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An integrated chance-constrained stochastic model for a mobile phone closed-loop supply chain network with supplier selection

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ABSTRACT

One of the important concerns in the world is electronic waste (e-waste). Ending up e-waste in the landfill and inappropriate disposing of it are hazardous to the environment. The goal of this research is to design and optimize a multi-period, multi-product, multi-echelon, and multi-customer Closed-Loop Supply Chain (CLSC) network for a mobile phone network considering different types of product returns. Commercial, end of life, and end-of-use returns are well-known in practice. In this research, a multi-objective mixed-integer linear programming formulation with stochastic demand and return is proposed to maximize the total profit in the mobile phone CLSC network, alongside maximizing the weights of eligible suppliers which are estimated based on a fuzzy method for efficient supplier selection and order allocation. The goal is to determine the appropriate location and number of different facilities including suppliers, manufacturers, retailers, drop-off centres, and consolidation centres as well as the amount of required materials to produce a mobile phone, and the number of products that should be transported between various facilities. The application of the proposed mathematical model is illustrated in Toronto, Canada using real maps.

1. Introduction

Closed-Loop Supply Chain (CLSC) plays a crucial role in both industrial and environmental aspects. The increasing attention on CLSC initiated with public consciousness when governments enforced laws in order to collect and recycle End-Of-Life products properly. The forward supply chain considers supplier, manufacturer, and retailer, whereas reverse logistics may include drop-off and recycling centres which are responsible for gathering, recycling, and disposing of the used products. Considering forward and reverse supply chains together results in creation of CLSC (Govindan et al., 2015; Tosarkani and Amin, 2019; Papen and Amin, In Press). CLSC can be explained as the combination of design, examination, and control of a network for maximization of the values of the returned products via recovery options such as recycling (Guide and Van Wassenhove, 2009). Interested readers may refer to Guide and Van Wassenhove (2009) for information about the history of this topic. According to Guide and Van Wassenhove (2009), various types of returns can be presented. If the product is returned to the retailer by the customer within a specific timeframe, it can be considered as a commercial return. End-Of-Use (EOU) returns are the replacement of a product by a technological upgrade. Obsoleteness or uselessness of a product results in End-Of-Life (EOL) returns. The quality of commercial and EOU products is nearly the same as new products so that they can be resold to the second customers. Therefore, second customers will be encouraged to purchase a used product with a lower price as compared to a new product (John et al., 2017). The EOL products are collected by drop-off centres. After sufficient investigations, all reusable materials such as metal, glass, and plastics will be returned to be processed into new products. Unproductive items will be shipped to disposal centres to reduce the environmental pollution. The CLSC topic is directly related to 'cleaner production'. 'Cleaner production' is defined as the strategy for minimizing the effects of products and production on the environment (Fresner, 1998; Nielsen, 2007). Management of wastes is an important element in both CLSC and 'cleaner production'.

Order allocation is the process of determining the sizes of the orders that are assigned to different suppliers. The total amount of orders should be equal to the demand of the product. Interested readers may refer to Ghodsypour and O'Brien (1998) which is a well-known paper about order allocation. One of the most critical

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concerns of producers is to reduce the total cost. Moreover, considering the green impacts of suppliers has become very important. Providing a balance between these two objectives has become a challenge for organizations. Incorporation of supplier selection and order allocation strategies, not only can profoundly reduce the total cost, but also can yield a tactical key regarding raised carbon footprint issue of the suppliers (Govindan et al., 2014). Different factors should be considered in supplier selection which is a multi-criteria decision-making problem (Amin and Razmi, 2009). Several criteria of materials such as durability, being state-of-the-art, and small size are the most important factors that should be taken into account for supplier selection in CLSC networks specially when we are dealing with the mobile phone industry.

2. Literature review

In order to provide adequate understanding of the contributions of this paper, this section investigates the literature related to closed-loop supply chain and supplier selection methodologies.

2.1. CLSC network configuration

Some studies in the field of CLSC design and planning can be mentioned, in which different attitudes of network configuration are considered. In most of these studies, a general network is designed, while some CLSC networks are arranged and analyzed for precise products. Daniel et al. (2002) investigated various products that were remanufactured, and explained their supply chains. A summary of different features of the supply chains as well as their management issues were discussed. Jayaraman (2006) presented a mathematical programming model to calculate the units of disassembled, disposed, remanufactured, and acquired core type in a certain time period with a nominal quality level. Inventory of modules and cores that remain at the end of a certain time period can be determined by the model. Tosarkani and Amin (2018a) designed a CLSC network for a battery recycling system. They provided a multi-component, multi-echelon, multi-product, and multi-period model under imprecise information. A Fully Fuzzy Programming (FFP) method has been applied for this model. This network was realistic based on real distances and real information related to Vancouver, Canada. Besides, by expanding the mathematical model to the multi-objective, green factors related to manufacturers and battery recovery centres have been considered. The objectives include maximization of the total profit and the green factors. Cho et al. (2017) provided a mixed-integer non-linear programming formulation to analyze EOL options of computer parts in order to maximize the total profit related to computer remanufacturing considering multiple production periods. They proposed Ant colony and genetic search algorithms because the problem was NP hard.

Efficiency of time and energy has been analyzed in the CLSC model proposed by Kadambala et al. (2017). They developed a multi-objective programming model to optimize customer surplus and profit, in addition to minimizing applied energy. Xu et al. (2017) provided a novel global reverse supply chain. Uncertainty of waste collection, carbon emission, and other issues such as exchange rate and transportation cost have been considered in their work. Soleimani and Govindan (2015) developed a new solution methodology based on particle swarm technique and genetic algorithm to deal with a multi-period closed-loop supply chain network. They utilized a case study about Iranian hospital furniture manufacturer to examine the results. They showed that the new hybrid method obtains better results than particle swarm technique and genetic algorithm that are applied separately. Huang and Wang (2017) considered the effects of technology on CLSC network design and return management. Cheraghalipour et al. (2018) proposed a multi-objective model to configure a CLSC network. They introduced an innovative solution approach to find Pareto solutions. In a recent paper, Islam and Huda (2018) focused on electronic-waste (e-waste), and categorized the literature in this area. Mobile phone is an important type of e-waste.

To our knowledge, very few papers have focused on the mobile phones CLSC network, especially in Canada. It should be mentioned that without considering a specific product, it would be hard to apply proposed model and transfer it from theory to practice (Soleimani and Govindan, 2015). Optimization methods and simulation were combined by Franke et al. (2006) to make an integrated solution methodology for reproducing mobile phones. An environmental assessment method was executed by Huisman (2004) regarding recycling the mobile phones. He compared two scenarios about the discarded mobile phones in Sweden for 2003. Guide et al. (2005) contributed some statistics about a remanufacturing mobile phone company in U.S. Ponce-cueto et al. (2011) analyzed a reverse logistics system for the mobile phone industry in Spain, and investigated the efficient factors included in this part. Their results illustrate that the issues in the system arise from the low recovery quantity through the legitimate networks, extensive increasing secondary markets because of the potential values of the mobile phones, and irregular logistics and supply chain networks for the returned mobile phones. Velmurugan (2016) investigated a mobile phones remanufacturing considering health and environmental impacts. In the study of Argenta et al. (2017), recovery the parts of mobile phones such as LCD screens was examined. Noman and Amin (2017) investigated various important characteristics of reverse logistics and recycling of mobile phone in Canada emphasizing on British Columbia, Ontario, and Nova Scotia. Jayant et al. (2014) considered an integrated decision analysis method consisting of TOPSIS and Analytic Hierarchy Process (AHP) to opt the best mobile phone service provider in an RL system. The performance of a reverse logistics firm has been measured by an agent-based modeling technique provided by Pandian (2015). The different agents considered in this network are collector agent, sorting-cum-reuse agent, supplier agent, recycler agent, distributor agent, and remanufacturing agent. These agents act independently, and their individual performances are measured.

Not only it is essential to consider multiple-products to design a CLSC network for its economical efficiency, but also various types of returns and quality levels of the returned products should be regarded. Multi-product scheme has been utilized in many papers (e.g., Salema et al., 2006; Lee and Dong, 2008; Amin and Zhang, 2013; Ramezani et al., 2013; Soleimani and Govindan, 2015; Amin et al., 2017), however a very few studies include the different classes of returns and their quality levels (e.g., Dat et al., 2012; Alumur et al., 2012). The important point is that various recovery choices such as recycling, remanufacturing, and repairing should be considered in the design and analysis of a CLSC network (John et al., 2017). Amin and Zhang (2012a) developed a mixed-integer formulation to optimize a general network considering commercial, EOU, and EOL returns. In their paper, it is assumed that commercial returns go to the repair site, whereas EOU and EOL returns are disassembled. John et al. (2017) presented an integer programming mathematical model to design a multi-product and multi-echelon reverse logistics for two electronic products including digital cameras and mobile phones. Different recovery options and the cost of grading in collection centre have been considered in their model. Ignoring multi-period in input parameters are the most important drawbacks of both aforementioned works. In addition, it has been assumed that EOU or commercial returns are directed toward collection centres or repair sites, whereas in reality, EOU and commercial returned mobile phones are returned to the retailers. Besides, EOL products are shipped to the collection and drop-off centres for further inspections. A three-period electric vehicle battery closed-loop supply chain network was proposed by Gu et al. (2018). In the first period the batteries are manufactured. The second period relates to the reusing of some of high-quality used batteries, while in period three reused batteries are recycled. They optimized the total profit of the proposed network in different battery stages by developing the optimal pricing strategies resulting in decreasing raw material consumption and environmental pollution. A multi stage non-linear model was proposed by Bhattacharya et al. (2018) to analyze the EOL and EOU returns in each phase of the closed loop supply chain. Taleizadeh et al. (2019) configured a sustainable closed-loop supply chain network to measure the social and environmental impacts of supply chain decisions. They considered a discount offer on the returned products, dependant on their quality, to encourage customers to return their used products. They assumed all returned products are directed to the collection centre to be classified by their quality.

2.2. Supplier selection

There are many publications in the field of supplier selection and order allocation. An integrated decision model was provided by Ordoobadi (2010) in which AHP and the Taguchi loss function are utilized. In fact, the weights regarding the importance of tangible and intangible decision criteria were estimated using AHP, while suppliers were ranked by calculating the weighted Taguchi loss scores. An integration of Analytic Network Process (ANP), TOPSIS, and Linear Programming (LP) was provided by Lin et al. (2011) in order to rank the suppliers for the application of Enterprise Resource Planning (ERP) system. Jafari Songhori et al. (2011) developed an integration of Data Envelopment Analysis (DEA) and multi-objective mixed-integer programming model to perform supplier selection at first and order allocation alone. Amin and Zhang (2012b) considered three groups of qualitative and quantitative criteria including supplier-relevant, part-relevant, and process-relevant and developed an integrated mixed-integer programming model for supplier selection, order allocation, and CLSC network configuration. They utilized fuzzy method in order to assess the suppliers. A multi-objective DEA model based on type-2 fuzzy sets theory was proposed by Zhou et al. (2016) so that the most proper sustainable suppliers were assessed and chosen. Moheb-Alizadeh and Handfield (2017) utilized a bi-objective DEA to assess the efficiency and sustainability of suppliers in a multi-objective mixed-integer non-linear programming network. Babbar and Amin (2018) presented a model for supplier selection and order allocation considering both qualitative and quantitative environmental criteria. They proposed a two-stage Quality Function Deployment (QFD) in order to examine all suppliers comprehensively. Lo et al. (2018) proposed a novel approach which combines the Best-Worst Method (BWM), modified fuzzy TOPSIS, and Fuzzy Multi-Objective Linear Programming (FMOLP) in order for green supplier selection and order allocation. However, very few studies have considered supplier selection for closed-loop supply chain.

According to the literature review, Table 1 is presented as a comprehensive analysis. The outstanding goal of this research and its difference are explained in the last row, where the emphasis is on supplier selection, type of product, uncertainty, multi-period, real locations, and various types of returns. There are some research gaps in the literature. To our knowledge, there is no publication about CLSC network configuration focusing on mobile phones in Canada. In addition, most of the publications in this field have ignored commercial, end-of-use, and end-of-life returns together considering first and second customers. Furthermore, most publications have ignored supplier selection problem with CLSC network configuration, simultaneously. Our research contributions that aim to fill these gaps, are explained in the next section.

3. Aims and contributions of research

In this research, we consider different types of product returns as well as various selling prices based on quality, which has been ignored in many supply chain investigations. Mobile phone industry is an example in which different types of product returns are outstanding. In order to perform supplier selection and order allocation, a method is developed by which qualitative criteria are ranked. Moreover, a multi-objective mixed-integer linear programming formulation is provided to optimize and configure a CLSC network for mobile phone industry considering three types of returned products including commercial, EOU, and EOL, separately and their associated selling prices to make the model more applicable in the real world of mobile phones. Indeed, reselling of repaired and reconditioned products to the second customers is calculated in our model which has been ignored in many studies. Our aim is maximizing the total profit in the network alongside maximizing the weights of suppliers where the demands of first and second customers and the rate of returned products are assumed to be stochastic to be more realistic. Utilizing chance-constrained programming the deterministic equivalent of the stochastic constraints are acquired. The mathematical model comprises multiple products, multiple periods, suppliers, manufacturers, retailers, second and first customers, drop-off, consolidation, and disposal centres. The maps of different wards of Toronto, the population of each ward (which affects the demand and return), and the amount of mobile phones recycled in Ontario in 2016 are derived from Statistics Canada (2016). Using Google Maps, the distances between various facilities are obtained. To our knowledge, this research is the first study that applies supplier selection and order allocation to a mobile phone CLSC network configuration and optimization in Toronto, Ontario.

The main research contributions of this study in CLSC field are as follows:

- Development of a mathematical formulation to configure a CLSC network for mobile phone recovery and recycling in a multi-period and multi-product situation with considering different types of returned products in Toronto, Canada.
- Investigating reselling commercial and EOU returned products to the second customers with different selling prices.
- Applying chance-constrained programming to deal with stochastic sources in the CLSC network such as demand and rate of returned products. Integration of chance-constrained programming and multi-objective programming for CLSC network configuration and supplier selection is new in the literature.
- Developing a fuzzy method to estimate the qualitative weights for supplier selection and order allocation in the proposed CLSC network.
- Providing real distances in the proposed multi-echelon model using Google Maps to consider real transportation costs.

There are some benefits in applying the integrated chance-constrained programming technique. Chance-constrained programming is a unique method to consider uncertainty in the parameters. This method uses confidence levels. Combining multi-objective programming enables us to select the best supplier in addition to CLSC network configuration under uncertainty.

This research is organized as follows: Problem statement is

Table 1
Review of some papers.

References	Uncertainty	Type of Uncertainty	Type of Products	Multi-Period	Objectives			Real Locations Based on Map	Commercial, EOU, EOL Returns
					Cost/ profit	Supplier selection	Green factors		
Amin et al. (2017)	Demand, return	Randomness	Tire	✓	✓			✓	
Xu et al. (2017)	Waste collection level	Randomness	Not Applicable (N/A)	✓	✓				
Amin and Zhang (2013)	Decision-making process	Randomness	N/A	✓	✓	✓			
Subulan et al. (2015)			Tire	✓	✓		✓	✓	
Özceylan et al. (2017)			Automotive industry	✓	✓			✓	
John et al. (2017)			Mobile phone and camera		✓			✓	
Das and Rao Posinasetti (2015)			N/A		✓		✓		
Garg et al. (2015)			N/A		✓		✓	✓	
Dutta et al. (2016)	Demand	Randomness	N/A	✓	✓				
Chen et al. (2017)			Solar energy		✓		✓		
Ruimin et al. (2016)	Demand, cost parameters	Randomness	N/A		✓		✓	✓	
Talaei et al. (2016)	Demand, variable cost	Randomness	N/A		✓				
Moheb-Alizadeh and Handfield (2017)	Demand	Randomness, Linguistic	N/A	✓	✓	✓			
Tosarkani and Amin (2018a)	All parameter and decision variables	Randomness	Battery	✓	✓		✓	✓	
Babbar and Amin (2018)	Demand and unit costs	Randomness, Linguistic	Beverages	✓	✓	✓	✓		
Hasanov et al. (2019)				✓	✓		✓		
Taleizadeh et al. (2019)			Bulb	✓	✓		✓		
Our model	Demand and return	Randomness, Linguistic	Mobile phone	✓	✓	✓	✓	✓	✓

provided in Section 4. Then in Section 5, definition of the model, the fuzzy method, the mathematical formulation, and the chance-constrained programming are provided. Section 6 is assigned to the application of the multi-objective model. The multi-objective model is solved by ε-constraint method and distance method, respectively. Value Path Approach (VPA) is investigated in Section 7. Sensitivity analysis is described in Section 8. Finally, Section 9 contains conclusions.

4. Problem statement

According to development of technology and increasing use of electronic products, electronic waste has become one of the most important concerns in the world. As stated in Statistics Canada (2014), the overall amount of electronic waste generated in Canada in 2014 is estimated about 83,377 tonnes. Inappropriate discarding electronic devices or ending up in landfills are hazardous due to dispersing their chemical components into soil and water reservoirs. While by recycling unusable electronics, not only they will be kept out of landfills, but also it prevents them being illegally handled or exported by unreliable recyclers. Moreover, important materials that can be returned into the manufacturing supply chain will be recovered. In many countries, severe legislation and different incentives are established to guarantee take back products to reduce waste. For example, the Waste Electrical and Electronic Equipment or WEEE directive (Directive, 2002/96/EC) turned into a European law in 2003, emphasizing on collecting, recycling, and remanufacturing of different types of electrical products (Georgiadis and Besiou, 2010). WEEE closed-loop supply chain management is much more essential than other EOL products, since not only it encounters recycling and manufacturing recoverable materials like glass, plastics, and precious metals (Cao et al., 2016), but also hazardous elements like nickel, lead, and mercury are required to be disposed of in order to protect both the health and safety of people and the environment (Oguchi et al., 2013; Yu and Solvang, 2016). Therefore, designing and planning CLSC networks for WEEE management is important. Ontario Electronic Stewardship (OES) is responsible for collecting end-of-life electronics (EOLE) and recycling them. EOL electronics are dropped off at OES authorized collection centres. Provincial data and statistics related to electronic devices can be found in their website. Most of the components of a mobile phone are recyclable. Particularly, 40% of Plastics, 15% of Glasses and Ceramics, and 15% of Coppers can be recycled (Mobile Phone Partnership Initiative, 2008; Noman and Amin, 2017). According to U.S. Environmental Protection Agency (2017), 35,274 lbs of Copper, 75 lbs of Gold, 772 lbs of Silver, 33 lbs of Palladium are extracted due to recycling each 1 million mobile phones. Although in this paper the focus is on the EOL mobile phones, the applied materials can be generalized to a lot of electronic devices like TVs, smart watches, and laptops.

Fig. 1 shows a closed-loop supply chain network for mobile phone recycling and reselling with multi-materials, multi-products in multiple periods. This network includes suppliers, manufacturers, retailers, first and second customers, drop-off centres, consolidation centres, and disposal centres. Manufacturers purchase the main materials of mobile phone from suppliers and generate four types of products. Then, the outputs are shipped to the retailers. It is required that the retailers satisfy the demands of both first and second customers by storing the least possible aggregating inventory to decrease related costs.

First customers purchase new mobile phones from retailers. Some of them can be returned to the retailers as commercial or EOU, whereas some others are directed toward drop-off centres (EOL). The mobile phones returned to the retailer are resold to the second customers with a lower price. EOL mobile phones are shipped to consolidation centres from drop-off centres for more investigations and decomposition to the main materials. Some of these materials can be recycled and forwarded to the

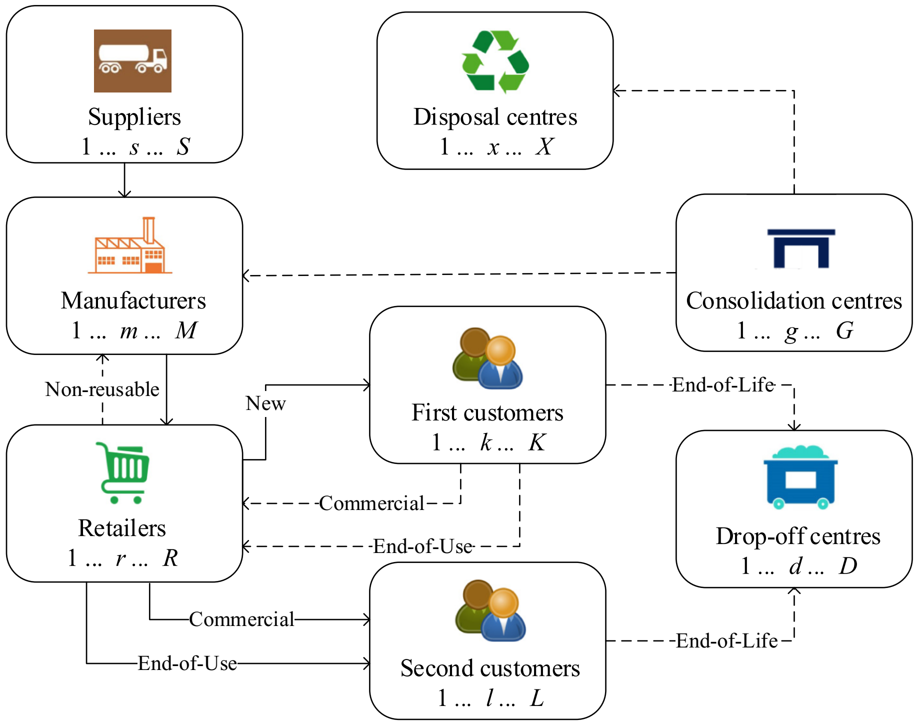

Fig. 1. A closed-loop supply chain of mobile phone including recycling and reselling.

manufacturers for further consumption, while unusable components are shipped to the disposal centres.

According to the network described in Fig. 1, suppliers are evaluated. The various steps of the problem definition are illustrated in Fig. 2. The first phase is devoted to the determination of the weights of suppliers using a fuzzy method. In the second phase, a multi-objective closed-loop supply chain network is proposed. The demand and return are considered to be stochastic. The final stage calculates the values of the variables.

The objective of this paper is to clarify the following issues: Which suppliers are appropriate for providing materials? Which locations should be selected for manufacturers? Which retailers should be opened? Which drop-off centres must be responsible for collecting EOL products? Which consolidation centres are suitable for decomposing of mobile phones? How many materials should be purchased from selected suppliers? How many products are transported between various facilities?

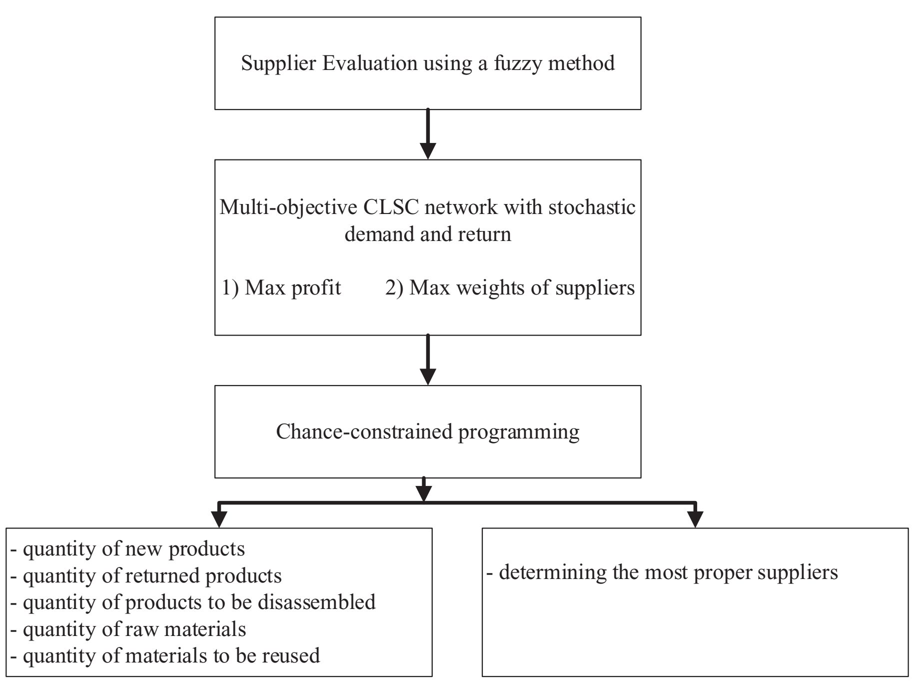

Fig. 2. The various steps of the problem definition.

5. Proposed model

In the first step, suppliers are evaluated. Then, a mathematical model is developed to configure the network. Besides, Chance-constrained programming is utilized to solve the problem.

5.1. Evaluation of suppliers

Amin and Zhang (2012b) developed a fuzzy model to rank the suppliers. In this section, we develop and apply a fuzzy method which is based on their proposed method. Our method considers linguistic variables and trapezoidal fuzzy numbers (TFNs) in order to calculate the weights of suppliers. Using this method, various criteria can be categorized in different groups and the importance of each group can be ranked. Specially for configuring a CLSC network for mobile phones, this issue becomes significant. A group of decision-makers including three managers (experts) with different levels of experience and expertise assign weights to different categories and criteria. Since the opinions of experienced decision-makers are more reliable, it is necessary to consider the level of experience of decision-makers to assess the weights of criteria. In order to evaluate the level of experience of each decision-maker, a linguistic variable is defined as depicted in Fig. 3. The lowest level of experience is determined by (0, 0, 3, 6), while the average level of experience is given by (0, 3, 9, 12), and the highest level of experience is assigned by (6, 9, 12, 12). Therefore, $\omega e_1 = (0, 3, 9, 12)$, $\omega e_2 = (6, 9, 12, 12)$, and $\omega e_3 = (6, 9, 12, 12)$, where ωe_{DM} is the level of experience (weight) of each decision-maker and $\Delta(\delta = 1, 2, 3, \ldots, \Delta)$ is the number of decision-makers. The number of criteria and the number of suppliers are given by N $(n = 1, 2, 3, \ldots, N)$ and S $(s = 1, 2, 3, \ldots, S)$, respectively. Each Supplier s provides J materials $(j = 1, 2, 3, \ldots, J)$. The steps of this process are as follows:

Step 1: In this step, appropriate criteria should be determined. Supplier, material, service, and environmental are the main categories of our framework which are shown in Fig. 4. In mobile phone CLSC network design, several criteria related to components such as defect rate, small size, being state-of-the-art, durability, and strength are significant. Moreover, because of the hazardous substances applied in mobile phones manufacturing, it is crucial for their materials to be recyclable and reusable. In addition, the latest technology should be taken into account to provide environmental friendly and less polluting components.

Step 2: Assume that the opinion of each decision-maker is expressed by the linguistic variables $\Lambda = \{VL, L, ML, M, MH, H, VH\}$. Utilizing trapezoidal fuzzy numbers, these variables are quantified as shown in Fig. 5.

Each decision-maker evaluates all categories and provides a level of importance for them using linguistic scales. The weight of decision-makers is multiplied by the weight of each category in order to contribute the level of experience of each decision-maker in their opinions regarding each category. Suppose λ_p represents the weight of each category, where p is defined as each category $(p = 1, 2, 3, 4)$. Therefore, the aggregated weight of each category is calculated by Eq. (1). The results are shown in Table 2.

$$\lambda_p = \frac{(\omega e_1 \times \lambda_{p1}) + (\omega e_2 \times \lambda_{p2}) + \ldots + \left(\omega e_D \times \lambda_{p\Delta}\right)}{\Delta} \tag{1}$$

Step 3: If we define $U_{pn\Delta}$ as the weight of criterion n in category p provided by decision-maker Δ, the aggregated weight of each criterion can be calculated using Eq. (2).

$$U_{pn} = \frac{(\omega e_1 \times U_{pn1}) + (\omega e_2 \times U_{pn2}) + \ldots + \left(\omega e_{DM} \times U_{pn\Delta}\right)}{\Delta} \tag{2}$$

The 3 decision-makers decided to focus on 14 criteria (selected from Fig. 4) to avoid complexity in the decision-making process. The results are written in Table 3.

Step 4: Assume that the evaluation of supplier s which provides material j (i.e., glass, metals, plastic, battery, screen, electrical units) regarding criterion n in category p established by decision-maker Δ is represented by $Ft_{sjpn\Delta}$. In this paper, we focus on EOL mobile phones. Some of these materials are common in EOL electronic products. The aggregated level of importance of supplier s according to criterion n and material j in category p is determined by Eq. (3). Table 4 illustrates decision-makers' ranking related to supplier 1 who provides material 1 (metal).

$$Ft_{sjpn} = \frac{(\omega e_1 \times Ft_{sjpn1}) + (\omega e_2 \times Ft_{sjpn2}) + \ldots + \left(\omega e_{DM} \times Ft_{sjpn\Delta}\right)}{\Delta} \tag{3}$$

Step 5: In this step, all calculated weights in the previous steps are multiplied as shown in Eq. (4). The results are provided in Table 5. Since the calculated number, $\zeta_{js} = (a, b, c, d)$, is a TFN, it is required to be defuzzified using Eq. (5) (Chou and Chang, 2008).

$$\zeta_{sj} = \sum_{p=1}^{4} \sum_{n=1}^{N} \lambda_p \times U_{pn} \times Ft_{sjpn} \tag{4}$$

$$\psi_{sj} = \frac{a + b + c + d}{4} \tag{5}$$

Step 6: In the final step, each supplier is ranked by normalizing its level of importance according to each criterion using Eq. (6). The rank of each supplier for each material is written in Table 6.

$$\pi_{sj} = \frac{\psi_{sj}}{\sum_{s=1}^{S} \psi_{sj}} \tag{6}$$

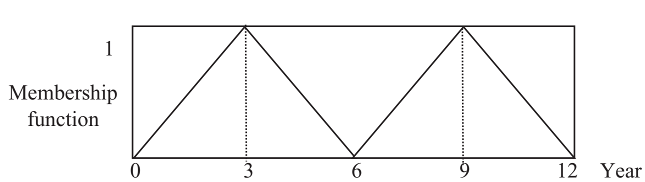

Fig. 3. A linguistic scale for providing experience level.

5.2. Mathematical model

In this section, a stochastic mathematical formulation is provided which deals with the mobile phone CLSC in Fig. 1. Different elements of the mathematical model are defined in this section.

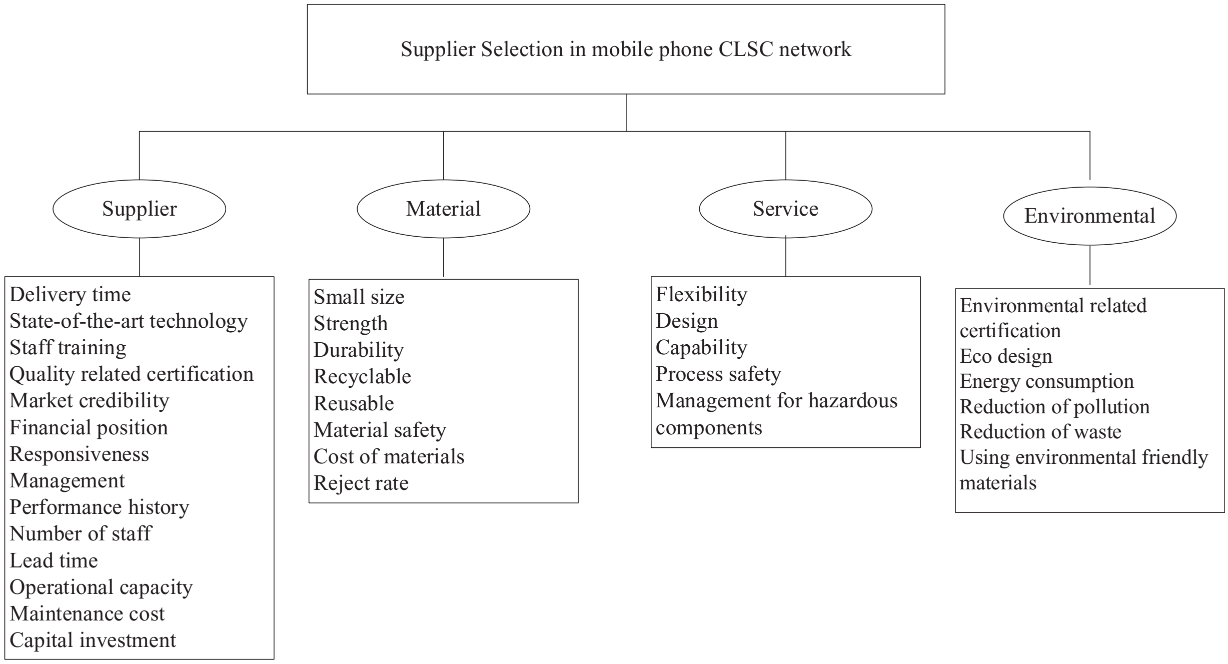

Fig. 4. Supplier selection framework in mobile phone CLSC network.

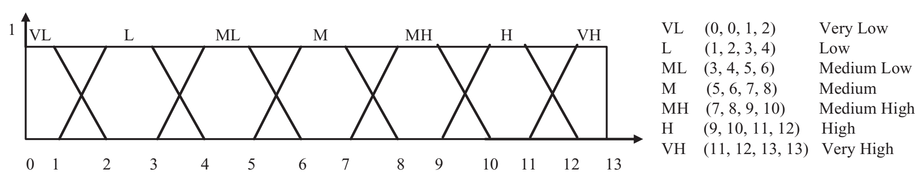

Fig. 5. Linguistic scale.

Table 2
Weights of categories.

Category	Δ_1	Δ_2	Δ_3	$\omega e_1 \times \lambda_{p1}$	$\omega e_2 \times \lambda_{p2}$	$\omega e_3 \times \lambda_{p3}$	λ_p
Supplier	H	MH	M	(0,30,99,144)	(42,72,108,120)	(30,54,84,96)	(24,52,97,120)
Material	MH	H	H	(0,24,81,120)	(54,90,132,144)	(54,90,132,144)	(36,68,115,136)
Service	MH	M	H	(0,24,81,120)	(30,54,84,96)	(54,90,132,144)	(28,56,99,120)
Environmental	M	M	MH	(0,18,63,96)	(30,54,84,96)	(42,72,108,120)	(24,48,85,104)

Table 3
Weights of criteria.

Criteria	Δ_1	Δ_2	Δ_3	$\omega e_1 \times U_{pn1}$	$\omega e_2 \times U_{pn2}$	$\omega e_3 \times U_{pn3}$	U_{pn}
State-of-the-art technology	H	VH	H	(36,68,115,136)	(36,68,115,136)	(36,72,127,148)	(40,76,129,148)
Market credibility	H	M	H	(0,30,99,144)	(30,54,84,96)	(54,90,132,144)	(28,58,105,128)
Performance history	H	MH	VH	(0,30,99,144)	(42,72,108,120)	(66,108,156,156)	(36,70,121,140)
Strength	MH	H	MH	(0,24,81,120)	(54,90,132,144)	(42,72,108,120)	(32,62,107,128)
Durability	MH	M	M	(0,24,81,120)	(30,54,84,96)	(30,54,84,96)	(20,44,83,104)
Recyclable	H	MH	H	(0,30,99,144)	(42,72,108,120)	(54,90,132,144)	(32,64,113,136)
Flexibility	H	VH	H	(0,30,99,144)	(66,108,156,156)	(54,90,132,144)	(40,76,129,148)
Design	H	MH	MH	(0,30,99,144)	(42,72,108,120)	(42,72,108,120)	(28,58,105,128)
Process safety	MH	MH	H	(0,24,81,120)	(42,72,108,120)	(54,90,132,144)	(32,62,107,128)
Energy consumption	VL	ML	L	(0,0,9,24)	(18,36,60,72)	(6,18,36,48)	(8,18,35,48)
Environmental friendly	MH	H	H	(0,24,81,120)	(54,90,132,144)	(54,90,132,144)	(36,68,115,136)
Lead time	MH	H	H	(0,24,81,120)	(54,90,132,144)	(54,90,132,144)	(36,68,115,136)
Cost of materials	VH	H	H	(0,36,117,156)	(54,90,132,144)	(54,90,132,144)	(36,72,127,148)
Reject rate	L	VL	L	(0,6,27,48)	(0,0,12,24)	(6,18,36,48)	(2,8,25,40)

Table 4
Evaluation of supplier 1 for material 1.

Criteria	Δ_1	Δ_2	Δ_3	$\omega e_1 \times Ft_{smjpn1}$	$\omega e_2 \times Ft_{smjpn2}$	$\omega e_3 \times Ft_{smjpn3}$	Ft_{smjpn}
State-of-the-art technology	H	MH	M	(0,30,99,144)	(42,72,108,120)	(30,54,84,96)	(24,52,97,120)
Market credibility	H	VH	H	(0,30,99,144)	(66,108,156,156)	(54,90,132,144)	(40,76,129,148)
Performance history	MH	H	MH	(0,24,81,120)	(54,90,132,144)	(42,72,108,120)	(32,62,107,128)
Strength	H	MH	VH	(0,30,99,144)	(42,72,108,120)	(66,108,156,156)	(36,70,121,140)
Durability	M	M	MH	(0,18,63,96)	(30,54,84,96)	(42,72,108,120)	(24,48,85,104)
Recyclable	H	VH	H	(0,30,99,144)	(66,108,156,156)	(54,90,132,144)	(40,76,129,148)
Flexibility	MH	MH	H	(0,24,81,120)	(42,72,108,120)	(54,90,132,144)	(32,62,107,128)
Design	M	M	M	(0,18,63,96)	(30,54,84,96)	(30,54,84,96)	(20,42,77,96)
Process safety	H	MH	H	(0,30,99,144)	(42,72,108,120)	(54,90,132,144)	(32,64,113,136)
Energy consumption	VL	VL	L	(0,0,9,24)	(0,0,12,24)	(6,18,36,48)	(2,6,19,32)
Environmental friendly	MH	M	M	(0,24,81,120)	(30,54,84,96)	(30,54,84,96)	(20,44,83,104)
Lead time	M	M	M	(0,18,63,96)	(30,54,84,96)	(30,54,84,96)	(20,42,77,96)
Cost of materials	H	VH	VH	(0,30,99,144)	(66,108,156,156)	(66,108,156,156)	(44,82,137,152)
Reject rate	L	ML	L	(0,6,27,48)	(18,36,60,72)	(6,18,36,48)	(8,20,41,56)

Table 5
Final score for supplier 1 according to material 1.

Criteria	λ_p	U_{pn}	Ft_{smjpn}	Final score
State-of-the-art technology	(24,52,97,120)	(40,76,129,148)	(24,52,97,120)	(23040,205504,1213761,2131200)
Market credibility	(24,52,97,120)	(28,58,105,128)	(40,76,129,148)	(26880,229216,1313865,2273280)
Performance history	(24,52,97,120)	(36,70,121,140)	(32,62,107,128)	(27648,225680,1255859,2150400)
Strength	(36,68,115,136)	(32,62,107,128)	(36,70,121,140)	(41472,295120,1488905,2437120)
Durability	(36,68,115,136)	(20,44,83,104)	(24,48,85,104)	(17280,143616,811325,1470976)
Recyclable	(36,68,115,136)	(32,64,113,136)	(40,76,129,148)	(46080,330752,1676355,2737408)
Flexibility	(28,56,99,120)	(40,76,129,148)	(32,62,107,128)	(35840,263872,1366497,2273280)
Design	(28,56,99,120)	(28,58,105,128)	(20,42,77,96)	(15680,136416,800415,1474560)
Process safety	(28,56,99,120)	(32,62,107,128)	(32,64,113,136)	(28672,222208,1197009,2088960)
Energy consumption	(24,48,85,104)	(8,18,35,48)	(2,6,19,32)	(384,5184,56525,159744)
Environmental friendly	(24,48,85,104)	(36,68,115,136)	(20,44,83,104)	(17280,143616,811325,1470976)
Lead time	(24,52,97,120)	(36,68,115,136)	(20,42,77,96)	(17280,148512,858935,1566720)
Cost of materials	(36,68,115,136)	(36,72,127,148)	(44,82,137,152)	(57024,401472,2000885,3059456)
Reject rate	(36,68,115,136)	(2,8,25,40)	(8,20,41,56)	(576,10880,117875,303640)
	ζ_{111}=(355136,2762048,14969536,25598720), $\psi_{111} = 10921360$			

Table 6
Weight of supplier s according to material j.

s	j				
	1	2	3	4	5
1	0.36	0.34	0.35	0.35	0.35
2	0.33	0.36	0.35	0.35	0.36
3	0.35	0.39	0.34	0.32	0.35
4	0.29	0.25	0.21	0.23	0.27
5	0.33	0.35	0.35	0.36	0.33
6	0.21	0.21	0.38	0.35	0.36

They are defined based on the details of the network (Fig. 1). Then, an application is shown, and sensitivity analysis is applied to make sure the model is valid.

Sets	
M	set of manufacturers ($1 \ldots m \ldots M$)
S	set of suppliers ($1 \ldots s \ldots S$)
R	set of retailers ($1 \ldots r \ldots R$)
K	set of first customers ($1 \ldots k \ldots K$)
L	set of second customers ($1 \ldots l \ldots L$)
D	set of drop-off centres ($1 \ldots d \ldots D$)
X	set of disposal centres ($1 \ldots x \ldots X$)
I	set of products ($1 \ldots i \ldots I$)
J	set of materials ($1 \ldots j \ldots J$)
G	set of consolidation centres ($1 \ldots g \ldots G$)
T	set of periods ($1 \ldots t \ldots T$)

(*continued*)

Parameters	
fa_m	fixed-cost of manufacturer m
fb_s	fixed-cost of supplier s
fc_r	fixed-cost of retailer r
fd_d	fixed-cost of drop-off centre d
fe_g	fixed-cost of consolidation centre g
$\widehat{Ac_{kit}}$	stochastic demand of product i by first customer k in period t
$\widehat{As_{lit}}$	stochastic demand of product i by second customer l in period t
P_i^n	unit price of selling new product i
P_i^u	unit price of selling used return product i
P_i^c	unit price of selling commercial return product i
ka_{smt}	unit transportation cost from supplier s to manufacturer m in period t
kb_{mrt}	unit transportation cost from manufacturer m to retailer r in period t
kc_{rmt}	unit transportation cost from retailer r to manufacturer m in period t
kd_{dgt}	unit transportation cost from drop-off centre d to consolidation centre g in period t
ke_{gmt}	unit transportation cost from consolidation centre g to manufacturer m in period t
kf_{gxt}	unit transportation cost from consolidation centre g to disposal centre x in period t
ω_{sjt}	unit price of raw material j from supplier s in period t
μ_{mit}	unit production cost of product i made by manufacturer m in period t
γ_{git}	unit decomposition cost of product i by consolidation centre g in period t
dw_{rit}	unit inspection cost of returned product i by retailer r in period t
dh_{xjt}	unit disposal cost of material j by disposal centre x in period t
θ_{sm}	the distance between supplier s and manufacturer m
θ_{mr}	the distance between manufacturer m and retailer r
θ_{dg}	the distance between drop-off centre d and consolidation centre g
θ_{gm}	the distance between consolidation centre g and manufacturer m

(*continued on next page*)

(continued)

θ_{gx}	the distance between consolidation centre g and disposal centre x
$\widehat{zc_{kit}}$	stochastic end-of-life returned product i from first customer k in period t
$\widehat{zs_{lit}}$	stochastic end-of-life returned product i from second customer l in period t
τc_{kit}	percentage of commercial returned product i from customer k in period t
τu_{kit}	percentage of end-of-use returned product i from customer k in period t
τl_{rit}	percentage of unusable product i from retailer r in period t
σ_{it}	unit penalty cost of product i in period t
η_j	unit cost saving of material j owing to product decomposition
β_{ij}	amount of material j used to produce product i
ρ_i	unit inventory cost of product i
ε_j	disposal fraction of the material j
π_{sj}	weight of supplier s for material j
$mcap_{mj}$	inventory capacity of manufacturer m for material j
$rcap_{ri}$	inventory capacity of retailer r for product i
$dcap_{di}$	inventory capacity of drop-off centre d for product i
$gcap_{gi}$	inventory capacity of consolidation centre g for product i
$scap_{sj}$	inventory capacity of supplier s for material j
Decision Variables	
a^n_{rkit}	quantity of new product i sold by retailer r to first customer k in period t
a^u_{rlit}	quantity of used product i sold by retailer r to second customer l in period t
a^c_{rlit}	quantity of commercial return product i sold by retailer r to second customer l in period t
q_{smjt}	quantity of raw material j shipped from supplier s to manufacturer m in period t
a_{mrit}	quantity of product i shipped from manufacturer m to retailer r in period t
b^c_{krit}	quantity of commercial return product i shipped from first customer k to retailer r in period t
b^u_{krit}	quantity of used product i shipped from first customer k to retailer r in period t
a^l_{rmit}	quantity of unusable product i shipped from retailer r to manufacturer m in period t
ef_{kdit}	quantity of product i shipped from first customer k to drop-off centre d in period t
es_{ldit}	quantity of product i shipped from second customer l to drop-off centre d in period t
n_{dgit}	quantity of product i shipped from drop-off centre d to consolidation centre g in period t
φ_{gmjt}	quantity of raw material j shipped from consolidation centre g to manufacturer m in period t
u_{gxjt}	quantity of material j shipped from consolidation centre g to disposal centre x in period t
In_{rit}	quantity of new product i holding as the inventory in retailer r in period t
ya_m	1 if manufacturer m is open; 0 otherwise
yb_s	1 if supplier s is open; 0 otherwise
yc_r	1 if retailer r is open; 0 otherwise
yd_d	1 if drop-off centre d is open; 0 otherwise
ye_g	1 if consolidation centre g is open; 0 otherwise

$$Max\ z_2 = \sum_s\sum_m\sum_j\sum_t \pi_{sj} q_{smjt} \tag{8}$$

s.t.

$$\sum_r\sum_i \beta_{ij} a_{mrit} = \sum_s q_{smjt} + \sum_g \varphi_{gmjt} + \sum_r\sum_i \beta_{ij} a^l_{rmit} \qquad \forall j, m, t \tag{9}$$

$$\sum_m a_{mrit} + In_{r(t-1)i} = In_{rit} + \sum_k a^n_{rkit} \qquad \forall i,\ r,\ t \tag{10}$$

$$\sum_r a^n_{rkit} \le \widehat{Ac_{kit}} \qquad \forall i,\ k,\ t \tag{11}$$

$$\sum_r a^u_{rlit} + \sum_r a^c_{rlit} \le \widehat{As_{lit}} \qquad \forall i,\ l,\ t \tag{12}$$

$$\sum_m a_{mrit} + In_{rit} \ge \sum_k a^n_{rkit} \qquad \forall i,\ r,\ t \tag{13}$$

$$\sum_r a^n_{rkit} \ge \sum_d ef_{kdit} \qquad \forall i,\ k,\ t \tag{14}$$

$$\sum_r a^u_{rlit} + \sum_r a^c_{rlit} \ge \sum_d es_{ldit} \qquad \forall i,\ l,\ t \tag{15}$$

$$\sum_k ef_{kdit} + \sum_l es_{ldit} = \sum_g n_{dgit} \qquad \forall i,\ d,\ t \tag{16}$$

$$\sum_d \beta_{ij} n_{dgit} = \sum_m \varphi_{gmjt} + \sum_x u_{gxjt} \qquad \forall i, j,\ g,\ t \tag{17}$$

$$\sum_d ef_{kdit} = \widehat{zc_{kit}} \qquad \forall i, k, t \tag{18}$$

$$\sum_d es_{ldit} = \widehat{zs_{lit}} \qquad \forall i, l, t \tag{19}$$

$$\begin{aligned} Max\ z_1 = & \sum_r\sum_k\sum_l\sum_i\sum_t \left(P^n_i a^n_{rkit} + P^u_i a^u_{rlit} + P^c_i a^c_{rlit}\right) \\ & - \Bigg[\sum_m fa_m ya_m + \sum_s fb_s yb_s + \sum_r fc_r yc_r + \sum_d fd_d yd_d + \sum_g fe_g ye_g \\ & + \sum_s\sum_m\sum_j\sum_t (\omega_{sjt} + ka_{smt}\theta_{sm}) q_{smjt} \\ & + \sum_m\sum_r\sum_i\sum_t (\mu_{mit} + kb_{mrt}\theta_{mr}) a_{mrit} + \sum_r\sum_i\sum_t \rho_i In_{rit} \\ & + \sum_r\sum_m\sum_k\sum_i\sum_t \left((dw_{rit} + \sigma_{it}) b^c_{krit} + dw_{rit} b^u_{krit} + (dw_{rit} + kc_{rmt}\theta_{mr}) a^l_{rmit}\right) \\ & + \sum_d\sum_g\sum_i\sum_t \left(\gamma_{git} + kd_{dgt}\theta_{dg}\right) n_{dgit} \\ & + \sum_m\sum_g\sum_x\sum_j\sum_t \left(\left(ke_{gmt}\theta_{gm} - \eta_j\right)\varphi_{gmjt} + \left(kf_{gxt}\theta_{gx} + dh_{xjt}\right) u_{gxjt}\right)\Bigg] \end{aligned} \tag{7}$$

$$\sum_r b^c_{krit} = \tau c_{kit} \sum_r a^n_{rkit} \qquad \forall i,k,t \tag{20}$$

$$\sum_r b^u_{krit} = \tau u_{kit} \sum_r a^n_{rkit} \qquad \forall i,k,t \tag{21}$$

$$\sum_m a^l_{rmit} = \tau l_{rit} b^u_{krit} \qquad \forall i,k,r,t \tag{22}$$

$$\varepsilon_j \sum_d \sum_i \beta_{ij} n_{dgit} \le \sum_m \varphi_{gmjt} \qquad \forall j,g,t \tag{23}$$

$$\sum_s \sum_j q_{smjt} + \sum_g \sum_j \varphi_{gmjt} + \sum_r \sum_i \sum_j \beta_{ij} a^l_{rmit} \le ya_m \sum_j mcap_{mj} \qquad \forall m,\ t \tag{24}$$

$$\sum_m \sum_i a_{mrit} + \sum_i In_{rit} + \sum_k \sum_i b^c_{krit} + \sum_k \sum_i b^u_{krit} \le yc_r \sum_i rcap_{ri} \qquad \forall r,\ t \tag{25}$$

$$\sum_k \sum_i ef_{kdit} + \sum_l \sum_i es_{ldit} \le yd_d \sum_i dcap_{di} \qquad \forall d,\ t \tag{26}$$

$$\sum_d \sum_i n_{dgit} \le ye_g \sum_i gcap_{gi} \qquad \forall g,t \tag{27}$$

$$\sum_m \sum_j q_{smjt} \le yb_s \sum_j scap_{sj} \qquad \forall s,t \tag{28}$$

$$ya_m,\ yb_s,\ yc_r,\ yd_d,\ ye_g \in \{0,1\} \qquad \forall m,\ s,\ r,\ d,\ g \tag{29}$$

$$a^n_{rkit},\ a^u_{rlit},\ a^c_{rlit},\ q_{smjt},\ a_{mrit},\ b^c_{krit},\ b^u_{krit},\ a^l_{rmit},\ e_{(k+l)dit},\ n_{dgit},\ \varphi_{gmjt},\ u_{gxjt},\ In_{rit} \ge 0 \qquad \forall i,j,s,\ m,\ r,\ k,\ l,\ d,\ g,\ x,\ t \tag{30}$$

The first objective function is designed to maximize the entire profit in the mobile phone CLSC network. The first section is about the net income provided by selling products including selling new products in addition to commercial and used returned products. The second part is deducted from the total fixed-costs related to the locations of the manufacturers, suppliers, retailers, drop-off centres, and consolidation centres. The third portion describes buying and transporting expenses of materials from suppliers to the manufacturers. Production and transportation costs among manufacturers and retailers are implied in the fourth portion. The expenses associated with the retailers include inventory cost, inspection cost of the returned products by the first customers, shipping cost of unreusable goods to the manufacturers, and penalty cost, σ_{it}. The commercial returned products are resold to the second customers with a lower price from that of a new product. This difference is considered as a penalty cost for retailers. In fact, $\sigma_{it} = p^n_i - p^c_i$. The expenses of transporting EOL products from drop-off centres to the consolidation centres as well as decomposition cost by the consolidation centres are considered in the next part of the objective function. It is assumed that after decomposition of EOL products to the principal materials, the usable materials will be shipped to the manufacturer to be consumed in the future products. Therefore, a revenue can be defined, η_j, which is the cost saving owing to the product decomposition. Finally, the costs related to shipping unrecoverable materials from consolidation centres to the disposal centres, and the disposal cost are mentioned in the objective function. Furthermore, the second objective function maximizes the weights of eligible suppliers which are estimated based on the developed fuzzy method.

Constraint (9) implies that the materials consumed to produce a product should be equal to the total materials purchased from suppliers and materials obtained from consolidation centres along with materials provided by unusable returned products from retailers. Constraint (10) shows that the quantity of the products sent from manufacturers to the retailers (a_{mrit}) and the inventory in period $(t-1)$ are identical to the inventory in period t and the amount of products sold by retailers to the first customer (a^n_{rkit}). It considers some excess materials that go to the next time slot. Constraint (11) satisfies the demands related to customers. Constraint (12) is related to the stochastic demand. The sign of this constraint is $\le$. The combination of the first objective function (maximization of profit) and this constraint, limits the values of the decision variables, and avoids unbounded solutions. Constraint (13) illustrates that the number of products transported from the manufacturers to the retailers plus the current inventory should exceed the number of products sold to the first customers. Constraints (14) and (15) signify the trade-off between the products sold to the first and second customers and the returned products. The number of products sold to either first or second customers should be greater than or equal to the number of returned products to drop-off centres. Constraint (16) is the network constraint. Constraint (17) specifies the balance between the materials of the returned products and the recovered materials directed to manufacturers in addition to unrecoverable materials shipped to the disposal centres. Constraints (18) and (19) imply that the items shipped from drop-off centres to consolidation centres must be equal to the number of products that are returned by first or second customers to drop-off centres. Constraints (20), (21), and (22) define the percentages of returns. Constraint (23) mentions the disposal part of the returned products. Constraints (24), (25), (26), (27), (28) are related to the capacities of the manufacturers, retailers, drop-off centres, consolidation centres, and suppliers, respectively. Eventually, Constraints (29) and (30) describe non-negative and binary variables. The demand of the first and second customers for product i and the returns of both markets, k and l, for product i in period t are assumed to be stochastic.

5.3. Chance-constrained programming

Some methodologies can be taken into account to deal with stochastic parameters in optimization models (Moheb-Alizadeh and Handfield, 2017). One of the methods that has been used in many studies is Chance-Constrained Programming (CCP) proposed by Charnes et al. (1990). Assume a mathematical programming with stochastic parameters as follows:

$$\begin{cases} \max f(x) \\ \textit{subject to}: \\ g_v(x,\xi) \le 0, v = 1,2,\ldots,p \end{cases} \tag{31}$$

where x and ξ are a decision vector and a stochastic vector, respectively. $f(x)$ is a non-stochastic objective function and $g_v(x,\xi)$ is a stochastic constraint. A stochastic decision problem can be also written as follows (Liu, 1999):

$$\begin{cases} \max f(x) \\ subject\ to: \\ Pr\{\xi | g_\nu(x,\xi) \le 0\} \ge \alpha_\nu, \nu = 1,2,\dots,p \end{cases} \tag{32}$$

where α_ν is a predetermined confidence level to the respective stochastic constraint and Pr{.} indicates the probability of the event in {.}. The stochastic constraint is required to be converted to its deterministic equivalent.

In our work, $\widehat{Ac_{kit}}$, $\widehat{AS_{lit}}$, $\widehat{zc_{kit}}$, and $\widehat{zs_{lit}}$ are stochastic parameters which are in some constraints. In order to deal with them, they are transferred to their respective deterministic equivalents based on their predetermined confidence levels. Hence, a deterministic programming model will be acquired which can be solved with typical solution approaches. Although this process sounds hard and can be only favourable for some special cases, using some known results we can deal with the stochastic constraints in our study.

Case I. Assume that the chance-constrained programming is as follows:

$$\Pr\{\xi_\nu | h_\nu(x) \le \xi_h\} \ge \alpha_h \quad h = 1,2,\dots,p \tag{33}$$

Where $h_\nu(x)$ and ξ_h are decision functions and stochastic parameters, respectively. $F_\nu(\xi_\nu)$, $\nu = 1, 2, \dots, p$ is defined as a cumulative distribution function. Therefore, the deterministic equivalent of Eq. (33) can be calculated by Eq. (34).

$$h_\nu(x) \le f_\nu^{-1}(1-\alpha_\nu) \tag{34}$$

where f_ν^{-1} is the inverse of cumulative distribution function.

On the other hand, if the chance-constrained programming is as follows:

$$\Pr\{\xi_\nu | h_\nu(x) \ge \xi_\nu\} \ge \alpha_\nu \quad \nu = 1,2,\dots,p \tag{35}$$

The deterministic equivalent of Eq. (35) can be written as Eq. (36).

$$h_\nu(x) \ge f_\nu^{-1}(\alpha_\nu) \tag{36}$$

Thus, we can reformulate the stochastic Constraints (11), (12), (18), and (19) as follows:

$$\Pr\left\{g\left(x,\widehat{Ac}\right) \le 0\right\} = \Pr\left\{\sum_r a^n_{rkit} \le \widehat{Ac_{kit}}\right\} \ge \alpha_1 \qquad \forall i,\ k,\ t \tag{37}$$

$$\Pr\left\{g\left(x,\widehat{As}\right) \le 0\right\} = \Pr\left\{\sum_r a^u_{rlit} + \sum_r a^c_{rlit} \le \widehat{As_{lit}}\right\} \ge \alpha_2 \qquad \forall i,\ l,\ t \tag{38}$$

$$\Pr\left\{g\left(x,\widehat{zc}\right) \le 0\right\} = \Pr\left\{\sum_d ef_{kdit} = \widehat{zc_{kit}}\right\} \ge \alpha_3 \qquad \forall i,\ k,\ t \tag{39}$$

$$\Pr\left\{g\left(x,\widehat{zs}\right) \le 0\right\} = \Pr\left\{\sum_d es_{ldit} = \widehat{zs_{lit}}\right\} \ge \alpha_4 \qquad \forall i,\ l,\ t \tag{40}$$

Then, the deterministic equivalent of the stochastic constraints can be derived:

$$\sum_r a^n_{rkit} \le f^{-1}_{\widehat{Ac_{kit}}}(1-\alpha_1) \qquad \forall i,\ k,\ t \tag{41}$$

$$\sum_r a^u_{rlit} + \sum_r a^c_{rlit} \le f^{-1}_{\widehat{As_{lit}}}(1-\alpha_2) \qquad \forall i,\ l,\ t \tag{42}$$

$$\sum_d ef_{kdit} = f^{-1}_{\widehat{zc_{kit}}}(\alpha_3) \qquad \forall i,k,t \tag{43}$$

$$\sum_d es_{ldit} = f^{-1}_{\widehat{zs_{lit}}}(\alpha_4) \qquad \forall i,l,t \tag{44}$$

where $f^{-1}_{\widehat{Ac_{kit}}}(.)$, $f^{-1}_{\widehat{As_{lit}}}(.)$, $f^{-1}_{\widehat{zc_{kit}}}(.)$, and $f^{-1}_{\widehat{zs_{lit}}}(.)$ are the inverse cumulative density functions of $\widehat{Ac_{kit}}$, $\widehat{As_{lit}}$, $\widehat{zc_{kit}}$, and $\widehat{zs_{lit}}$, respectively. Now, our multi-objective mixed-integer linear programming model can be solved considering Constraints (9), (10), (13)–(17), (20)–(30), (41)–(44).

6. Application of the multi-objective model

We applied the multi-objective optimization model to configure a mobile phone CLSC network in Toronto, Canada. Toronto is divided into 44 wards which have been illustrated in Fig. 6. In this study, each ward is considered as a potential first customer. It is supposed that there are 22 s demand markets. Furthermore, it is assumed that there exist 4 potential manufacturer locations, 5 eligible suppliers, 15 locations for retailers, 7 locations for drop-off centres, 5 locations for consolidation centres, and 3 potential sites for disposal centres. Moreover, 4 types of mobile phones and 6 types of materials are considered in the model. The stochastic demand and return are modelled using lognormal density function. Not only lognormal distribution maintains the non-negativity of the values of both demand and return, but also Kamath and Pakkala (2002) proved that the most suitable distribution to model some stochastic parameters such as demand is lognormal. The parameters of demand and return lognormal density functions are calculated using Chi-square test based on historical data as follows: $\widehat{Ac_{kit}}$ and $\widehat{As_{lit}} \sim lognormal\,(7.82,\ 0.17)$, and $\widehat{zc_{kit}}$ and $\widehat{zs_{lit}} \sim lognormal\,(5.52,\ 0.12)$. We assume that all of the stochastic constraints have a confidence level of 0.95. Moreover, distances among various facilities are estimated using Google Maps. The values of other parameters are presented in Table 7. They are based on three sources including historical data collected and provided by the company, Statistics Canada (2014), Statistics Canada (2016), and papers in the literature. It is noticeable that mobile phone is an electronic product. Therefore, it is expected that some data may be similar for other electronic products.

The weights of suppliers in the second objective function are determined according to Eq. (6). In order to solve the proposed multi-objective closed-loop supply chain configuration, two methodologies, ε-constrained and distance methods, are employed. These methods are popular solution techniques that can discover efficient solutions for both convex and non-convex functions (Collette and Siarry, 2003). IBM ILOG CPLEX 12.7.1.0. is utilized to solve the model. The model was solved in 42 s.

6.1. ε-constrained method and the results

The application of ε-constraint method is to transfer a multi-objective model to a single-objective one. The methodology is that the most privilege objective function is considered as the main objective and other objectives are supposed to be as constraints

(Ehrgott, 2005). The obtained single-objective model is as follows:

$$Max\ z_3 = z_1 \tag{45}$$

$s.t.$

$z_2 \geq \varepsilon_1$

Eqs. ((9), (10), (13)–(17), (20)–(30), (41)–(44)

Various values of ε are examined in order to obtain the trade-off solution. We change ε from 800,000 to 856,709. For the values of ε under 800,000, the value of the main objective function (maximization of the profit) is equal to 24,236,760.294. However, for every ε higher than 856,709, the solution is unbounded or infeasible. The values of first and second objective functions for the values of ε in the mentioned range are illustrated in Table 8. It is noticeable that based on some studies such as Chircop and Zammit-Mangion (2013), one of the setbacks of this method is that the transformed single-objective problem feasible solutions may be lost.

6.2. Distance method and the results

The distance method is an approach to deal with a multi-objective CLSC network in order to obtain an approximate solution close to the perfect one. In this method, the perfect solution is the best value achieved for each objective function while other functions are ignored (Branke et al., 2008). According to Eq. (46), W_o is utilized as the distance metric representing the weight of each module mentioned in the objective function (Mirzapour Al-E-Hashem et al., 2011). A set of solutions named Pareto or efficient solutions will be created as the result of solving the multi-objective model. The final set of solutions acquired at the end of the exploration is called the Trade-off surface or Pareto front (Collette and Siarry, 2003). In this paper, our goal is to maximize the total profit along with maximization of the weights of suppliers. Hence, the model can be presented as follows:

$$z = \left(\sum_{o} W_o^{\tau a} \left(\frac{z_o - z_o^*}{z_o^*} \right)^{\tau a} \right)^{\frac{1}{\tau a}} \qquad \forall o = 1, 2, \ldots \tag{46}$$

$$Max\ z = \left(W_1^{\tau a} \left(\frac{z_1 - z_1^*}{z_1^*} \right)^{\tau a} + W_2^{\tau a} \left(\frac{z_2 - z_2^*}{z_2^*} \right)^{\tau a} \right)^{\frac{1}{\tau a}} \tag{47}$$

$s.t.$

Eqs. ((9), (10), (13)–(17), (20)–(30), (41)–(44)

First of all, the value of each objective function is calculated separately. The optimal values of the total profit and weights of suppliers are 24,236,760.294 and 828,778.368, respectively. Then, the distance method is implemented to solve the multi-objective problem.

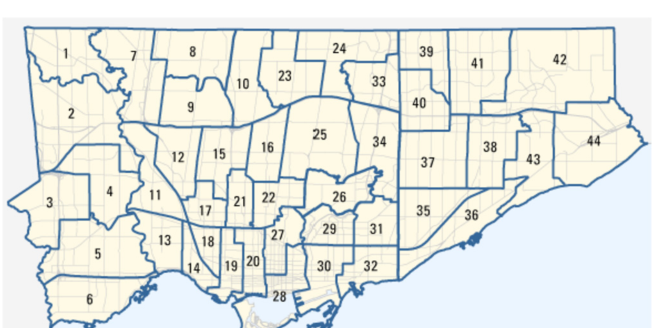

Fig. 6. Toronto wards.

Table 7
Values of some parameters defined to solve the mathematical model.

$M = 4$	$fa_m = 100,000,000$	$\sigma_{it} = 20$
$S = 5$	$fb_s = 100,000$	$mcap_{mj} = 500,000$
$R = 15$	$fc_r = fd_d = fe_g = 150,000$	$rcap_{ri} = 14,000$
$K = 44$	$P_i^n = 100$	$dcap_{di} = 10,000$
$L = 22$	$P_i^n = 100$	$gcap_{gi} = 10,000$
$D = 7$	$P_i^u = 50$	$scap_{sj} = 150,000$
$I = 4$	$P_i^c = 80$	$\eta_j = 10$
$J = 6$	$ka_{smt} = ke_{gmt} = kf_{gxt} = 0.002$	$\varepsilon_j = 0.1$
$G = 5$	$kb_{mrt} = kc_{rmt} = kd_{dgt} = 0.005$	$\rho_i = 35$
$T = 2$	$\mu_{mit} = 15$	

We examined various values of W_o while satisfying $\sum W_o = 1$ condition in order to obtain the trade-off solution between our two objective functions. The values for the first and second objective functions are shown in Table 9 with respect to different values of W_1.

7. Value Path Approach (VPA)

In this section, the Value Path Approach (VPA) is investigated in order to describe the tradeoffs among various objectives of a multi-objective problem and compare the obtained results (Schilling et al., 1983; Wadhwa and Ravindran, 2007; Tosarkani and Amin, 2018b). The display consists of a set of parallel scales, one for each criterion, on which is drawn the value path for each of the alternatives. Each element of Table 10 is the value of non-dominated solutions which is calculated as the value of each objective function divided by the best value of that objective. Hence, 1 will be the minimum value for each axis. The results are depicted in Fig. 7. Based on VPA, value paths that intersect are considered as non-dominated, while inferior solutions are non-intersecting paths, where one lies above the other one. Therefore, Fig. 7 illustrates that all solutions are non-dominated.

8. Sensitivity analyses

Fig. 8 depicts the optimal mobile CLSC network considering Product 1 (to avoid complication). The sensitivity analysis is discussed in this section. To do so, it is assumed that ε is equal to 800,000. Table 11 indicates the results of some variables of the model.

One of the most important parameters that can be changed to evaluate the sensitivity of the model is customers' demand. Hence, α as a parameter determined by decision-maker and effective for demand is examined. In the previous section, the confidence level was set to 0.95. We investigated the effect of a decrease in α on profit regarding both first and second customers' demand for Product 1 in the first ward (to avoid complexity). The changes in the profit according to the changes in α are illustrated in Fig. 9. It is clear that as α decreases, the demand increases, resulting in a rise in the profit.

9. Conclusions

Several regulated recycling programs are conducted to ensure that EOL mobile phones are managed in a secure and safe manner considering environmental factors. Moreover, appropriate recycling methods of EOL mobile phones help to recycle and recover important materials that can be returned to the manufacturing cycles. Commercial and EOU are other types of returns. By

Table 8
Values of objective functions obtained by ε-constraint method.

ε	850,000	845,000	840,000	835,000	830,000	825,000
First objective	5,817,150.987	10,152,341.026	14,487,531.065	18,822,721.105	23,157,911.144	24,236,760.294
Second objective	850,000	845,000	840,000	835,000	828,430	810,780

Table 9
Values of objective functions obtained by distance method.

W_1	0	0.2	0.3	0.4	0.5	0.6	0.8	1
First objective	987,500	3,246,700	9,607,100	11,550,000	18,764,000	20,411,000	22,832,000	22,954,000
Second objective	863,390	861,390	847,750	775,460	642,630	472,190	336,980	80,255

Table 10
Results of value path approach (VPA).

W_1	0	0.2	0.3	0.4	0.5	0.6	0.8	1
First objective	1	3.287	9.728	11.696	19.001	20.67	23.121	23.244
Second objective	10.758	10.733	10.563	9.662	8.007	5.883	4.198	1

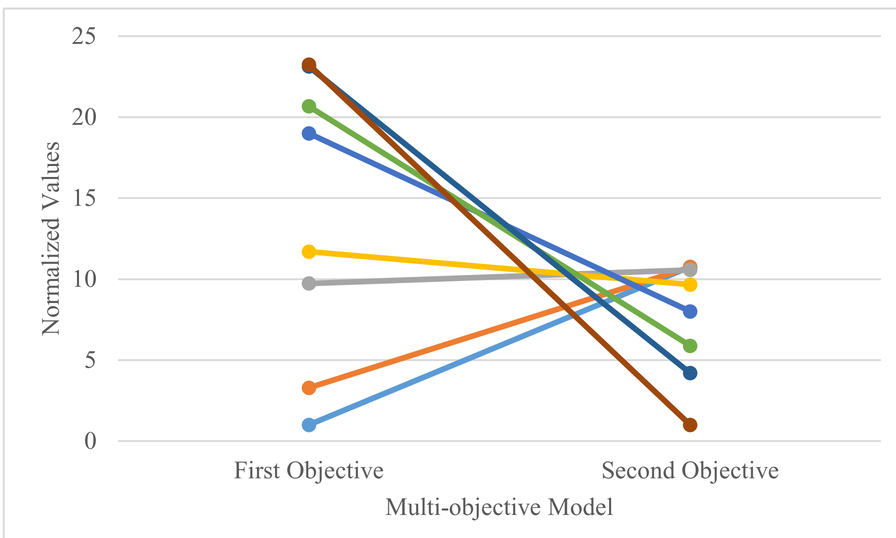

Fig. 7. Value path approach (VPA).

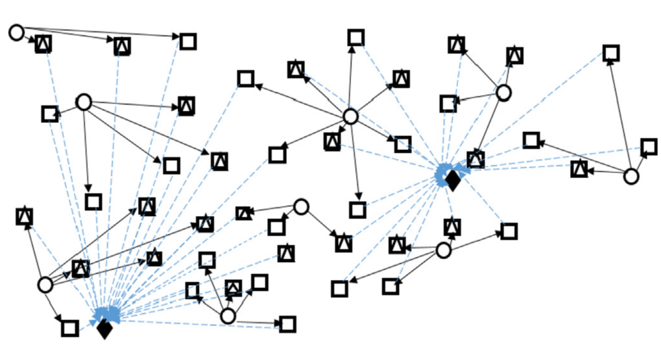

Fig. 8. The optimal mobile CLSC network (forward supply chain, reverse supply chain) Retailer, First customers, Second customers, Drop-off centre.

Table 11
Some values of the model for $i = j = t = 1s = 3$, $m = 2$, $r = 12$, $k = 18$, $l = 13$, $d = 6$, $g = 5$, $x = 1$, $\varepsilon = 800,000$.

Single variable	Value	Binary variables
First objective	24, 236, 760.294	Suppliers: 3, 4
Second objective	828, 778.368	Manufacturers: 2, 3
a^n_{rkit}	1, 241.125	Retailers: 1, 2, 3, 4, 6, 12, 13, 14,15
a^c_{rlit}	231.5	Drop-off centres: 2, 6
a^u_{rlit}	222.3	Consolidation centres: 5
q_{smjt}	59, 886.66	
a_{mrit}	22, 647.183	
b^c_{krit}	744.675	
b^u_{krit}	992.9	
a^l_{rmit}	151.52	
ef_{kdit}	284.35	
es_{ldit}	249.1	
φ_{gmjt}	6, 565.54	
u_{gxjt}	9, 848.31	

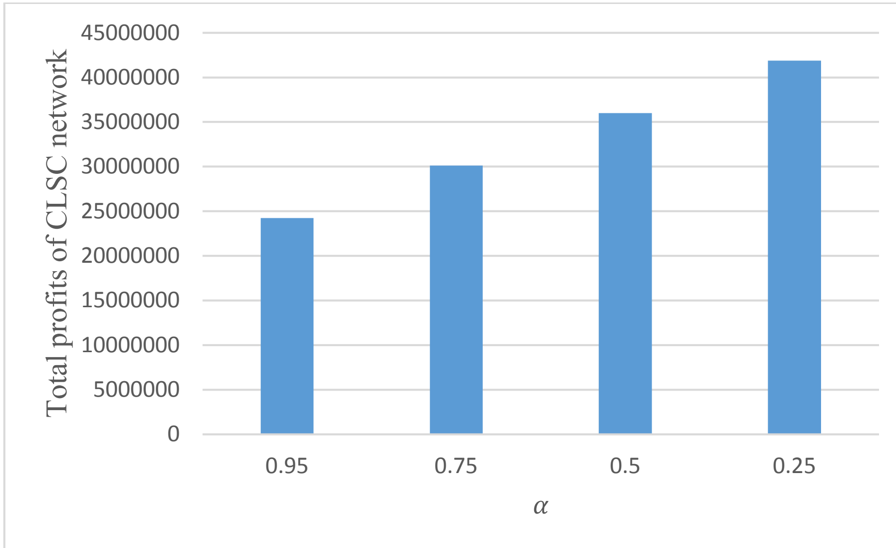

Fig. 9. The changes of the profit due to the change in α.

configuring a comprehensive mobile CLSC network, the optimal number of drop-off and recycling centres and their convenient locations can be determined. As a result, customers can simply bring their old and unwanted mobile phones to a collection centre.

In this investigation, a mixed-integer linear programming formulation has been provided and analyzed to configure a stochastic CLSC for mobile phone industry. The proposed mathematical model comprises of suppliers, manufacturers, retailers, first and second customers, drop-off centres, consolidation centres and disposal centres considering multi-product, multi-material, and multi-period. As an extension to the model, supplier selection and order allocation have been applied to the model. A fuzzy method is developed to estimate the weights of qualified suppliers. Therefore, the objectives are the maximization of the whole profit as well as maximization of the weights of suppliers. Chance-constrained programming has been employed to deal with uncertainty in the proposed model. The operation of the proposed mathematical model has been illustrated in Toronto, Canada using real maps. The proposed network can be utilized by the countries that plan to design closed-loop supply chain networks and reverse logistics systems. The proposed model is comprehensive, and can be utilized for other countries by applying the map of that country, and changing the parameters such as population (which affects the demand and return), and costs.

ε-constraint and distance method have been utilized to solve the multi-objective model. Furthermore, the level of confidence has been changed in order to investigate the sensitivity of the model. The most outstanding contribution of this paper is considering different types of returned products. It is supposed that commercial and End-Of-Use returned products can be resold to the second customer with a lower price from that of a new product. Non-reusable mobile phones can be returned to the plants for remanufacturing. Moreover, useless items will be shipped to disposal centres to reduce the environmental pollution. The most important benefit that first customers get is that by recycling and disposing of the EOL products, the environmental pollution is reduced. This study is the first research that implements stochastic programming for a multi-objective mobile phone CLSC network in Canada.

In our study, it is assumed that product return rate and demand are stochastic. Furthermore, the objectives of the model are the maximization of the entire profit alongside the weights of suppliers. According to these points, taking into account robust optimization in order to accomplish uncertainties in more parameters such as manufacturing cost or selling price, and adding more objectives considering defect rate and delivery time are the future extensions of this work.

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