS, VS, SS	VS, FS, 1/FS					
Q		E, E, E	E, 1/SS, 1/AS					
SP			E, E, E					
EMS				E, E, E	FS, SS, FS	1/SS, 1/FS, 1/SS		
PR					E, E, E	1/VS, 1/VS, 1/VS		
GR						E, E, E		
SH							E, E, E	SS, FS, 1/SS
EP								E, E, E

Table 7 Interval type-2 fuzzy weights for criteria

	Weights
ECD	((0.210, 0.292, 0.539, 0.816; 1, 1), (0.226, 0.311, 0.502, 0.739; 0.8, 0.8))
EVD	((0.104, 0.149, 0.275, 0.403; 1, 1), (0.113, 0.159, 0.257, 0.369; 0.8, 0.8))
EVD	((0.174, 0.283, 0.567, 0.831; 1, 1), (0.196, 0.306, 0.529, 0.763; 0.8, 0.8))
C	((0.281, 0.410, 0.733, 1.006; 1, 1), (0.307, 0.437, 0.691, 0.938; 0.8, 0.8))
Q	((0.077,0.097, 0.167, 0.265; 1, 1), (0.081, 0.101, 0.156, 0.236; 0.8, 0.8))
SP	((0.191,0.255, 0.414, 0.551; 1, 1), (0.204, 0.268, 0.393, 0.516; 0.8, 0.8))
EMS	((0.124,0.178,0.350,0.560; 1, 1), (0.135,0.197,0.322,0.501; 0.8, 0.8))
PR	((0.045,0.058,0.103,0.157; 1, 1), (0.047,0.063,0.093,0.142; 0.8, 0.8))
GR	((0.334,0.497,0.911,1.268; 1, 1), (0.367,0.538,0.839,1.178; 0.8, 0.8))
SH	((0.306,0.447,0.835,1.209; 1, 1), (0.334,0.478,0.783,1.111; 0.8, 0.8))
EP	((0.206,0.291,0.519,0.741; 1, 1), (0.223,0.309,0.488,0.683; 0.8, 0.8))

Table 8 Linguistic variables for the assessments of suppliers

Linguistic variables	IT2FSs
Very poor (VP)	((0, 0, 0, 1; 1, 1), (0, 0, 0, 0.5; 0.9, 0.9))
Poor (P)	((0, 1, 1, 3; 1, 1), (0.5, 1, 1, 2; 0.9, 0.9))
Medium poor (MP)	((1, 3, 3, 5; 1, 1), (2, 3, 3, 4; 0.9, 0.9))
Medium (M)	((3, 5, 5, 7; 1, 1), (4, 5, 5, 6; 0.9, 0.9))
Medium good (MG)	((5, 7, 7, 9; 1, 1), (6, 7, 7, 8; 0.9, 0.9))
Good (G)	((7, 9, 9, 10; 1, 1), (8, 9, 9, 9.5; 0.9, 0.9))
Very good (VG)	((9, 10, 10, 10; 1, 1), (9.5, 10, 10, 10; 0.9, 0.9))

Table 9 Linguistic assessments for the four suppliers

	Suppliers	Decision-makers		
		D1	D2	D3
C11	S1	MP	MG	MP
	S2	M	G	M
	S3	VG	G	VG
	S4	MP	MG	M
C12	S1	MP	M	M
	S2	VG	VG	G
	S3	M	M	G
	S4	M	P	G
C13	S1	MG	MG	MG
	S2	M	P	MP
	S3	MG	G	M
	S4	G	MG	MG
C21	S1	G	G	MG
	S2	G	MG	G
	S3	M	P	MP
	S4	MG	P	G
C22	S1	VG	M	G
	S2	MP	G	G
	S3	MG	VG	M
	S4	G	MP	P
C23	S1	VG	M	VG
	S2	G	MG	MG
	S3	G	VG	G
	S4	P	MP	M
C31	S1	P	VP	P
	S2	G	M	MG
	S3	G	MP	MP
	S4	MP	G	MP
C32	S1	MG	P	MP
	S2	VP	P	P
	S3	G	G	MG
	S4	MG	M	G

Then, the integrated OLSC model formulated by TH approach based on the weights of 0.383, 0.483, and 0.179 and $\gamma = 0.6$ is as follows:

$$Max \gamma\lambda + (1-\gamma)\left[0.383.\mu_1\left(Z_1(x)\right) + 0.483.\mu_2\left(Z_2(x)\right) + 0.179.\mu_3\left(Z_3(x)\right)\right]$$

$$\lambda \le \mu_1\left(Z_1(x)\right) = \frac{260743861 - Z_1(x)}{260743861 - 17990123}$$

$$\lambda \le \mu_2\left(Z_2(x)\right) = \frac{101254381.76 - Z_2(x)}{101254381.76 - 15693344.80}$$

$$\lambda \le \mu_3\left(Z_3(x)\right) = \frac{Z_3(x) - 1861}{458.37 - 1861}.$$

(C7-C104)

$$\gamma, \lambda\epsilon[0,1]. \tag{109}$$

The results according to the different approaches are given in Table 13. Table 13 shows that objective function and satisfaction levels differ according to methods. The results indicate that satisfaction levels are increased with

Table 10 Aggregated assessment scores of both interval type-2 fuzzy and crisp values

Attributes	Suppliers	Interval type-2 fuzzy scores	Crisp scores
C11	S1	((7, 13, 13, 19; 1, 1), (10, 13, 13, 16; 0.9, 0.9))	0.433
	S2	((13, 19, 19, 24; 1, 1), (16, 19, 19, 21,5; 0.9, 0.9))	0.595
	S3	((25, 29, 29, 30; 1, 1), (27, 29, 29, 29,5; 0.9, 0.9))	0.900
	S4	((9, 15, 15, 21;1, 1), (12, 15, 15, 18; 0.9, 0.9))	0.475
C12	S1	((7, 13, 13, 19; 1, 1), (10, 13, 13, 16; 0.9, 0.9))	0.433
	S2	((25, 29, 29, 30; 1, 1), (27, 29, 29, 29,5; 0.9, 0.9))	0.900
	S3	((13, 19, 19, 24; 1, 1), (16, 19, 19, 21,5; 0.9, 0.9)))	0.595
	S4	((10, 15, 15, 20; 1, 1), (12,5, 15, 15, 17,5; 0.9, 0.9))	0.475
C13	S1	((15, 21, 21, 27; 1, 1), (18, 21, 21, 24; 0.9, 0.9))	0.700
	S2	((4, 9, 9, 15; 1, 1), (6.5, 9, 9, 12; 0.9, 0.9)	0.291
	S3	((15, 21, 21, 26; 1, 1,), (12, 15, 15, 18; 0.9, 0.9))	0.571
	S4	((17, 23, 23, 28; 1, 1), (20, 23, 23, 25.5; 0.9, 0.9))	0.722
C21	S1	((19, 25, 25, 29; 1, 1), (22, 25, 25, 27; 0.9, 0.9))	0.821
	S2	((19, 25, 25, 29; 1, 1), (22, 25, 255, 27; 0.9, 0.9))	1.546
	S3	((4, 9, 9, 15,;1, 1), (6.5, 9, 9, 12; 0.9, 0.9))	0.291
	S4	((12, 17, 17, 22; 1, 1,), (14,5, 17, 17, 19,5, 0.24, 0.24))	0.538
C22	S1	((19, 24, 24, 27; 1, 1), (21,5, 24, 24, 25,5, 0.25, 0.25))	0.788
	S2	((15, 21, 21, 25; 1, 1), (18, 21, 21, 23, 0.26, 0.26))	0.653
	S3	((17, 22, 22, 26; 1, 1), (19,5, 22, 22, 24, 0.27, 0.27))	0.690
	S4	((8, 13, 13, 18; 1, 1), (10.5, 13, 13, 15.5; 0.9, 0.9))	0.412
C23	S1	((21, 25, 25, 27; 1, 1), (23, 25, 25, 26; 0.9, 0.9))	0.821
	S2	((17, 23, 23, 28; 1, 1), (20, 23, 23, 25.5; 0.9, 0.9))	0.722
	S3	((23, 28, 28, 30; 1, 1), (25.5, 28, 28, 29; 0.9, 0.9))	0.868
	S4	((4, 9, 4, 15; 1, 1), (6.5, 9, 9, 12; 0.9, 0.9))	0.270
C31	S1	((0, 2, 2, 7; 1, 1), (1, 2, 2, 4,5; 0.9, 0.9))	0.494
	S2	((15, 21, 21,26; 1, 1), (18, 21, 21, 23,5; 0.9, 0.9))	0.659
	S3	((9, 15, 15, 20; 1, 1), (12, 15, 15, 17.5; 0.9, 0.9))	0.082
	S4	((9, 15, 15, 20; 1, 1), (12, 15, 15, 17.5; 0.9, 0.9))	0.469
C32	S1	((6, 11, 11, 17; 1, 1), (8.5, 11, 11, 14; 0.9, 0.9))	0.694
	S2	((0, 2, 2, 7; 1, 1), (1, 2, 2, 4,5; 0.9, 0.9))	0.082
	S3	((19, 25, 25, 29; 1, 1), (22, 25, 25, 27; 0.9, 0.9))	0.779
	S4	((15, 21, 21, 26; 1, 1), (18, 21, 21, 23.5; 0.9, 0.9))	0.355

Table 11 Final scores of suppliers

Suppliers	Final scores
S1	0.272
S2	0.259
S3	0.253
S4	0.215

Table 12 Payoff table

Objective function	$\mu = 1(Z^{-})$	$\mu = 0(Z^{+})$
Z_1	17,990,123	260,743,861
Z_2	15,693,344.80	101,254,381.76
Z_3	1861	458.37

the use of weighted approaches and that decision-makers can choose the appropriate solutions according to their objectives.

The share of suppliers on the basis of parts is shown in Fig. 2. For the problem being addressed, according to the consensus solution, in the ZIM approach, the Supplier 4 holds 67% of the total parts transferred to factories. Similarly, in the TH approach, the Supplier 1 delivers 66% of the parts, and in the F-WAMG approach, the Supplier 2 acquires 88% of the parts. Suppliers 1 and 2 are being found to be the most preferred suppliers in the proposed assessment approach. By using weighted approaches, it is determined that they have become effective in the distribution in-network and that these suppliers adequately assume the entire supply.

Table 13 Satisfaction degree and order allocation of objectives

Objective functions	Zimmermann [27]		Tiwari et al. [36]		F-WAMG	
	Z_1	$\mu_1(Z_1(x))$	Z_2	$\mu_2(Z_2(x))$	Z_3	$\mu_3(Z_3(x))$
1	19,814,551	0.993	19,787,310	0.994	19,447,435	0.480
2	16,265,546.08	0.993	15,799,386.4	0.999	15,747,418.4	0.999
3	467.47	0.993	468.22	0.993	509.9	0.380

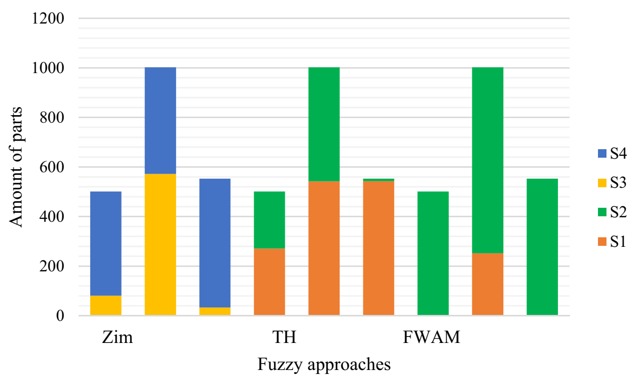

Fig. 2 Share of the parts procured at each supplier

6 Conclusion

In this study, a multi-objective OLSC model is proposed by considering sustainable supplier selection. The model presented has two features: First, environmental factors are included in the model, which includes environmental impacts from vehicles as well as different cost and traditional cost components. Secondly, the performances of the suppliers are evaluated considering the sustainability dimensions and included in the developed model. Initially, the relevant criteria and sub-criteria are determined according to the literature and the opinions of the experts. The interval type-2 fuzzy AHP method is then used to weight the selected criteria. Subsequently, the performance evaluation of suppliers under each sub-criterion is implemented and the final scores of the suppliers are calculated by considering the weights found in the previous step.

The multi-objective OLSC model has been transformed into a single-objective model by using three different fuzzy programming approaches to reach compromise solutions for the developed objectives. The changes in total cost, environmental cost, and weight of suppliers between objectives are analyzed. Using weighted solution approaches, it is determined that the majority of the parts sent to the factories are procured by the selected suppliers.

For future studies, the model can be adapted to real-world problems. At the same time, the model can be expanded taking into account the uncertainty in parameters. Also, the effectiveness of the proposed assessment approach can be tested with other methods using heuristic and meta-heuristic algorithms for multidimensional network design models.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Shakourloo A, Kazemi A, Javad MOM (2016) A new model for more effective supplier selection and remanufacturing process in a closed-loop supply chain. Appl Math Model 40:9914–9931. https://doi.org/10.1016/J.APM.2016.06.039
2. Ghayebloo S, Tarokh MJ, Venkatadri U, Diallo C (2015) Developing a bi-objective model of the closed-loop supply chain network with green supplier selection and disassembly of products: the impact of parts reliability and product greenness on the recovery network. J Manuf Syst 36:76–86. https://doi.org/10.1016/J.JMSY.2015.02.011
3. Özceylan E (2016) Simultaneous optimization of closed- and open-loop supply chain networks with common components. J Manuf Syst 41:143–156. https://doi.org/10.1016/J.JMSY.2016.08.008
4. Hamdan S, Cheaitou A (2017) Supplier selection and order allocation with green criteria: an MCDM and multi-objective optimization approach. Comput Oper Res 81:282–304. https://doi.org/10.1016/J.COR.2016.11.005
5. Yeh W-C, Chuang M-C (2011) Using multi-objective genetic algorithm for partner selection in green supply chain problems. Expert Syst Appl 38:4244–4253. https://doi.org/10.1016/J.ESWA.2010.09.091
6. Fakhrzad M, Goodarzian F (2019) A fuzzy multi-objective programming approach to develop a green closed-loop supply chain network design problem under uncertainty: modifications of imperialist competitive algorithm. RAIRO Oper Res 53:963–990. https://doi.org/10.1051/ro/2019018
7. Pourjavad E, Mayorga RV (2019) Multi-objective fuzzy programming of closed-loop supply chain considering sustainable measures. Int J Fuzzy Syst 21:655–673. https://doi.org/10.1007/s40815-018-0551-y
8. Tosarkani BM, Amin SH (2019) An environmental optimization model to configure a hybrid forward and reverse supply chain network under uncertainty. Comput Chem Eng 121:540–555. https://doi.org/10.1016/J.COMPCHEMENG.2018.11.014
9. Taleizadeh AA, Haghighi F, Niaki STA (2019) Modeling and solving a sustainable closed loop supply chain problem with pricing decisions and discounts on returned products.

J Clean Prod 207:163–181. https://doi.org/10.1016/J.JCLEPRO.2018.09.198
10. Arabsheybani A, Paydar MM, Safaei AS (2018) An integrated fuzzy MOORA method and FMEA technique for sustainable supplier selection considering quantity discounts and supplier's risk. J Clean Prod 190:577–591. https://doi.org/10.1016/J.JCLEPRO.2018.04.167
11. Amid A, Ghodsypour SH, O'Brien C (2011) A weighted max–min model for fuzzy multi-objective supplier selection in a supply chain. Int J Prod Econ 131:139–145. https://doi.org/10.1016/j.ijpe.2010.04.044
12. Aissaoui N, Haouari M, Hassini E (2007) Supplier selection and order lot sizing modeling: a review. Comput Oper Res 34:3516–3540. https://doi.org/10.1016/J.COR.2006.01.016
13. Azadnia AH, Saman MZM, Wong KY (2015) Sustainable supplier selection and order lot-sizing: an integrated multi-objective decision-making process. Int J Prod Res 53:383–408. https://doi.org/10.1080/00207543.2014.935827
14. Gören HG (2018) A decision framework for sustainable supplier selection and order allocation with lost sales. J Clean Prod 183:1156–1169. https://doi.org/10.1016/J.JCLEPRO.2018.02.211
15. Ghadimi P, Ghassemi Toosi F, Heavey C (2018) A multi-agent systems approach for sustainable supplier selection and order allocation in a partnership supply chain. Eur J Oper Res 269:286–301. https://doi.org/10.1016/J.EJOR.2017.07.014
16. Zarbakhshnia N, Jaghdani TJ (2018) Sustainable supplier evaluation and selection with a novel two-stage DEA model in the presence of uncontrollable inputs and undesirable outputs: a plastic case study. Int J Adv Manuf Technol 97:2933–2945. https://doi.org/10.1007/s00170-018-2138-z
17. Vahidi F, Torabi SA, Ramezankhani MJ (2018) Sustainable supplier selection and order allocation under operational and disruption risks. J Clean Prod 174:1351–1365. https://doi.org/10.1016/J.JCLEPRO.2017.11.012
18. Mendel JM (2016) A comparison of three approaches for estimating (synthesizing) an interval type-2 fuzzy set model of a linguistic term for computing with words. Granul Comput 1:59–69. https://doi.org/10.1007/s41066-015-0009-7
19. Mendel JM, Rajati MR, Sussner P (2016) On clarifying some definitions and notations used for type-2 fuzzy sets as well as some recommended changes. Inf Sci (Ny) 340–341:337–345. https://doi.org/10.1016/J.INS.2016.01.015
20. Gou Q, Liang L, Huang Z, Xu C (2008) A joint inventory model for an open-loop reverse supply chain. Int J Prod Econ 116:28–42. https://doi.org/10.1016/J.IJPE.2008.07.009
21. Ene S, Öztürk N (2014) Open loop reverse supply chain network design. Procedia Soc Behav Sci 109:1110–1115. https://doi.org/10.1016/J.SBSPRO.2013.12.596
22. Kalverkamp M, Young SB (2019) In support of open-loop supply chains: expanding the scope of environmental sustainability in reverse supply chains. J Clean Prod 214:573–582. https://doi.org/10.1016/J.JCLEPRO.2019.01.006
23. Ghahremani-Nahr J, Kian R, Sabet E (2019) A robust fuzzy mathematical programming model for the closed-loop supply chain network design and a whale optimization solution algorithm. Expert Syst Appl 116:454–471. https://doi.org/10.1016/J.ESWA.2018.09.027
24. Papen P, Amin SH (2019) Network configuration of a bottled water closed-loop supply chain with green supplier selection. J Remanufacturing 9:109–127. https://doi.org/10.1007/s13243-018-0061-y
25. Ahmadi S, Amin SH (2019) An integrated chance-constrained stochastic model for a mobile phone closed-loop supply chain network with supplier selection. J Clean Prod 226:988–1003. https://doi.org/10.1016/J.JCLEPRO.2019.04.132
26. Amin SH, Zhang G (2012) An integrated model for closed-loop supply chain configuration and supplier selection: multi-objective approach. Expert Syst Appl 39:6782–6791. https://doi.org/10.1016/J.ESWA.2011.12.056
27. Zimmermann H-J (1978) Fuzzy programming and linear programming with several objective functions. Fuzzy Sets Syst 1:45–55. https://doi.org/10.1016/0165-0114(78)90031-3
28. Torabi SA, Hassini E (2008) An interactive possibilistic programming approach for multiple objective supply chain master planning. Fuzzy Sets Syst 159:193–214. https://doi.org/10.1016/J.FSS.2007.08.010
29. Çalık A, Paksoy T, Huber S (2019) Lean and green supplier selection problem: a novel multi objective linear programming model for an electronics board manufacturing company in turkey BT. In: Huber S, Geiger MJ, de Almeida AT (eds) Multiple criteria decision making and aiding: cases on models and methods with computer implementation. Springer, Cham, pp 281–309
30. Rashidi K, Cullinane K (2019) A comparison of fuzzy DEA and fuzzy TOPSIS in sustainable supplier selection: implications for sourcing strategy. Expert Syst Appl 121:266–281. https://doi.org/10.1016/J.ESWA.2018.12.025
31. Memari A, Dargi A, Akbari Jokar MR et al (2019) Sustainable supplier selection: a multi-criteria intuitionistic fuzzy TOPSIS method. J Manuf Syst 50:9–24. https://doi.org/10.1016/J.JMSY.2018.11.002
32. Yu C, Shao Y, Wang K, Zhang L (2019) A group decision making sustainable supplier selection approach using extended TOPSIS under interval-valued Pythagorean fuzzy environment. Expert Syst Appl 121:1–17. https://doi.org/10.1016/J.ESWA.2018.12.010
33. Kahraman C, Öztayşi B, Uçal Sarı İ, Turanoğlu E (2014) Fuzzy analytic hierarchy process with interval type-2 fuzzy sets. Knowl Based Syst 59:48–57. https://doi.org/10.1016/J.KNOSYS.2014.02.001
34. Alikhani R, Torabi SA, Altay N (2019) Strategic supplier selection under sustainability and risk criteria. Int J Prod Econ 208:69–82. https://doi.org/10.1016/J.IJPE.2018.11.018
35. Darbari JD, Kannan D, Agarwal V et al (2019) Fuzzy criteria programming approach for optimising the TBL performance of closed loop supply chain network design problem. Ann Oper Res 273:693–738. https://doi.org/10.1007/s10479-017-2701-2
36. Tiwari RN, Dharmar S, Rao JR (1987) Fuzzy goal programming – an additive model. Fuzzy Sets Syst 24(1):27–34. https://doi.org/10.1016/0165-0114(87)90111-4