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An Integrated Hybrid Approach for Circular supplier selection and Closed loop Supply Chain Network Design under Uncertainty

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ABSTRACT

In recent decades, reverse logistics has garnered considerable attention since it recovers value of returning products, satisfies environmental requirements, and pays attention to customers' rights. Suppliers, as the first layer of the supply chain network, pose a great impact on environmental pollution. Therefore, in this paper a hybrid approach of fuzzy analysis network process (FANP), fuzzy decision-making trial and evaluation laboratory (FDEMATEL), and multi-objective mixed-integer linear programming (MOMILP) models are developed for circular supplier selection and order allocation in a multi-product circular closed-loop supply chain (C-CLSC) considering multi-depot, capacitated green routing problem using heterogeneous vehicles. In this regard, a mathematical model concerning an inventory-location-routing problem is developed that minimises cost and shortage simultaneously and also deals with imposed uncertainties. A fuzzy solution approach is proposed to simultaneously incorporate uncertainty and to change the multi-objective model into a single-objective model. To motivate the practical aspect of the proposed model in real world applications, we applied the model to an automotive timing belt manufacturer. The obtained results indicate that the proposed model is cost efficient and environmentally friendly for CLSC network designs.

1. Introduction

As the result of intense globalisation, fierce competition and also customers' awareness, many firms are strategically rethinking ways to control their environmental footprints. Being an eco-friendly organisation is no longer a competitive advantage, but it is a necessity to remain commercially viable and attractive to its stakeholders. In this regard, research on quantifying and controlling the environmental impacts of business operations has received a considerable deal of attention (Olsthoorn et al., 2001). On the other hand, firms are experiencing a pressing need to incorporate the circular economy (CE) into their supply chain network (Geissdoerfer et al., 2017; European Commission, 2015). CE tries to keep products and materials at the highest possible utility in both environmental and technical perspectives. This concept heads toward zero waste that aims to return the useful ingredients to the environment to enhance the natural resources (EMF, 2017). These steps provide advantages for SCM in terms of sustainability. Incorporating CE into SCM could extend the boundary of sustainability through reducing the need for virgin materials, which contributes to circulation of resources (Genovese et al., 2017; Shankar et al., 2017).

Although integrating CE in SCM is in its infancy, in recent years, an increasing number of studies pay more attention to integrating forward and reverse flows to transform supply chains into circular and closed models (Mardan et al., 2019; Darbari et al., 2019). In this stream, including recycling, disassembly, and reuse activities, there are several implications when it comes to incorporating environmental considerations into the traditional supply chain design (Ghayebloo et al., 2015; Li et al., 2018). Environmental issues are critical to understand and manage from several points of view such as regulatory requirements and corporate social responsibility (Tate et al., 2010 Govindan et al., 2018). Several well-known

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organisations such as Kodak, Xerox, and General Motors have a central focus on their reverse logistics with respect to legislative requirements, economic benefits, and reputation (Üster et al., 2007). According to Cardoso et al. (2013), design of forward and reverse flows in separation will have devastating impacts on the overall supply chain's performance. Thus, in order to develop sustainable solutions which are commercially viable and environmentally friendly, decisions about forward and reverse flows must be made jointly (Fleischmann et al., 2001; Pishvaee and Torabi, 2010).

Decision making in supply chain management should be done with the estimation of different types of costs. It is of high importance to understand the fundamental nature of costs in order to determine which to take into account with its particular behaviour. This estimation generally depends on what we want to do. In the CLSC context, economy of scale for procurement is considered as de-carbonisation and cost reduction opportunities. Economies of scale happen when marginal costs fall as activity level increases. Therefore, procurement purchase costs are less as purchase quantity rises. Lower rates usually stem from better utilization of available resources of the suppliers.

In this paper, we propose a novel hybrid approach on the basis of the FANP, FDEMATEL, and MOMILP models for supplier selection and order allocation focusing on the inventory-location-routing problem in the CLSC context considering demand uncertainty. First, suppliers are evaluated regarding the essential criteria using the FANP and FDEMATEL approaches. Accordingly, the MOMILP model is developed to design a CLSC under uncertainty, considering multi-product, location routing problem, economies of scaleand inventory optimisation assumptions.

This paper makes several contributions. First, a strategic-operational level hybrid approach is developed based on FDEMATEL, FANP, and mathematical programming for circular supplier evaluation, selection and order allocation. As far as the authors are concerned, this is the first attempt to investigate circular supplier selection. Second, demand uncertainty is introduced into the design of the CLSC. Third, a unique linearisation approach is developed and practiced in the solution approach. Finally, the proposed approach has been applied in an automotive timing belt network in Iran. To achieve these goals, the present research addresses the following main research questions.

1. How could the circular supplier selection and order allocation be integrated into a CLSC network design?
2. Which criteria are suitable for circular supplier selection?
3. Which method is appropriate for weighting the criteria and prioritizing the suppliers?

The remainder of this paper is organised as follows. In Section 2, a literature review is provided on CLSCs with a focus on analysing the methodological approaches and objective functions. Section 3 presents the problem context, mathematical model development, and the linearisation method. The proposed model is tested and validated in Section 4 through an application of the model to a real world case in the automotive parts industry. Finally, conclusions are drawn and directions are given for future studies in Section 5.

2. Literature review

There are several rich survey and review studies in the field of CLSCs and reverse logistics such as Fleischmann et al. (1997), Rubio et al. (2008), Guide and Van Wassenhove (2009), Akçalı and Cetinkaya (2011), Govindan et al. (2015b), Govindan and Soleimani (2017), and Govindan and Bouzon (2018). This research area is still under development and the number of research works has magnified over the last decade. Sustainability aspects of business operations and the availability and commercial viability of recycling and reuse technologies has been a dominant focus of research studies. The aim of this section is to present a brief review of the body of knowledge, relevant to our context. The first part of this section focuses on the major studies contributing to the development of CLSC research, and the section's second part aims to summarise the works in circular supply chain. The last section aims at summarizing the relation to circular supplier selection and order allocation.

2.1. Reverse logistics and CLSC network

As one of the early efforts in reverse logistics area, Jayaraman et al. (1999) presented a mixed-integer linear programming (MILP) model to optimise the reverse flow quantities in a reverse supply chain network. The authors state that an aspect of the recoverable product environment is the recoverable manufacturing system must be developed in a way to extend the product life cycles through remanufacturing and repair processes. Fleischmann et al. (2001) were one of the pioneers in studying and defining CLSC characteristics by extending the forward logistics model into reverse logistics and incorporating the differences using the mixed-integer linear programming model (MILPM).

Several papers in this field discuss the issue of greenness and environmental issues. Pati et al. (2008) presented a mixed-integer goal programming (MIGP) model to design a multi-product paper recycling network in line with reducing reverse logistics costs. The model aims to improve product quality by increasing segregation in the source points and to achieve environmental benefits by increasing the rate of wastepaper recovery. Govindan et al. (2009) studied the tyre and plastic goods manufacturers' supply chain by applying genetic algorithm (GA) and particle swarm optimisation (PSO) techniques. Later, Govindan et al. (2010) investigated a battery recycling supply chain in a reverse logistics setting. The authors state that although recycling products containing chemical and hazardous materials (such as lead) require more consideration, revenue generation opportunities exist when the materials are scarce. Amin and Zhang (2012) provided a mixed-integer mathematical model to design a CLSC network configuration. They presented an integrated model in two phases including a supplier selection stage in reverse logistics and a fuzzy approach to evaluate suppliers according to the defined qualitative criteria. Pishvaee and Torabi (2010) introduced uncertainty and risk in CLSC by proposing a bi-objective possibilistic mixed-integer programming (MIP) model for the network design decisions in both forward and reverse flows. The presented model also integrates the strategic network design decisions along with tactical material flows to prevent the phenomenon of sub-optimality arising from separated design decisions. Similarly, Shi et al. (2011) introduced a model for CLSC network design. They investigated optimisation of a multi-product, multi-period capacitated CLSC considering uncertain parameters, including demand, return rates, recycling utilities, and other supply chain-related costs using fuzzy numbers.

A MILP model was introduced by Amin and Zhang (2013) to minimise the total costs of establishing and managing CLSCs under uncertain demand and return levels using scenario-based stochastic programming. The model was also developed to incorporate environmental factors using weighted sums and ε-constraint methods.

Soleimani et al. (2017) examined a CLSC network design problem, including suppliers, manufacturers, distribution centres, customers, central warehouses, return centres, and recycling centres. Their chain modeling was designed in order to maximise meeting customer demand, maximise total profits, and minimise the lost working days due to occupational events.

Chen et al. (2017) examined the design problem of an integrated CLSC network by taking into account chain costs and environmental concerns in the solar industry from the sustainability perspective. Their proposed model includes practical features, such as flow protection in each production/recycling unit whether in the progressive flow or in the reverse flow, expansion of capacity, and recycled parts. The results of the analysis indicate that a company must adopt a proper recycling strategy or energy-saving technology to achieve an optimal economic efficiency due to regulations pertaining to carbon emissions.

Sahebjamnia et al. (2018) developed a MOMILP model for sustainable CLSC network design in the tyre industry. The proposed model considers the environmental impacts of setting up centres, tyre processing, and transport between each level, as well as social impacts, including job opportunities and occupational injuries in order to optimise overall costs.

To date, a vast number of studies have been done on CLSCN design. However, few studies have been conducted on routing/location-routing problem in this area. Fang et al. (2017) assessed the combination of reverse logistics in a CLSC network with routing problems to reduce carbon emissions. In that study, a MIP model was proposed for the routing problem with reverse logistics and with pickup and delivery possibilities.

Guo et al. (2018) investigated an inventory-location-routing problem in order to minimise the total costs of the chain in a CLSC network. To this end, they used a mixed-integer non-linear programming (MINLP) model.

A MILP model to solve a location-routing problem in the CLSC network is developed by Sadeghi et al. (2019). Their routing problem was capacitated and multi-depot in which vehicles were considered heterogeneously. In addition, several transportation modes were also considered for the transfer of raw materials from suppliers to producers where the optimal transportation mode is determined by the model. In order to validate their proposed model, they implemented it in a manufacturing-distribution chain of automotive parts in Iran.

2.2. Circular supplier selection

As the first level of the network, suppliers have a noteworthy impact on the efficiency of the whole network. Around 70% of the products' overall cost is related to the cost of purchasing raw materials from suppliers (Mirzaee et al., 2018). Likewise, the utmost environmental damage is caused by suppliers and manufacturers. Consequently, selecting the right supplier can reduce both environmental damage and costs and lead to circularity of used materials. The CE imposes suppliers to provide raw materials that are technically restorative, recoverable, and regenerative and would not have negative effects on the environment (Genovese et al., 2017).

Supplier selection with complex and conflicting criteria is the matter of multi criteria decision making (MCDM) problems (Guarnieri and Trojan, 2019). MCDM problems constitute a framework for structuring decision making problems, as well as a set of methods for generating preferences among alternatives (Govindan et al., 2013; Kannan et al., 2014).

A review of the related literature indicates that many researchers have used MCDM methods to evaluate suppliers (Awasthi et al., 2018; Banaeian et al., 2018; Jain et al., 2018) and mathematical models for order allocation and lot-sizing problems (Baraki and Kianfar, 2017; Vahidi et al., 2018). However, circularity assumptions, besides a combination of these two methods, result in circular supplier selection and order allocation. In this context, just a few researches have been conducted. Witjes and Lozano (2016) proposed a procurement framework toward reducing resource utilization. They aimed at improving efficiency through lower waste generation and recycling. Similarly, Popa and Popa (2016) focused on green industrial requirements and addressed resource efficiency, but they did not use quantitative approaches in their framework.

Much research has been conducted on the greenness of supplier selection. Humphreys et al. (2003) introduced a new framework involving environmental considerations such as solid waste, chemical waste, and wastewater disposal to select the most suitable supplier. Aissaoui et al. (2007) investigated supplier selection and order allocations in a literature review. The authors provided a comprehensive review by covering the entire purchasing process that includes both parts and services, outsourcing activities, and procurement models based on E-commerce. Ho et al. (2010) reviewed the papers published between 2000 and 2008 that utilised MCDM approaches for evaluating suppliers and ordering allocation. Authors reveal that the most commonly used MCDM method is data envelopment analysis (DEA). However, the most popular integrated approach is analytical hierarchy process (AHP) with goal programming (GP). Their study reveals that price and cost of procurement are not the most widely considered factors in supplier selection; rather, quality, delivery, and price are ranked respectively. Hsu and Hu. (2009) incorporated greenness issues by controlling hazardous substance management (HSM) in supplier evaluation and selection using AHP. These authors stress that the success of HSM relies on five key dimensions, including procurement management, process management, R&D management, incoming quality control, and the management system.

To evaluate green suppliers in the high-tech industry context, Lee et al. (2009) employed the Delphi method to discriminate the criteria for assessing traditional and green suppliers. The authors constructed a hierarchy to evaluate the importance of the chosen factors and the performance of green suppliers. As experts may not ascertain the importance of factors, the results of questionnaires may be prejudiced and biased. To reflect the ambiguity of experts' opinions, the fuzzy extended analytic hierarchy process (FEAHP) was utilised to minimise any preconceptions in the experts' opinions.

Quality function deployment (QFD) was integrated with fuzzy techniques for the evaluation and selection of suppliers by Amin and Razmi (2009). Employing QFD was beneficial as the supplier selection, evaluation, and development process was combined in one integrated framework for supplier management. In order to consider the interdependencies among the criteria in a green supplier selection problem, Hashemi et al. (2015) investigated the application of analytic network process (ANP) by employing grey rational analysis (GRA) to incorporate uncertainties in supplier selection decisions. The authors presented a novel approach by utilising ANP and improved GRA to define weights for the criteria, which was validated in the automotive industry.

Many research studies have been conducted on green supplier selection through MCDM methods. Mina et al. (2014a), Hashemi et al. (2015), Chung et al. (2016), and Tavana et al. (2017) used ANP method to calculate criteria weight and evaluate green suppliers. TOPSIS (dos Santos et al., 2019), DEA (Dobos and Vörösmarty, 2019), VIKOR (Banaeian et al., 2018), and AHP (Mavi, 2015) are commonly used methods in the literature. Moreover, some papers have provided comprehensive reviews on MCDM methods (Govindan et al., 2015a; Khan et al., 2018). Some other papers have investigated green supplier selection and order allocation problem; see Gören (2018), Lo et al. (2018), Mohammed et al. (2018), Park et al. (2018), and Kellner and Utz (2019).

Table 1
Comparison among the proposed approach and other related studies.

Author	Evaluation method	Mathematical model				Supplier Selection	Fuzzy evaluation	Fuzzy mathematical model	Economies of scale	Environmental issues	Vehicle routing problem	Location problem	Closed-loop supply chain
		LP	MOLP	MILP	MOMILP								
Demirtas and Üstün (2008)	ANP	–	–	–	✓	✓	–	–	–	–	–	–	–
Guneri et al. (2009)	TOPSIS	✓	–	–	–	✓	✓	–	–	–	–	–	–
Wang and Yang (2009)	AHP	–	✓	–	–	–	–	–	✓	–	–	–	–
Ku et al. (2010)	FAHP	✓	–	–	–	✓	✓	✓	–	–	–	–	–
Amin et al. (2011)	Fuzzy SWOT	✓	–	–	–	✓	✓	✓	–	–	–	–	–
Amid et al. (2011)	–	–	✓	–	–	–	–	✓	–	–	–	–	–
Haleh and Hamidi (2011)	AHP	–	✓	–	–	–	–	✓	–	–	–	–	–
Yücel and Güneri (2011)	TOPSIS	–	✓	–	–	✓	✓	✓	–	–	–	–	–
Amin and Zhang (2012)	MCDM	–	–	–	✓	✓	✓	–	–	–	–	–	✓
Khalili-Damghni et al. (2013)	ANFIS	–	✓	–	–	✓	✓	✓	–	–	–	–	–
Kannan et al. (2013)	FAHP-TOPSIS	–	✓	–	–	✓	✓	✓	–	✓	–	–	–
Sharma and Balan (2013)	FAHP	✓	–	–	–	✓	✓	–	–	–	–	–	–
Kazemi et al. (2014)	FTOPSIS	–	✓	–	–	✓	✓	✓	✓	–	–	–	–
Arabzad et al. (2015)	FTOPSIS	–	✓	–	–	✓	✓	–	–	–	–	–	–
Govindan and Sivakumar (2016)	FTOPSIS	–	✓	–	–	✓	✓	–	–	✓	–	–	–
Qazvini et al. (2016)	–	–	–	✓	–	–	–	–	–	✓	✓	✓	–
Awasthi and Kannan (2016)	Fuzzy NGT and VIKOR	–	–	–	–	✓	✓	–	–	✓	–	–	–
Baraki and Kianfar (2017)	MOLP	–	–	–	✓	–	–	✓	✓	–	✓	–	–
Hamdan and Cheaitou (2017)	AHP-FTOPSIS	–	✓	–	–	✓	✓	–	–	✓	✓	✓	–
Soleimani et al. (2018)	–	–	✓	–	–	–	–	✓	–	✓	✓	✓	–
Babbar and Amin (2018)	FQFD	–	–	–	✓	✓	✓	–	–	✓	–	–	–
Taleizadeh et al. (2019)	–	–	–	–	✓	–	–	✓	✓	✓	–	✓	✓
Proposed approach	FDEMATEL-FANP	–	–	–	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 1 represents a summary for the body of knowledge in CLSCs that is most relevant to this research in terms of the modelling approach and objective functions.

Although supplier selection is found to be a strategic function of firms, much less research has been conducted on integrating circular specifications into supplier selection. Moreover, while it is clear that there is a positive move towards the development of models that are capable of solving a wide range of supplier evaluation and selection problems, there seems to be concerns in relation to their practicality in the real world environments and to their adaptability by the industry. Many of the models covered in this review require a significant amount of investment in data collection and analysis. Furthermore, several criteria are subject to change in the face of new business practices and technologies. Therefore, efforts must be made to transform the models to practical and simplified tools that are adaptable in the supplier management field. The next section describes the formulation of our model and our approach in filling the research gap.

3. Problem definition and the proposed approach

In this study, a two-stage optimisation model is proposed to evaluate and select the circular suppliers and, accordingly, to allocate optimal orders in the CLSC. In the first stage, which is designed at a strategic level, suppliers are assessed using a decision support system (DSS) based on a FDEMATEL and FANP. The second stage, which is linked to tactical and operational decisions, aims to model a CLSC using a fuzzy bi-objective model. Fig. 1 demonstrates the decision-making order framework.

3.1. First stage: supplier evaluation

Supplier management is a costly and time-consuming task, particularly when it comes to evaluation and selection activities. On the other hand, organisations potentially deal with a large number of suppliers for their outsourcing requirements. Hence, models that assist businesses in evaluating and selecting the best subset of suppliers in an efficient manner are in high demand.

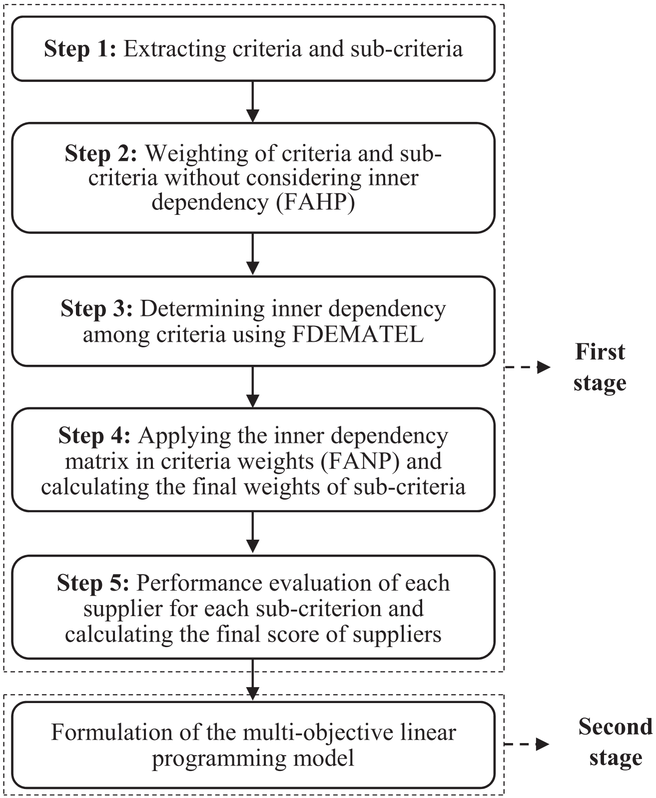

Fig. 1. Procedure of decision-making strategy.

Since the evaluation criteria have interdependencies, these factors should be taken into account for calculating the exact criteria weights. In the related literature (Zhang et al., 2015), the ANP and supermatrix methods are most often used to achieve this aim. However, in this research, to ease the calculation process, FDEMATEL is utilised instead of supermatrix since the latter imposes heavy computational efforts. The employed method is described through the following steps.

Step 1 In this step, the critical criteria and sub-criteria of supplier quality for the selection process are identified. An extensive literature survey was done to develop an inclusive set of criteria and sub-criteria. Furthermore, experts' opinions were also collected to complement the criteria set from the literature and to achieve a level of practicality. The selected criteria and sub-criteria for circular supplier evaluation and selection are presented in Table 2.

For this purpose, questionnaires, with the possibility of pairwise comparison between factors, were used and experts were requested to determine the status and importance of the paired comparisons through Table 3 (Kahraman et al., 2006).

After completion of the questionnaires, the pairwise comparison matrix can be extracted. Then, the local weight of each factor is used to defuzzify and obtain each factor by means of the method proposed by Bozbura and Beskese (2007).

In this process, we assume that φ_{pq} represents the triangular fuzzy numbers located in the pth row and the qth column of the pairwise comparison matrix, and the following is accurate:

$$\sum_{q=1}^{Q}\varphi_{pq}=\left(\sum_{q=1}^{Q}l_{pq},\sum_{q=1}^{Q}m_{pq},\sum_{q=1}^{Q}u_{pq}\right),\qquad p=1,2,3,\dots,P \tag{1}$$

where l, m, and u represent the lower, middle, and upper bounds of each triangular fuzzy number, respectively. Fuzzy synthetic extent is shown with S_p and is defined through Eq. (2):

$$S_p=\sum_{q=1}^{Q}\varphi_{pq}\otimes\left[\sum_{p=1}^{P}\sum_{q=1}^{Q}\varphi_{pq}\right]^{-1} \tag{2}$$

Eq. (3) is enacted to obtain $[\sum_{p=1}^{P}\sum_{q=1}^{Q}\varphi_{pq}]^{-1}$:

$$\begin{aligned}\left[\sum_{p=1}^{P}\sum_{q=1}^{Q}\varphi_{pq}\right]&=\left(\sum_{p=1}^{P}\sum_{q=1}^{Q}l_{pq},\sum_{p=1}^{P}\sum_{q=1}^{Q}m_{pq},\sum_{p=1}^{P}\sum_{q=1}^{Q}u_{pq}\right)\\ \left[\sum_{p=1}^{P}\sum_{q=1}^{Q}\varphi_{pq}\right]^{-1}&=\left(\frac{1}{\sum_{p=1}^{P}\sum_{q=1}^{Q}u_{pq}},\frac{1}{\sum_{p=1}^{P}\sum_{q=1}^{Q}m_{pq}},\frac{1}{\sum_{p=1}^{P}\sum_{q=1}^{Q}l_{pq}}\right)\end{aligned} \tag{3}$$

Accordingly, the degree of possibility is determined. For example, this possibility is defined for $S_q\geq S_p$ as follows:

$$V(S_q\geq S_p)=Sup\left[min\left(\mu_{S_p}(x),\mu_{S_q}(y)\right)\right],y\geq x \tag{4}$$

Degree of possibility is obtained via Eq. (5):

$$V(S_q\geq S_p)=\begin{cases}1 & \\ 0 & if \quad b_j\geq b_i\\ \dfrac{l_p-u_q}{(m_q-u_q)-(m_p-l_p)} & if \quad a_i\geq c_j\\ & Otherwise\end{cases} \tag{5}$$

In the next stage, the degree of possibility for convex fuzzy numbers is defined as Eq. (6):

$$d'(A_p)=Min\ \ V(S_p\geq S_k)p=1,2,\dots,k \tag{6}$$

Then, the weight vector is defined as Eq. (7):

$$W'=(d'(A_1),d'(A_2),\dots,d'(A_P))^T \tag{7}$$

The obtained weight vector is normalised as Eq. (8):

$$W=(d(A_1),d(A_2),\dots,d(A_P))^T \tag{8}$$

Using this approach, it is possible to obtain the local weight for the criteria and sub-criteria.

Step 3 In this step, FDEMATEL is used to determine the interdependencies between the factors. To achieve this, the following five procedures are proposed:

1. Initially, the experts were asked to schematically display the impact of factors on each other using their experience.
2. Based on the impacts demonstrated by the experts, a fuzzy direct-relation matrix should be obtained. For this

Table 2
Selected criteria and sub-criteria for supplier evaluation.
Step 2 For step 2, weights are assigned to the criteria and sub-criteria resulting from the previous step. Afterwards, ANP is used to analyse the interdependencies that exist among the criteria. Thus, it is assumed that there is no dependency between criteria and sub-criteria. A pairwise comparison matrix is also used to define the local weight of factors.

Criteria	Sub-criteria	Description	References
Circular	Air pollution (**Circular 1**)	Consideration of decreased air pollution in procedure of recycling the products	Grisi et al. (2010); Rashidi and Saen (2018); dos Santos et al. (2019)
	Environmental standards (**Circular 2**)	Utilization of the environmental standards in recycling the products	Thongchattu and Siripokapirom (2010); Rashidi and Saen (2018)
	Eco-friendly raw materials (**Circular 3**)	Utilization of recyclable raw materials in producing the products	Mangla et al. (2015); Gupta and Barua (2017)
	Eco-design (**Circular 4**)	Designing a product with the least environmental degradation effects and the most recycling capability	Hong-jun and Bin (2010); Scur and Barbosa. (2017); Vieira et al. (2018); Rashidi and Saen (2018); dos Santos et al. (2019)
	Eco-friendly packaging (**Circular 5**)	Utilization of recyclable materials in packaging the products	Lee et al. (2009); Chatterjee et al. (2018)
	Eco-friendly transportation (**Circular 6**)	Utilization of clean and appropriate vehicles to distribute and collect the products	Awasthi and Govindan (2016)
	Clean technology (**Circular 7**)	Utilization of proper technology for recycling the returned products	Humphreys et al. (2003); Humphreys et al. (2006)
Quality	Quality control system (**Quality 1**)	Applying proper systems for increasing quality of products	Kuo and Lin (2012); Sari and Timor (2016)
	Previous customers' satisfaction (**Quality 2**)	Providing conditions to demonstrate customers' satisfaction	Bafrooei et al. (2014)
	Quality of after sales service (**Quality 3**)	Providing conditions to return defective products and utilization of grantee	Jinturkar et al. (2014); Mina et al. (2014a); Parkouhi et al. (2019)
On-time delivery	On time and efficient production (**On-time delivery 1**)	Application of project control and efficient ordering system	Yadav and Sharma (2015)
	Time management (**On-time delivery 2**)	Appropriate mechanisms to reduce the processing time	
	Delivery time (**On-time delivery 3**)	Application of methods based on scheduling and routing problem	

Table 3
Linguistic scales for difficulty and importance (Kahraman et al., 2006).

Linguistic scales for difficulty	Linguistic scales for importance	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	Just equal	(1, 1, 1)	(1, 1, 1)
Equally difficult	Equally important	(0.5, 1, 1.5)	(0.667, 1, 2)
Weakly more difficult	Weakly more important	(1, 1.5, 2)	(0.5, 0.667, 1)
Strongly more difficult	Strongly more important	(1.5, 2, 2.5)	(0.4, 0.5, 0.667)
Very strongly more difficult	Very Strongly more important	(2, 2.5, 3)	(0.333, 0.4, 0.5)
Absolutely more difficult	Absolutely more important	(2.5, 3, 3.5)	(0.286, 0.333, 0.4)

Table 4
Scale of determining criteria's impacts.

Linguistic term	Fuzzy scales
None	(0,0,0.1)
Very low	(0.1,0.2,0.3)
Low	(0.2,0.3,0.4)
More or less low	(0.3,0.4,0.5)
Medium	(0.4,0.5,0.6)
More or less good	(0.5,0.6,0.7)
Good	(0.6,0.7,0.8)
Very good	(0.7,0.8,0.9)
Excellent	(0.8,0.9,1)

purpose, experts were provided with the pairwise comparison matrix and table of linguistic scales (Table 4) to rate the impact of factors on each other.

3. Now, Eq. (9) is used to normalise the resultant matrix.

$$\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij}) \quad and \quad s = \frac{1}{\max_{1 \le i \le n} \sum_j u_{ij}}, \quad then \quad \tilde{X} = s \times \tilde{A}. \tag{9}$$

4. The full fuzzy relation matrix is obtained in this step. Similar to the normalised direct-relation matrix $(\tilde{X})$, the total fuzzy relation matrix $(\tilde{T})$ is obtained using Eq. (10). Here, I represents the identity matrix. Therefore, matrix $\tilde{X}_{ij}$ is converted into three defuzzified matrices where the first, second, and third matrices are composed of low, middle, and high entries of triangular fuzzy numbers, respectively.

$$X_1 = \begin{bmatrix} 0 & l_{12} & \cdots & l_{1n} \\ l_{21} & 0 & \cdots & l_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1} & l_{n2} & \cdots & 0 \end{bmatrix}, \quad X_2 = \begin{bmatrix} 0 & m_{12} & \cdots & m_{1n} \\ m_{21} & 0 & \cdots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & 0 \end{bmatrix}, \quad X_3 = \begin{bmatrix} 0 & u_{12} & \cdots & u_{1n} \\ u_{21} & 0 & \cdots & u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{n1} & u_{n2} & \cdots & 0 \end{bmatrix}$$

Accordingly, the total fuzzy relation matrix is defined as follows.

$$\tilde{T} = \tilde{X}(I-\tilde{X})^{-1}\ \tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \cdots & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & \tilde{t}_{nn} \end{bmatrix},\ where\ \ \tilde{t}_{ij} = \left(l'_{ij}, m'_{ij}, u'_{ij}\right)\quad then\ Matrix\ \left[l'_{ij}\right] = X_l(I-X_l)^{-1}\ Matrix\ \left[m'_{ij}\right] = X_m(I-X_m)^{-1}\ Matrix\ \left[u'_{ij}\right] = X_u(I-X_u)^{-1} \tag{10}$$

5. Finally, the interdependency matrix is calculated. For this purpose, the total fuzzy relation matrix is defuzzified and normalised as per Eqs. (11) and (12).

$$Defuzzy(t_{ij}) = \frac{t_{ij}^{a} + 4t_{ij}^{b} + t_{ij}^{c}}{6} \tag{11}$$

$$Normalized\ \ Defuzzy(t_{ij}) = \frac{Defuzzy(t_{ij})}{\sum_i Defuzzy(t_{ij})} \tag{12}$$

Step 4 In this step, the interdependence matrix obtained from Step 3 is applied to the weight of the factors achieved from Step 2. As the result, the weights of factors are obtained by considering the interdependencies between them. The local weights of criteria which are obtained in this step are applied to the sub-criteria so that the final sub-criteria weight can be achieved.

Step 5 Using a questionnaire, experts assigned the relevant factors to each supplier. The linguistic words and triangular fuzzy numbers associated with the linguistic terms are shown in Table 5 (Dagdeviren and Yüksel, 2010).

Finally, the mean score of experts' opinions on each sub-criterion is calculated for each supplier. To obtain the final score of each supplier, the sum of factors' weights multiplied by numerical values are calculated, so the suppliers who obtain the minimum score are considered as qualified suppliers.

3.2. Second stage: mathematical model

Once the evaluation and selection of qualified suppliers is finalised, we focus on the design and optimisation of the CLSC. The schematic representation of the proposed supply chain network is shown in Fig. 2.

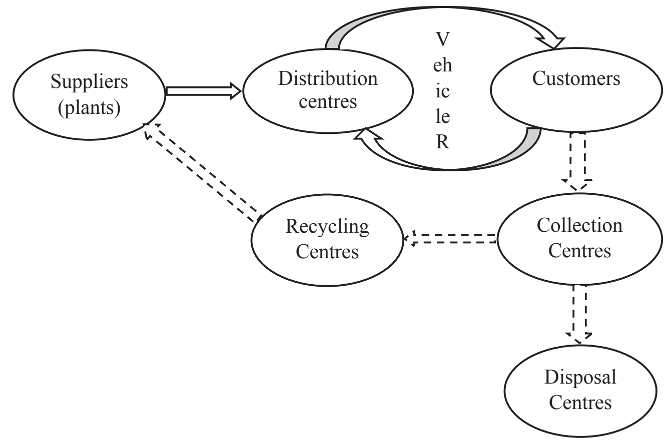

Fig. 2. The CLSC network in this study.

As can be seen in Fig. 2, distribution centres purchase the required products from the selected suppliers (manufacturers), and then distribute them among the customers through optimal routes of a heterogeneous fleet of vehicles. Defective products are then returned to the collection centres to be inspected and to determine their next direction. Repairable products are sent to recycling centres and, if they are not repairable, they are sent to disposal centres. The recycled products should be returned to suppliers in order to start the cycle from the first step.

Therefore, a bi-objective mathematical model is proposed under uncertainty for the given supply chain network, where the following decision variables are included: the locations of distribution, collection, recycling, and disposal centres; the presence or absence of any relationship with the suppliers, vehicle ownership, the level of product transition between different tiers, the volume of purchase from the supplier considering the discount and economies of scale option, the degree of shortage, the storage levels in customers' warehouses, and even the arrival time window for the vehicles to the customers' location. The proposed model and the notations are presented in the remainder of this section.

Assumptions

- The supply chain in this study is closed-loop with the consideration of reverse logistics.
- There is only one production plant.
- The setting of the proposed supply chain is single period and multi-product.
- Determining the geographical location of customers and suppliers is not in the scope of this model.
- All centres and suppliers are considered capacious.
- The demand pattern is uncertain (fuzzy).
- The transition between levels is intended to have capacity.

Table 5
Linguistic values and mean values of fuzzy numbers (Dagdeviren and Yüksel, 2010).

Linguistic values for positive sub-factors	Linguistic values for negative sub-factors	Triangular fuzzy numbers	The mean of fuzzy numbers
Very weak	Very strong	(0,0,0)	0
Weak	Strong	(0,0.167,0.333)	0.167
Weak-Mid	Mid-Strong	(0.167,0.333,0.5)	0.333
Mid	Mid	(0.333,0.5,0.667)	0.5
Mid-Strong	Weak-Mid	(0.5,0.667,0.833)	0.667
Strong	Weak	(0.667,0.833,1)	0.833
Very strong	Very weak	(1,1,1)	1

- The number and capacity of the vehicles involved in the distribution network is given, but the allocation of vehicles is performed by the model.
- The time required for travelling vehicles is predetermined.
- The vehicle routing problem is considered between distribution levels and demand only and the routing problem considers multiple depots.

Indices

i	Set of products	$(1 \le i \le I)$
d	Set of potential distributors	$(1 \le d \le D)$
s	Set of potential suppliers	$(1 \le s \le S)$
$c, \widehat{c}$	Set of customers	$(1 \le c \le C)$
o	Set of potential collection centres	$(1 \le o \le O)$
n	Set of potential recycling centres	$(1 \le n \le N)$
f	Set of potential disposal centres	$(1 \le f \le F)$
k	Set of price levels	$(1 \le k \le K)$
v	Set of vehicles	$(1 \le v \le V)$

Parameters

$CSSP_s$	Cost of communicating with the supplier s
$CSDST_d$	Cost of establishing a distribution centre in potential location d
$CSCL_o$	Cost of establishing a collection centre in potential location o
$CSRCY_n$	Cost of establishing a recycling centre in potential location n
$CSDS_f$	Cost of establishing a disposal centre in potential location f
$CSPSP_{is}$	Processing cost of product i by supplier s
$CSPDST_{id}$	Processing cost of product i by distribution centre d
$CSPCL_{io}$	Processing cost of product i by collection centre o
$CSPRCY_{in}$	Recycling cost of product i by recycling centre n
$CSPDS_{if}$	Disposal cost of product i by disposal centre f
$CSVH_v$	Supplying cost of vehicle v
$CSCSCL_{ico}$	Cost of moving product unit i from customer c to collection centre o
$CSCLDS_{iof}$	Cost of moving product unit i from collection centre o to disposal centre f
$CSCLRCY_{ion}$	Cost of moving product unit i from collection centre o to recycling centre n
$CSRCYSP_{ins}$	Cost of moving product unit i from recycling centre n to supplier s
$CSSPDST_{isd}$	Cost of moving product unit i from supplier s to distribution centre d
CSP_{iks}	Cost of purchasing product unit i from supplier s at price level k
A_{iks}	The upper limit of the volume of product i purchased from supplier s at price level k
$CPSP_{is}$	Capacity of supplier s for product i
$CPDST_{id}$	Capacity of distribution centre d for product i
$CPCL_{io}$	Capacity of collection centre o for product i
$CPRCY_{in}$	Capacity of recycling centre n for product i
$CPDS_{if}$	Capacity of disposal centre f for product i
$CPVH_v$	Capacity of vehicle v
$DSCS_{\widehat{c}c}$	Distance of customer location c from customer location $\widehat{c}$
$TMCS_{v\widehat{c}c}$	Time distance of customer location c from customer location $\widehat{c}$ by vehicle v
DS_{dc}	Distance of supplier s from customer c
TM_{vdc}	Time distance of supplier s from customer location c by vehicle v
$DMND_{ic}$	Demand of customer c for product i
$FCSCL_{ico}$	Maximum flow of moving product i from customer c to collection centre o
$FCLDS_{iof}$	Maximum flow of moving product i from collection centre o to disposal centre f
$FCLRCY_{ion}$	Maximum flow of moving product i from collection centre o to recycling centre n
$FRCYSP_{ins}$	Maximum flow of moving product i from recycling centre n to supplier s
$FSPDST_{isd}$	Maximum flow of moving product i from supplier s to distribution centre d
w_{ic}	Return rate of product i from customer c
RF_i	Recycling rate of product i
h_i	Holding cost of each product unit i
f_v	Fuel consumption per distance unit by vehicle v
δ	Cost of each emission unit of greenhouse gases
bigm~∞	Big number

Variables

$YSP_{iks}\begin{cases}1\\0\end{cases}$	Binary	If the supplier s is contacted for the purchase of product i at price level k Otherwise
$YDST_d\begin{cases}1\\0\end{cases}$	Binary	If distribution centre d is established Otherwise
$YCL_o\begin{cases}1\\0\end{cases}$	Binary	If collection centre o is established Otherwise
$YRCY_n\begin{cases}1\\0\end{cases}$	Binary	If recycling centre n is established Otherwise
$YDS_f\begin{cases}1\\0\end{cases}$	Binary	If disposal centre f is established Otherwise
$\beta_{vd}\begin{cases}1\\0\end{cases}$	Binary	If vehicle v is allocated to supplier d Otherwise
$ZVH_v\begin{cases}1\\0\end{cases}$	Binary	If vehicle v is supplied Otherwise
$Z_{v\widehat{c}c}\begin{cases}1\\0\end{cases}$	Binary	When vehicle v travels from customer $\widehat{c}$ to customer c Otherwise
AT_{vc}	Positive	Arrival time of vehicle v to customer location c
$INVP_{ic}$	Integer	The amount of product i available in the warehouse of customer c
$INVN_{ic}$	Integer	The shortage of product i (negative balance) for customer c
INV_{ic}	Free	Stock (auxiliary variable)
X_{ivdc}	Integer	The amount of product i moved from distribution centre d to customer c by vehicle v
$XCSCL_{ico}$	Integer	The amount of product i moved from customer c to collection centre o
$XCLDS_{iof}$	Integer	The amount of product i moved from collection centre o to disposal centre f
$XCLRCY_{ion}$	Integer	The amount of product i moved from collection centre o to recycling centre n
$XRCYSP_{ins}$	Integer	The amount of product i moved from recycling centre n to supplier s
$XSPDST_{iksd}$	Integer	The amount of product i purchased from supplier s by distribution centre d at price level k
η_{is}	Integer	The amount of product i processed by supplier s

3.2.1. Mathematical model

3.2.1.1. Objective function.

$$
\begin{aligned}
Min \quad z^{cost} = & \sum_{v} CSVH_v \times ZVH_v + \sum_{i,k,s} CSSP_s \times YSP_{iks} + \sum_{o} CSCL_o \times YCL_o + \\
& \sum_{n} CSRCY_n \times YRCY_n + \sum_{f} CSDS_f \times YDS_f + \sum_{d} CSDST_d \times YDST_d + \\
& \sum_{i,c,o} CSPCL_{io} \times XCSCL_{ico} + \sum_{i,o,n} CSPRCY_{in} \times XCLRCY_{ion} + \\
& \sum_{i,o,f} CSPDS_{if} \times XCLDS_{iof} + \sum_{i,n,s} CSPSP_{is} \times XRCYSP_{ins} + \\
& \sum_{i,s,d} CSPDST_{id} \times XSPDST_{iksd} + \sum_{i,c,o} CSCSCL_{ico} \times XCSCL_{ico} + \\
& \sum_{i,k,s,d} CSSPDST_{isd} \times XSPDST_{iksd} + \sum_{i,o,n} CSCLRCY_{ion} \times XCLRCY_{ion} + \\
& \sum_{i,o,f} CSCLDS_{iof} \times XCLDS_{iof} + \sum_{i,n,s} CSRCYSP_{ins} \times XRCYSP_{ins} + \\
& \sum_{i,k,s,d} CSP_{iks} \times XSPDST_{iksd} + \sum_{i,c} h_i \times INVP_{ic} + \\
& \delta \times \left(\sum_{v,\widehat{c},c} f_v \times Z_{v\widehat{c}c} \times DSCS_{\widehat{c}c} + \sum_{v,d,c} f_v \times (Z_{v1c} + Z_{vc1}) \times \beta_{vd} \times DS_{dc} \right)
\end{aligned}
\tag{13}
$$

The first objective function aims to minimise the total costs of the system. These costs include costs of vehicle supply, transportation costs, costs of product processing in each level, costs of product maintenance in customers' warehouses, cost of providing products from suppliers, and cost of producing greenhouse gas emissions.

$$Min \quad z^{shortage} = \sum_{i,c} INVN_{ic} \tag{14}$$

The second objective function is designed to ensure shortages are minimised.

Subject to:

$$\sum_{i,c} X_{ivdc} \le CPVH_v \times ZVH_v \, \forall v, d \tag{15}$$

Constraint (15) states that the amount of products carried by each vehicle should not exceed capacity.

$$\sum_{i,c} X_{ivdc} \le bigm \times \beta_{vd} \, \forall v, d \tag{16}$$

According to constraint (16), the condition for product movement to customers by vehicles is that the vehicle should be allocated to the distribution centre.

$$\sum_{d} \beta_{vd} \le 1 \, \forall v \tag{17}$$

Based on constraint (17), each vehicle is allocated at most to one distribution centre.

$$\sum_{v} \beta_{vd} \le bigm \times YDST_d \, \forall d \tag{18}$$

If no distribution centre has been established, no vehicle is allocated, which is included in constraint (18).

$$\sum_{\hat{c}} Z_{v\hat{c}c} \le 1 \, \forall v, c \tag{19}$$

There is the possibility of each customer's visit from each vehicle just once, but there is the possibility of demand overlap which is shown in constraint (19).

$$\sum_{\hat{c}} Z_{v\hat{c}c} = \sum_{\hat{c}} Z_{vc\hat{c}} \, \forall v, c \tag{20}$$

Based on constraint (20), if a vehicle arrives to the customer location, it should leave as well.

$$AT_{vc} + bigm \times (1 - Z_{v\hat{c}c}) \ge AT_{v\hat{c}} + TMCS_{v\hat{c}c} \, \forall v, \hat{c}, c > 1 \tag{21}$$

$$AT_{v1} + bigm \times (1 - Z_{vc1}) \ge AT_{vc} + TM_{vdc} \times \beta_{vd} \, \forall v, d, c > 1 \tag{22}$$

Sub-tour elimination constraint has been provided by the constraint and calculation of arrival time to each customer location in constraints (21) and (22).

$$\sum_{i,d} X_{ivdc} \le bigm \times \sum_{\hat{c}} Z_{v\hat{c}c} \, \forall v, c \tag{23}$$

$$\sum_{i,d,c} X_{ivdc} \le bigm \times ZVH_v \, \forall v \tag{24}$$

The condition for product delivery to the customer is that the customer's vehicle should be visited and this vehicle should be a purchased one that is presented in constraints (23) and (24), respectively.

$$INV_{ic} = \sum_{v,d} X_{ivdc} - DMND_{ic} - \sum_{o} w_{ic} \times XCSCL_{ico} \, \forall i, c \tag{25}$$

Constraint (25) considers the stock balance in customers' warehouses.

$$INV_{ic} = INVP_{ic} - INVN_{ic} \, \forall i, c \tag{26}$$

Warehouse stock and shortages are shown in constraint (26).

$$\sum_{n} XRCYSP_{ins} + \eta_{is} \ge \sum_{k,d} XSPDST_{iksd} \, \forall i, s \tag{27}$$

Constraint (27) sets the input and output balances for each supplier and each product.

$$\sum_{n,s} XRCYSP_{ins} \le \sum_{n,s} FRCYSP_{ins} \, \forall i \tag{28}$$

$$\sum_{n} XRCYSP_{ins} + \eta_{is} \le CPSP_{is} \, \forall i, s \tag{29}$$

Constraints (28) and (29) show the state of transferred product is not exceeding the flow capacity between recycling centres and the supplier, and the states of processed and received products is not exceeding the capacity of each supplier, respectively.

$$\sum_{c,o} XCSCL_{ico} \le \sum_{c,o} FCSCL_{ico} \, \forall i \tag{30}$$

According to constraint (30), there is no possibility that the product movement from the customer to the collection centres exceeds the capacity flow of transfer between them.

$$\sum_{c} XCSCL_{ico} \ge \sum_{f} XCLDS_{iof} + \sum_{n} XCLRCY_{ion} \, \forall i, o \tag{31}$$

Constraint (31) calculates the balance of products' entry for each collection centre and product.

$$\sum_{c} XCSCL_{ico} \le CPCL_{io} \, \forall i, o \tag{32}$$

Constraint (32) states that the amount of products moved to collection centres must not exceed their capacity.

$$\sum_{o} XCSCL_{ico} = \sum_{v,d} w_{ic} \times X_{ivdc} \, \forall i, c \tag{33}$$

Constraint (33) calculates the amount of products returned from customers.

$$\sum_{o,f} XCLDS_{iof} \le \sum_{o,f} FCLDS_{iof} \, \forall i \tag{34}$$

$$\sum_{o,n} XCLRCY_{ion} \le \sum_{o,n} FCLRCY_{ion} \, \forall i \tag{35}$$

Constraints (34) and (35) state that the quantity of products transferred from collection centres to disposal centres and to recycling centres must not exceed the flow capacity between them.

$$\sum_{o} XCLDS_{iof} \le CPDS_{if} \, \forall i, f \tag{36}$$

$$\sum_{o} XCLRCY_{ion} \le CPRCY_{in} \, \forall i, n \tag{37}$$

Constraints (36) and (37) prevent exceeding the capacity of disposal and recycling centres.

$$\sum_{k,s,d} XSPDST_{iksd} \le \sum_{s,d} FSPDST_{isd} \, \forall i \tag{38}$$

Constraint (38) shows that the products transferred from suppliers to distribution centres must not exceed the maximum transfer rate between them.

$$\sum_{k,s} XSPDST_{iksd} \le CPDST_{id} \forall i, d \quad (39)$$

Constraint (39) indicates the capacity constraints of distribution centres.

$$\sum_{k,s} XSPDST_{iksd} \ge \sum_{v,c} X_{ivdc} \forall i, d \quad (40)$$

Constraint (40) states that the amount of products transferred from the total of suppliers to distribution centres should not be less than the sum of the products delivered to the customers.

$$A_{iks} - bigm \times (1 - YSP_{iks}) \le XSPDST_{iksd} \le A_{i(k+1)s} + bigm \times (1 - YSP_{iks}) \quad \forall i, k, s, d \quad (41)$$

Constraints (41) are presented to apply piecewise economies of scale on the purchase of products from suppliers.

$$\sum_{k} YSP_{iks} \le 1 \forall i, s \quad (42)$$

Constraint (42) indicates the purchase of each product from any supplier is at one price level only.

$$XSPDST_{iksd} \le bigm \times YSP_{iks} \forall i, k, s, d \quad (43)$$

$$XRCYSP_{ins} \le bigm \times YSP_{iks} \forall i, k, n, s \quad (44)$$

Constraints (43) and (44) ensure that products can be purchased from and sent to the suppliers that are selected.

$$XSPDST_{iksd} \le bigm \times YDST_d \forall i, k, s, d \quad (45)$$

$$X_{ivdc} \le bigm \times YDST_d \forall i, v, d, c \quad (46)$$

$$XCSCL_{ico} \le bigm \times YCL_o \forall i, c, o \quad (47)$$

$$XCLDS_{iof} \le bigm \times YCL_o \forall i, o, f \quad (48)$$

$$XCLRCY_{ion} \le bigm \times YCL_o \forall i, o, n \quad (49)$$

$$XCLRCY_{ion} \le bigm \times YRCY_n \forall i, o, n \quad (50)$$

$$XRCYSP_{ins} \le bigm \times YRCY_n \forall i, n, s \quad (51)$$

$$XCLDS_{iof} \le bigm \times YDS_f \forall i, o, f \quad (52)$$

Constraints (45)–(52) ensure that products flow to and from the only established distribution centres, collection centres, and recycling centres.

3.3. Linearisation process

According to the developed mathematical model, the term $\beta_{vd} \times Z_{v\hat{c}c}$ makes the model nonlinear. So, to linearise the model, a new binary variable is defined that includes all the indices in β_{vd} and $Z_{v\hat{c}c}$.

$$Z\beta_{vd\hat{c}c} \begin{cases} 1 \\ 0 \end{cases} \quad \text{Binary}$$

Now, the nonlinear term is replaced with new variable in the objective function as follows.

$$Z\beta_{vd\hat{c}c} = \beta_{vd} \times Z_{v\hat{c}c} \quad (53)$$

$$\begin{aligned} Min \quad z^{cost} = & \sum_{v} CSVH_v \times ZVH_v + \sum_{i,k,s} CSSP_s \times YSP_{iks} + \sum_{o} CSCL_o \times YCL_o + \\ & \sum_{n} CSRCY_n \times YRCY_n + \sum_{f} CSDS_f \times YDS_f + \sum_{d} CSDST_d \times YDST_d + \\ & \sum_{i,c,o} CSPCL_{io} \times XCSCL_{ico} + \sum_{i,o,n} CSPRCY_{in} \times XCLRCY_{ion} + \\ & \sum_{i,o,f} CSPDS_{if} \times XCLDS_{iof} + \sum_{i,n,s} CSPSP_{is} \times XRCYSP_{ins} + \\ & \sum_{i,s,d} CSPDST_{id} \times XSPDST_{iksd} + \sum_{i,c,o} CSCSCL_{ico} \times XCSCL_{ico} + \\ & \sum_{i,k,s,d} CSSPDST_{isd} \times XSPDST_{iksd} + \sum_{i,o,n} CSCLRCY_{ion} \times XCLRCY_{ion} + \\ & \sum_{i,o,f} CSCLDS_{iof} \times XCLDS_{iof} + \sum_{i,n,s} CSRCYSP_{ins} \times XRCYSP_{ins} + \\ & \sum_{i,k,s,d} CSP_{iks} \times XSPDST_{iksd} + \sum_{i,c} h_i \times INVP_{ic} + \\ & \delta \times \left(\sum_{v,\hat{c},c} f_v \times Z_{v\hat{c}c} \times DSCS_{\hat{c}c} + \sum_{v,d,c} f_v \times (\beta Z_{vd1c} + \beta Z_{vdc1}) \times DS_{dc} \right) \end{aligned} \quad (54)$$

The logical relations between the new binary variable $Z\beta_{vd\hat{c}c}$ and the ones in the nonlinear term are as follows.

$$Z\beta_{vd\hat{c}c} \le Z_{v\hat{c}c} + bigm \times (1 - \beta_{vd}) \quad (55)$$

$$Z\beta_{vd\hat{c}c} \le \beta_{vd} + bigm \times (1 - Z_{v\hat{c}c}) \quad (56)$$

$$Z\beta_{vd\hat{c}c} \ge 1 + bigm \times (\beta_{vd} + Z_{v\hat{c}c} - 2) \quad (57)$$

$$Z\beta_{vd\hat{c}c} \le bigm \times (\beta_{vd} + Z_{v\hat{c}c}) \quad (58)$$

4. Case study and model validation

In this section, we focus on the implementation and validation of the proposed model in an automotive parts industry involved in producing automotive timing belts. The factory is located in the Alborz Province (Iran) and includes three production lines that produce timing belts for Peugeot 405, Peugeot 206, Peugeot Pars, Samand, and Pride.

In the considered case study, automotive timing belts are produced by suppliers (plants) and sent to distribution centres. Then, they are distributed to customers' sites (spare parts sales agencies) with the routing plans. During the sale process, some of the products may be determined as defective. Such products should be sent to either disposal or recycling centres according to their deficiency level. In the recycling centres, the defective products are repaired and re-sent for further usages. Recycling centres and disposal centres are of two activities that lead to CE in the network. This CLSC network is illustrated in Fig. 2.

In this paper, the data from production line 1 is used to validate the proposed model. Production line 1 produces three products, including the timing belts for Peugeot 405, Peugeot 206, and Peugeot Pars. The final products of this production line are then distributed to three distribution centres in the proximity of the main production plant. To collect the required data to test the model, five experts and six suppliers were contacted and relevant data collection procedures were conducted. The step-by-step implementation of the model in the case study environment is explained below.

Table 6
Local weights pertaining to each criterion and sub-criteria.

Criteria (Local weight)	Sub-criteria	Local weight
Circular (0.2898)	Air pollution	0.1761
	Environmental standards	0.1661
	Eco-friendly raw materials	0.137
	Eco-design	0.1715
	Eco-friendly packaging	0.1643
	Eco-friendly transportation	0.1022
	Clean technology	0.0828
Quality (0.3722)	Quality control system	0.4075
	Previous customers' satisfaction	0.3474
	Quality of after sales service	0.2451
On-time delivery (0.338)	On time and efficient production	0.4495
	Time management	0.2072
	Delivery time	0.4333

First stage/Step 1 In this step, the evaluation criteria and sub-criteria that were obtained from the literature survey and experts' opinions are extracted and presented. In Table 2, the selective criteria and sub-criteria are shown.

Step 2 In this step, weights are assigned to the criteria and sub-criteria derived from the previous step. It is assumed that there is no interdependency between the criteria. The local weights for criteria and sub-criteria are calculated using a pairwise comparison matrix between factors and Bozbura and Beskese's (2007) method (Table 6).

Step 3 The interdependencies between the factors are obtained in this step using the FDEMATEL method. This procedure is presented in the following steps:

1. Initially, the impact of factors on each other was schematically drawn by experts' opinions (Fig. 3).
2. The impact of each criteria on each other is obtained from experts' opinions and displayed in Table 7.
3. The matrix resulting from the previous procedure is normalised using Eq. (9) (Table 8). and the fuzzy normalised matrix is obtained.

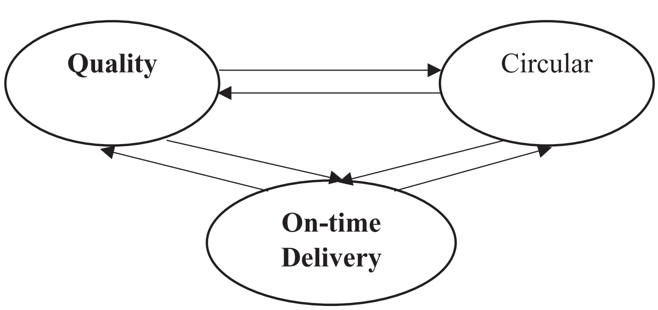

Fig. 3. Dependence among criteria.

Table 7
Matrix of criteria's impacts.

Criteria	Circular	Quality	On-time delivery
Circular	*	(0.6,0.7,0.8)	(0.1,0.2,0.3)
Quality	(0.1,0.2,0.3)	*	(0.3,0.4,0.5)
On-time delivery	(0.1,0.2,0.3)	(0.1,0.2,0.3)	*

4. The full fuzzy relation matrix is obtained by conversion into the three following matrices.

$$X_1 = \begin{bmatrix} 0 & 0.545 & 0.091 \\ 0.091 & 0 & 0.273 \\ 0.091 & 0.091 & 0 \end{bmatrix} \quad X_2 = \begin{bmatrix} 0 & 0.636 & 0.181 \\ 0.181 & 0 & 0.363 \\ 0.181 & 0.181 & 0 \end{bmatrix} \quad X_3 = \begin{bmatrix} 0 & 0.727 & 0.273 \\ 0.273 & 0 & 0.454 \\ 0.273 & 0.273 & 0 \end{bmatrix}$$

$$T_1 = X_1(I - X_1)^{-1} \qquad T_1 = \begin{bmatrix} 0.0799 & 0.6127 & 0.2655 \\ 0.1283 & 0.0983 & 0.3115 \\ 0.1099 & 0.1557 & 0.0525 \end{bmatrix}$$

$$T_2 = X_2(I - X_2)^{-1} \qquad T_2 = \begin{bmatrix} 0.2648 & 0.9053 & 0.5576 \\ 0.3340 & 0.3094 & 0.5358 \\ 0.2894 & 0.4009 & 0.1979 \end{bmatrix}$$

$$T_3 = X_3(I - X_3)^{-1} \qquad T_3 = \begin{bmatrix} 0.7784 & 1.6271 & 1.2242 \\ 0.8058 & 0.8787 & 1.0729 \\ 0.7055 & 0.9571 & 0.6271 \end{bmatrix}$$

5. Finally, the interdependence matrix is calculated from the defuzzification of the matrices obtained from the previous procedure. For example, calculations for the first entry of matrix are presented as follows.

$$Defuzzy(t_{ij}) = \frac{t_{ij}^a + 4t_{ij}^b + t_{ij}^c}{6} = \frac{t_{1,1}^a + 4t_{1,1}^b + t_{1,1}^c}{6} = \frac{0.0799 + 4 \times 0.2648 + 0.7784}{6} = 0.3195$$

And the interdependency matrix is as follows:

$$Defuzzy(t_{ij}) = \begin{bmatrix} 0.3195 & 0.9768 & 0.62 \\ 0.3783 & 0.3691 & 0.5879 \\ 0.3288 & 0.4527 & 0.2452 \end{bmatrix} \; Normalised\, defuzzy(t_{ij}) = \begin{bmatrix} 0.3112 & 0.5431 & 0.4267 \\ 0.3685 & 0.2052 & 0.4046 \\ 0.3203 & 0.2517 & 0.1687 \end{bmatrix}$$

Step 4 The interdependency matrix obtained from the previous step is applied to the weight of factors from Step 2 as follows:

$$\begin{bmatrix} 0.3112 & 0.5431 & 0.4267 \\ 0.3685 & 0.2052 & 0.4046 \\ 0.3203 & 0.2517 & 0.1687 \end{bmatrix} \times \begin{bmatrix} 0.2898 \\ 0.3722 \\ 0.338 \end{bmatrix} = \begin{bmatrix} 0.43655 \\ 0.31992 \\ 0.24353 \end{bmatrix}$$

Accordingly, the local weights of criteria are obtained using the interdependence matrix. Then, the local weights of criteria are applied to the local weights of sub-criteria along with the application of their interdependence matrix to obtain the global weights of sub-criteria. This procedure is presented in Table 9.

The final score results of the mean scores for each supplier is demonstrated in Table 10. The final scores are calculated by the sum of multiplying the sub-criteria's weight by the evaluation values.

According to the experts' opinions, suppliers with a minimum

Table 8
Normalised matrix of criteria's impacts.

Criteria	Circular	Quality	On-time delivery
Circular	*	(0.545,0.636,0.727)	(0.091,0.181,0.273)
Quality	(0.091,0.181,0.273)	*	(0.273,0.363,0.454)
On-time delivery	(0.091,0.181,0.273)	(0.091,0.181,0.273)	*

Table 9
Global weights of sub-criteria.

Step 5 In this step, suppliers are evaluated based on sub-criteria. For this purpose, experts are asked to score each supplier in relation to each sub-criterion using the linguistic terms provided in Table 5.

Criteria	Weight	Sub-criteria	Local weight	$Weight_{criteria} \times Weight_{sub-criteria}$
Circular	0.43655	Circular **1**	0.1761	0.0769
		Circular **2**	0.1661	0.0725
		Circular **3**	0.137	0.0598
		Circular **4**	0.1715	0.0749
		Circular **5**	0.1643	0.0717
		Circular **6**	0.1022	0.0446
		Circular **7**	0.0828	0.0361
Quality	0.31992	**Quality 1**	0.4075	0.1304
		Quality 2	0.3474	0.1111
		Quality 3	0.2451	0.0784
On-time delivery	0.24353	**On-time delivery 1**	0.4495	0.1095
		On-time delivery 2	0.2072	0.0505
		On-time delivery 3	0.4333	0.1055

Table 10
Final score of suppliers.

Sub-criteria	Weight	Supplier #1	Supplier #2	Supplier #3	Supplier #4	Supplier #5	Supplier #6
Circular 1	0.0769	0.3998	0.3	0.5	0.5	0.3332	0.3668
Circular 2	0.0725	0.3002	0.4668	0.4	0.5664	0.3	0.2002
Circular 3	0.0598	0.3666	0.3002	0.4332	0.4332	0.4666	0.3668
Circular 4	0.0749	0.3666	0.4332	0.3664	0.3334	0.4332	0.2336
Circular 5	0.0717	0.2334	0.5668	0.4666	0.4332	0.2332	0.2662
Circular 6	0.0446	0.2668	0.3998	0.2666	0.4332	0.1668	0.1336
Circular 7	0.0361	0.4	0.4666	0.6668	0.6668	0.4666	0.5332
Quality 1	0.1304	0.6002	0.6002	0.5668	0.8664	0.5334	0.6002
Quality 2	0.1111	0.6002	0.6336	0.6002	0.7002	0.6334	0.5332
Quality 3	0.0784	0.7334	0.7668	0.6668	0.6334	0.6668	0.6336
On-time delivery 1	0.1095	0.8	0.4666	0.3998	0.5002	0.5332	0.7668
On-time delivery 2	0.0505	0.6668	0.6002	0.5	0.6002	0.5668	0.5332
On-time delivery 3	0.1055	0.8	0.6668	0.6002	0.8	0.5	0.5332
Final score	–	**0.55307**	**0.54317**	**0.51545**	**0.61477**	**0.48069**	**0.48076**

score of 0.5 will enter the second stage as the qualified suppliers. Based on Table 10, alternatives 1, 2, 3, and 4 are the selected suppliers.

Second stage In this stage, the GAMS 24.1/CPLEX software is used to validate the model. The required information for supply, distribution, and recycling was extracted from the historical data of the factory and the data of other levels was simulated with the assistance of experts. The proposed model was run for three products, three distribution centres, four selected suppliers, six customers, three potential collection, recycling and disposal centres, four price levels, and six vehicles.

Due to the existence of uncertainty in cost and demand figures, the fuzzy approach proposed by Zimmermann (1978) and Lin (2012) is used to solve the model:

$$
\begin{aligned}
&Max\ \alpha\\
&Subject\ to:\\
&\alpha \le \mu_{z_k^{\min}}(x)\\
&\alpha \le \mu_{z_r^{\max}}(x)\\
&\alpha \le \mu_{g_l}(x)
\end{aligned}
\tag{59}
$$

These membership functions are defined as follows (Zimmermann, 1978):

$$
\mu_{Z_k^{\min}}(x) = \begin{cases} 1 & z_k(x) > z_k^{positive} \\ 0 & z_k(x) < z_k^{negative} \\ f_{\mu_{z_k^{\min}}} = \dfrac{z_k^{positive} - z_k(x)}{z_k^{positive} - z_k^{negative}}, & z_k^{negative} \le z_k(x) \le z_k^{positive} \end{cases}
\tag{60}
$$

Table 11
Values of objective functions.

- All four suppliers are contracted.
- DC 1 and 3 are established.
- Collection centre 1, recycling centre 3, and disposal centre 1 are established.
- Vehicles 1, 2, and 3 are purchased.
- Vehicles 1 and 2 are allocated to DC 1 and Vehicle 3 is allocated to DC 3.
- The routes formed by cars are given below:

$For v = 1$ $(\widehat{c} \rightarrow c) : c_1(DC\ 1) \rightarrow c_5 \rightarrow c_4 \rightarrow c_3 \rightarrow c_2 \rightarrow c_1$
$For v = 2$ $(\widehat{c} \rightarrow c) : c_1(DC\ 1) \rightarrow c_3 \rightarrow c_1$
$For v = 3$ $(\widehat{c} \rightarrow c) : c_1(DC\ 3) \rightarrow c_6 \rightarrow c_3 \rightarrow c_2 \rightarrow c_1$

α	$z^{\cos t}$	$z^{shortage}$
0.2057	1163535000	130

$$\mu_{Z_l^{\max}}(x) = \begin{cases} 1 z_l(x) > z_l^{positive} \\ 0 z_l(x) < z_l^{negative} \\ f_{Z_l^{\max}} = \dfrac{z_l(x) - z_l^{negative}}{z_l^{positive} - z_l^{negative}}, z_l^{negative} \le z_l(x) \le z_l^{positive} \end{cases} \tag{61}$$

$$\mu_{g_l}(x) = \begin{cases} 1 g_l(x) > b_l \\ 0 g_l(x) < b_l + d_l \\ f_{Z_l^{\max}} = \dfrac{1 - [g_l(x) - b_l]}{d_l}, \qquad b_l \le g_l(x) \le b_l + d_l \end{cases} \tag{62}$$

Where the objective function $z_k(z_l)$ values change from lower bound $z_k^{negative}$ $(z_l^{negative})$ to upper bound $z_k^{positive}(z_l^{positive})$. Also $\mu_{z_k^{\min}}(x)$, $\mu_{z_r^{\max}}(x)$, $\mu_{g_l}(x)$, and d_l represent the maximum membership function, minimum membership function, constraints, and tolerance values respectively. Thus, the objective functions are converted to the following constraints:

$$\mu_{z^{\cos t}} = \frac{1464881000 - z^{\cos t}}{1464881000} \ge \alpha \tag{63}$$

$$\mu_{z^{shortage}} = \frac{1130 - z^{shortage}}{1130} \ge \alpha \tag{64}$$

Since customers' demands vary and are not fixed for all time periods, the average, maximum, and minimum values are determined. It was observed that the demand quantities do not violate more than 10 per cent. Thus, the demand satisfaction constraint (constraint (25)) considering 10 per cent of violations in the degree of demand is indicated as follows.

$$\mu^{+}_{Z_{DMND}} = \frac{1.1 \times DMND_{ic} - \sum_{v,d} X_{ivdc} + INV_{ic} + \sum_{o} w_{ic} \times XCSCL_{ico}}{0.1 \times DMND_{ic}} \ge \alpha \tag{65}$$

$$\mu^{-}_{Z_{DMND}} = \frac{\sum_{v,d} X_{ivdc} - INV - 0.9 \times DMND_{ic} - \sum_{o} w_{ic} \times XCSCL_{ico}}{0.1 \times DMND_{ic}} \ge \alpha \tag{66}$$

Based on these constraints, the model was run in the GAMS 24.1/CPLEX software for 1103.37 s to maximise α and the following results were obtained in the relative gap of less than 5%. The objective function values are shown in Table 11:

For instance, the route traveled by the vehicle 1 is from the distribution centre 1 to the customer 5 and then customers 4 and 3, respectively. It is finally returned to the distribution centre 1 after serving customer 2. As the results show, each vehicle returns to its centre after servicing the allocated customers.

- Arrival times to each customer point are calculated as follows:

$at_{1,5} = 26$ $at_{1,4} = 75$ $at_{1,3} = 118$ $at_{1,2} = 161$ $at_{1,1} = 190$
$at_{2,3} = 34$ $at_{2,1} = 68$
$at_{3,6} = 24$ $at_{3,3} = 57$ $at_{3,2} = 96$ $at_{3,1} = 121$

$at_{1,5} = 26$ indicates the arrival time of vehicle 1 to customer 5. Hence, based on the results, it is possible to see the arrival time of each purchased vehicle to each allocated customer.

Based on the second objective function, the model shows shortages of 130 in total demand quantity. The total demand was 1130, out of which 1000 units is satisfied.

4.1. Managerial insights

As mentioned earlier, a portion of the data was extracted from the historical data and documents of the company under study, and the remaining datasets were simulated according to the experts' opinions. In this section, the level of improvement in the chain is presented based on actual data that pertain to the levels of production (plant), distribution, and customers.

Before applying the proposed model, all products manufactured in production line 1 were transferred to three distribution centres in the vicinity of the factory. In other words, each product was allocated to one distribution centre and these products were delivered to customers by six vehicles. With the implementation of the model, it was determined that two distribution centres would suffice for distributing this product among the customers, and three vehicles would be required for transferring these products from distribution centres to customers. The management had allocated each product to one distribution centre to sort and separate products from each other, which had increased the costs of the chain. On the other hand, the non-use of proper routing in the distribution of products among customers had led to the selection of short routes and the increased frequency of vehicular returns to the centres. Thus, the number of vehicles for this task, increased fuel consumption, environmental pollution, and, eventually, the chain costs had experienced an increase. The analysis of the results of the proposed mode in the production, distribution, and customer levels led to the removal of one distribution centre and three vehicles, which had a significant impact on costs and environmental pollution.

5. Conclusions

Circular economy offers much potential to help firms and organisations achieve dramatic impact on sustainability of supply chains. However, it has not received enough attention so far. This paper sets out to integrate CE in supplier selection and supply chain network design. To do so, in this paper, a two-stage hybrid approach is developed to fulfil circular supplier selection and order allocation in a CLSC by means of MCDM methods and a MOMILP. This approach concurrently focuses on the minimisation of the network costs and shortages. In the first stage, the suppliers of the studied firm were evaluated using three criteria, namely circularity, quality, and on-time delivery through the integrated approach of FANP and FDEMATEL; then, four qualified suppliers were selected from them. In the second stage, a mathematical model was developed and all four selected suppliers were chosen for collaboration after the model's implementation in GAMS software. The proposed model led to the reduction of one distribution centre and three vehicles. Consequently, this brought about a reduction in costs and emissions.

The suppliers' evaluations phase was conducted based on circular and traditional criteria; it is suggested that social research be taken into account in future research in order to select sustainable suppliers (Kannan, 2018). The design of a circular/sustainable supply chain network, considering the inventory-location-routing problem, is also an attractive problem that is suggested to be considered as a future research direction. Using new methods such as the fuzzy best-worst method, and its combination with other decision-making methods, can also be suggested for future research. As the last suggestion, due to the NP-hardness of the problem, employing meta-heuristic algorithms could ease the solvability of the considered models.

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