Optimizing Closed-Loop Supply Chain in The Electric Vehicle Battery Industry: A Fully Fuzzy Approach

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Abstract. Increasing vehicle emissions are major causes of global warming which is the most serious threat to human life. To alleviate this process, the Net-zero regulations enforce car manufacturers and encourage the population to shift from gasoline- to Electric vehicles. Although EV usage is unprecedently amplified, existing uncertainty in the supply chain of batteries of electric vehicles (BEVs) endangers EV's future market. For example, the scarcity of battery minerals, and the vagueness of supply chain parameters like costs. Reverse logistics in the BEVs supply chain can cope with the shortage of raw materials, and fuzzy theory is a promising approach to handle the vagueness. This study aims to put forward a fully fuzzy multi-Objective mathematical model by considering the uncertainty to optimize the BEVs closed-loop supply chain according to sustainable development principles in Canada. To do so, three objective functions are developed. Two objective functions maximize the profits of all supply chain players and service levels. The last one minimizes environmental impacts. Eventually, the model obtains the optimal amount of material flow, as decision variables, between all components of the supply chain.

Keywords: Battery Electric Vehicle, Sustainable Closed-Loop Supply Chain, Fully Fuzzy Multi-Objective Programming, Echelon Utilization.

1 Introduction

Road transport generated 43.3% of GHG emissions in 2019, in Quebec (Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC), 2021). Emitted GHG contributes to global warming that poses significant threats to human societies. For example, it increases the frequency of extreme weather like heatwaves and droughts that can disrupt food supplies, affect critical infrastructure, and cause widespread displacement. To avert the global warming implications, governments take various actions, from establishing binding actions to increasing public awareness to reduce vehicle emissions (Yarahmadi, Morency and Trepanier, 2023). For example, according to the Canadian Net-Zero Emissions Accountability Act, Canada committed to decreasing its GHG emissions to zero by 2050 (Association, 2021). Over the last decade, due to zero-emission regulations, vehicle industries have shifted from developing fossil fuel engines to electric vehicles. Statistics imply that electric cars will play a significant role in the future of transportation. One of the essential parts of EVs is their Lithium-ion battery. The battery of an EV (BEV) composes almost 50% of the cost of an EV (Gu *et al.*, 2018) and designates the EVs range. It is predicted that the EV demand will surge; lithium-ion battery demand will increase.

Figure **1** depicts the prediction of the universal market size of EVs (a) (Nogueira, Sousa and Alves, 2022) and BEV production by 2030 (b) (Shine, 2022). Obviously, both the EV markets and BEV production will notably increase by 2030.

Achilles' Heel of BEVs is its supply chain because, first, a few countries possess most of the minerals. For instance, the Democratic Republic of Congo produces more than 50% of cobalt globally, and China reserves over 66% of natural graphite(Igogo, Sandor, Mayyas and Engel-Cox, 2019). The scarcity of critical minerals is another issue. For example, the International Energy Agency (IEA) announced lithium shortage would be a global challenge by 2025 (Tracy, 2022).

Although battery minerals storage is restricted, focusing on a closed-loop supply chain could significantly compensate for this problem. A closed-loop supply chain comprises two parts: forward flow to generate products from raw materials and reverse flow to collect and reuse product waste. Scientific resources demonstrate that almost 90% of battery electric vehicles can be recycled. The reverse logistics can be composed of different actors, involving remanufacturing, refurbishing, echelon utilization, and recycling.

Reviewing the literature revealed that there are two critical gaps. First, according to the authors' best knowledge, previous studies used crisp mathematical models to optimize the BEVs supply chain (Zhang, Tian and Han, 2022). Although owing to the deficiency of the developed model in handling uncertainties related to the supply chain components, their results cannot be reliable. At the same time, uncertainties can limit the developed model in the real world. For example, parameters like the demand for BEVs and raw materials, order quantity, costs, and return rate of BEVs are vague. Moreover, their values are not certain because they depend on other issues. For example, transportation costs fluctuate because of political factors and fuel prices, and BEV demand is a function of various factors like EV demand. Therefore, to optimize the network parameters and variables should be fuzzy.

Second, most conducted research is needed to model the BEVs supply chain comprehensively. For example, Gonzales-Calienes, Yu and Bensebaa, (2022) utilized Geographic Information System to optimize the reverse flow, but the forward flow needs to be addressed. On the other hand, Li, Dababneh and Zhao, (2018) optimized the supply chain without contributing to the echelon utilization and market. A complete closed-loop supply chain of BEVs embarks by mine, refinery, BEV factory, EV manufacture, EV retailer, and EV market. It is followed by a collection and sorting center, recycling center, echelon utilization, echelon market, and disposal center.

To fill the gap, it is necessary to employ methods to consider all supply chain components, at the same time, take ambiguity, uncertainty, and indecision into account.

To do that, first, this study aims to consider sustainable development criteria to put forward a multi-objective model.

(a)

(b)

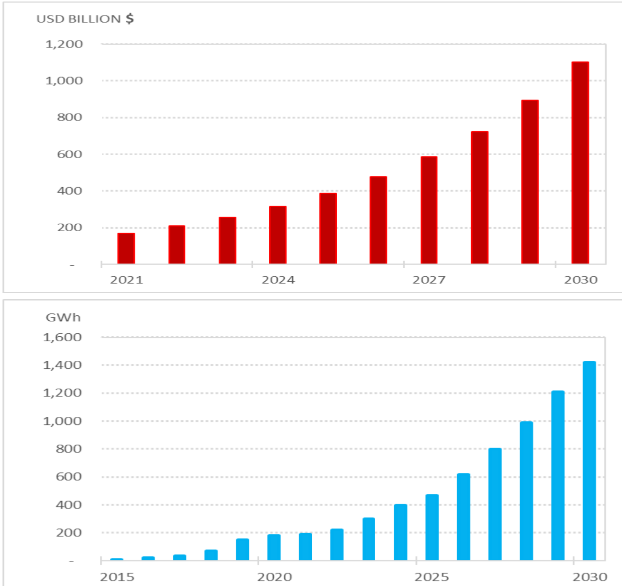

Fig. 1. The universal trend of the EV market (a) (Nogueira, Sousa and Alves, 2022) And BEV production (b) (Shine, 2022) by 2030

In addition, the developed model considers all BEV supply chain players. Furthermore, the proposed model is fully fuzzy, meaning all parameters and variables are fuzzy. Finally, it is worth mentioning that fuzzy techniques, like fuzzy mathematical programming, are potent approaches to dealing with environmental uncertainty and bridging the gaps between real-world conditions and the developed model.

The remainder of this paper is structured as follows. In the next section, previous studies that explored the problem are described. Section 3 discusses what steps should be taken to achieve the desired objective. Finally, the contribution of the paper is discussed, and the results are reviewed.

2 Literature review

To further clarify our contributions, we summarize and arrange Table 1 to highlight the research gap concisely and clearly between our work and relevant studies. As demonstrated, the number of supply chain components in the present study is more comprehensive than previous efforts. In forward flow, mine, BEV manufacture, EV factory, EV retailer, and EV market. In reverse flow, players are collection and sorting centers, echelon utilization, recycling, disposal, and echelon market.

In addition, a previous practice rarely developed the supply chain according to sustainable development criteria. Lastly, this study develops a fully fuzzy multi-objective model contrary to almost all former deterministic optimization models.

Table 1. Comparison between the proposed model and conducted research in the BEV supply chain

Author (year)	Supply Chain components[1]	Criteria			Technique	Model type	Problem type	
		Ec	En	So			Certain	Uncertain
(Li, Dababneh and Zhao, 2018)	M, B, E, Re, A, C, Y, RM, D	*			Artificial intelligence	PSO[2]	*	
(Gu *et al.*, 2018)	M, B, Eu, A, Y, H	*			Game theory	Nash equilibrium	*	
(Zhang, Tian and Han, 2022)	E, Re, A, Y, D, H	*	*		Game theory	Stackelberg model	*	
(Gonzales-Calienes, Yu and Bensebaa, 2022)	C, Y, Eu	*	*		GIS	shortest path	*	
(Huster *et al.*, 2022)	B, E, A, Y, RM		*		Simulation	Discrete event	*	
(Pamucar, Torkayesh and Biswas, 2022)	Ranking of recycling centers	*	*	*	MCDM	Fuzzy WASPS		*
(Scheller *et al.*, 2020)	B, Y, Eu, RM	*			Simulation & Artificial intelligence	AIMMS & GUROBI	*	
(Zhang, Chen and Tian, 2023)	E, Re, A, Y, D, H	*	*		Game theory	Stackelberg model	*	
Purposed model	**M, B, E, Re, A, C, Y, Eu, D, H**	*	*	*	**Mathematical model**	**FFMOM[3]**		*

1. M: mine; B: BEV manufacture; E: EV manufacture; Re: retailer; A: EV market; C: collection center; Eu: echelon utilization; Y: recycling; D: disposal center; H: echelon market; RM: remanufacture
2. Ec: Economical; En: Environmental; So: Social;
3. Particle Swarm Optimization
4. Fully Fuzzy Multi-Objective Model

3 Model description and formulation

Figure 2 illustrates the designed research methodology. The methodology is developed in two phases, phases1, and 2 consisting of three and one steps.

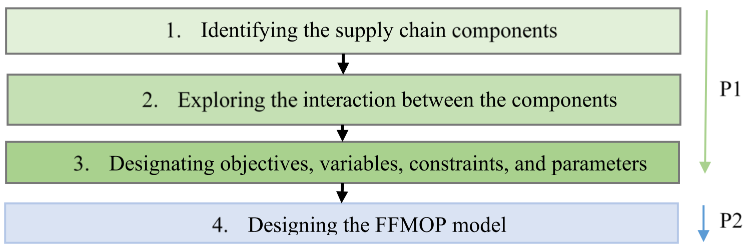

Fig. 2. Steps of the research methodology

The main objective of phase 1 is business understanding related to BEVs. Indeed, through three steps, all components are identified, their interactions are explored, and finally, objective functions, decision variables, and parameters are defined. Eventually, in phase 2 the FFMOP model is developed.

Figure 3 depicts the structure of the BEV closed-loop supply chain. The configuration includes two flows, forward and reverses flow showing in the order in black and green dot arrow. In forward flow, minerals are turned into the battery through the refining process and BEV manufacturing. Next, batteries are installed in EVs and are sold in the market using retailers. With time, the life of batteries is decreased; when they lose 20% of their life, batteries are replaced (Lai *et al.*, 2021).

So, the used batteries are collected in the collection centers, and via a qualification assessment, their high quality is shipped to echelon markets for reuse, and low-quality ones are transported to recycling centers. More than 90% of a battery is recycled and is send to refining centers for more processing. The main difference between the designed supply chain network and previous ones is reverse flow. Indeed, not only all reverse flow components are taken into account but also their relationships are investigated. Then the model designates the optimal values of all variables.

Next step, objective functions are developed. In this study, three objective functions are designed to cover all aspects of sustainable development.

The following defines assumptions, notations (sets, decision variables and parameters) used in our proposed model.

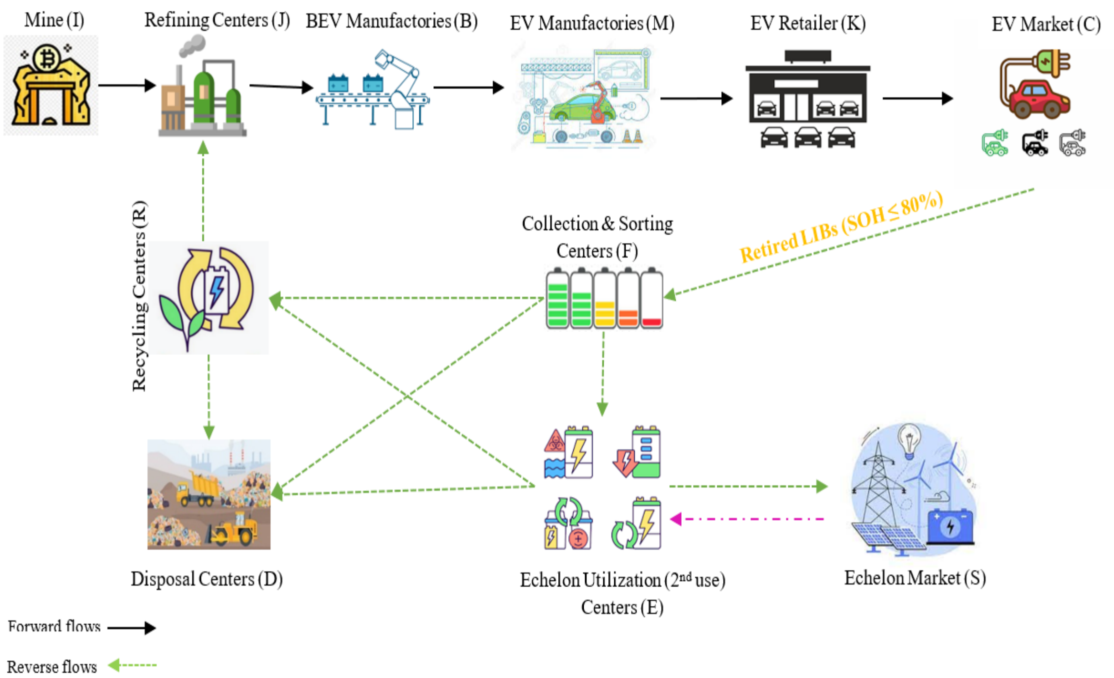

Fig. 3. Thematic configuration of the BEVs supply chain

3.1 Model assumptions

- The capacity of all facilities is determined and limited.
- The BEVs closed-loop supply chain is pull system. In pull supply chain, production is based on a real demand and inventory cost outweighs the benefit of stocking products (Koo, 2020). So, there is no inventory cost.
- Quantity discounts are not considered in the purchase.
- Parameters and variables in the model like BEV demand, EV demand, costs, BEV return rate, energy consumption, facilities capacity, and BEV and mineral batteries order amount etc. are fuzzy.
- Shortage of products to supply customer's demand is allowed and incur a cost.

3.2 Notations

The following notation is used to formulate the problem. Also, "~" denotes that the parameter or variable is fuzzy.

Sets

- I: Set of Suppliers (Mines), index by i.
- J: Set of Refining centers, index by j.
- B: Set of BEV Manufactories, index by b.
- M: Set of EV Manufactories, index by m.
- K: Set of EV Retailer, index by k.
- C: Set of EV Market, index by c.
- F: Set of Collection & Sorting Centers, index by f.
- S: Set of Echelon Markets, index by s.
- R: Set of Recycling Centers, index by r.
- D: Set of Disposal Centers, index by d.
- E: Set of Echelon Utilization Centers, index by e.
- G: Set of nodes, index by g.

Parameters

- $\widetilde{\mathrm{PS}}_{bm}$: Unit sale price of EV batteries from BEV manufactories b to EV manufactories m (Dollar)
- $\widetilde{\mathrm{PS}}_{mk}$: Unit sale price of EVs from EV manufactories m to EV retailer k (Dollar)
- $\widetilde{\mathrm{PS}}_{kc}$:Unit sale price of EVs from EV retailer k to EV market c (Dollar)
- $\widetilde{\mathrm{P}}_{\mathrm{ib}}$:Unit purchase cost of raw material from mine i to BEV manufactories b (Dollar)
- $\widetilde{\mathrm{P}}_{\mathrm{rb}}$:Unit purchase cost of raw material from recycling center r to BEV manufactories b (Dollar)
- $\widetilde{\mathrm{D}}b$:The demand for BEV (Ton)
- $\widetilde{\mathrm{D}}EV$:The demand for EV (Ton)
- $\widetilde{M}$:Required raw materials to produce an EV battery unit (Ton)
- $\widetilde{\mathrm{C}}_g$:The capacity of facilities g ∈I,J,B,M,K,F,S,R,D,E (Ton)
- $\widetilde{\mathrm{Pr}}_g$:Unit Processing cost in node g ∈I,B,M,F,R,D,E (Dollar)
- $\tilde{T}_{gh}$:Unit Transport cost from node g to node h (Dollar)

- $\widetilde{\text{Sh}}b$:Unit Shortage cost of EV batteries in BEV manufactories (Dollar)
- $\widetilde{\text{Sh}}m$: Unit Shortage cost of EV in EV manufactories (Dollar)
- $\widetilde{\text{Sh}}k$: Unit Shortage cost of EV in EV retailer (Dollar)
- $\widetilde{\text{R}}$: Return percentage of retired batteries from EV markets
- $\widetilde{\text{Rs}}$: Return percentage of second retired batteries from echelon markets
- $\widetilde{\text{PS}}_{es}$:Unit sale price of retired batteries from echelon utilization centers e to echelon markets s (Dollar)
- $\widetilde{\text{PS}}_{rb}$:Unit sale price of raw material from recycling centers r to BEV manufactories b (Dollar)
- $\widetilde{\text{P}}_{cf}$: Unit purchase cost of retired batteries from EV markets c to Collection & Sorting Centers f (Dollar)
- $\widetilde{Ec}_{g}$: Unit of energy consumed in processing in node g∈ I,J,B,M,K,C,F,S,R,D,E (Dollar)

Decision Variables

- $\widetilde{QR}_{ib}$: Quantity of raw material purchased by BEV manufactories b from mines I (Ton)
- $\widetilde{QR}_{rb}$: Quantity of raw material purchased by BEV manufactories b from recycling centers r (Ton)
- $\widetilde{QB}_{bm}$: Quantity of EV batteries transported from BEV manufactories b to EV manufactories m (Ton)
- $\widetilde{QB}_{mk}$: Quantity of EV transported from EV manufactories m to EV retailer k (Ton)
- $\widetilde{QB}_{kc}$: Quantity of EV transported from EV retailers k to EV market c (Ton)
- $\widetilde{QB}_{fr}$: Quantity of retired batteries transported from collection centers f to recycling centers r (Ton)
- $\widetilde{QB}_{fe}$: Quantity of retired batteries transported from collection centers f to echelon utilization centers e (Ton)
- $\widetilde{QB}_{fd}$: Quantity of retired batteries transported from collection centers f to disposal centers d (Ton)
- $\widetilde{QB}_{es}$: Quantity of retired batteries transported from echelon utilization centers e to echelon markets s (Ton)
- $\widetilde{QB}_{er}$: Quantity of retired batteries transported from echelon utilization centers e to recycling centers r (Ton)
- $\widetilde{QB}_{ed}$: Quantity of retired batteries transported from echelon utilization centers e to disposal centers d (Ton)
- $\widetilde{QC}_{rd}$: Quantity of scraps transported from recycling centers r to disposal centers d (Ton)

3.3 Mathematical Model

The following presents the mathematical model of the fully fuzzy multi-objective problem in this study:

$$\textbf{Max } \mathbf{F_1}(\widetilde{\mathbf{X}}) = (\text{T}\tilde{R}\text{F} \oplus \text{T}\tilde{\text{R}}\text{R}) \ominus (T\tilde{C}R \oplus T\tilde{C}P \oplus T\tilde{C}T \oplus T\tilde{C}S) \quad (1)$$

$$\textbf{Min } \mathbf{F_2}(\widetilde{\mathbf{X}}) = \left[\sum_{b} \widetilde{\text{EC}}_{\text{b}} \otimes \sum_{m} \widetilde{\text{QB}}_{\text{bm}}\right] \oplus \left[\sum_{i} \widetilde{\text{EC}}_{\text{i}} \otimes \sum_{b} \widetilde{\text{QR}}_{\text{ib}}\right] \oplus \left[\sum_{m} \widetilde{\text{EC}}_{\text{m}} \otimes \sum_{k} \widetilde{\text{QB}}_{\text{mk}}\right]$$

$$\oplus [\sum_f \widetilde{EC}_f \otimes (\tilde{R} \otimes \sum_c \widetilde{QB}_{kc})] \oplus [\sum_e \widetilde{EC}_e \otimes (\sum_r \widetilde{QB}_{er} \oplus \sum_s \widetilde{QB}_{es} \oplus \sum_d \widetilde{QB}_{ed})]$$
$$\oplus [\sum_r \widetilde{EC}_r \otimes \left(\sum_b \widetilde{QR}_{rb} \oplus \sum_d \widetilde{QC}_{rd}\right)]$$
$$\oplus [\sum_d \widetilde{EC}_d \otimes \left(\sum_f \widetilde{QB}_{fd} \oplus \sum_e \widetilde{QB}_{ed} \oplus \sum_r \widetilde{QC}_{rd}\right)] \quad (2)$$

$$\mathbf{Max\ F_3}(\tilde{\mathbf{X}}) = \left(\frac{\sum_c \sum_k \widetilde{QB}_{kc}}{\widetilde{D}EV}\right) \oplus \left(\frac{\sum_k \sum_m \widetilde{QB}_{mk}}{\widetilde{D}EV}\right) \oplus \left(\frac{\sum_b \sum_m \widetilde{QB}_{bm}}{\widetilde{D}b}\right) \quad (3)$$

st:

$$\sum_b \widetilde{QR}_{ib} \le \widetilde{C_i} \qquad \forall i \in I \quad (4)$$
$$\sum_i \widetilde{QR}_{ib} \oplus \sum_r \widetilde{QR}_{rb} \le \widetilde{C_b} \quad \forall b \in B \quad (5)$$
$$\sum_b \widetilde{QB}_{bm} \le \widetilde{C_m} \quad \forall m \in M \quad (6)$$
$$\tilde{R} \otimes \sum_c \widetilde{QB}_{kc} \le \sum_f \widetilde{C_f} \quad (7)$$
$$\sum_f \widetilde{QB}_{fe} \oplus \left(\widetilde{Rs} \otimes \sum_s \widetilde{QB}_{es}\right) \le \widetilde{C_e} \qquad \forall e \in E \quad (8)$$
$$\sum_e \widetilde{QB}_{es} \le \widetilde{C_s} \qquad \forall s \in S \quad (9)$$
$$\sum_f \widetilde{QB}_{fr} \oplus \sum_e \widetilde{QB}_{er} \le \widetilde{C_r} \qquad \forall r \in R \quad (10)$$
$$\tilde{R} \otimes \sum_k \sum_c \widetilde{QB}_{KC} = \sum_r \widetilde{QB}_{fr} \oplus \sum_d \widetilde{QB}_{fd} \oplus \sum_e \widetilde{QB}_{fe} \qquad \forall f \in F \quad (11)$$
$$\sum_f \widetilde{Q_{fe}} \oplus \left(\widetilde{Re} \otimes \sum_s \widetilde{Q_{es}}\right) = \sum_r \widetilde{QB}_{er} \oplus \sum_d \widetilde{QB}_{ed} \oplus \sum_s \widetilde{QB}_{es} \quad \forall e \in E \quad (12)$$
$$\sum_i \widetilde{QR}_{ib} \oplus \sum_r \widetilde{QR}_{rb} = \tilde{M} \otimes \sum_m \widetilde{QB}_{bm} \qquad \forall b \in B \quad (13)$$
$$\sum_k \sum_c \widetilde{QB}_{KC} \le \widetilde{D}EV \quad (14)$$
$$\sum_k \sum_m \widetilde{QB}_{Km} \le \widetilde{D}EV \quad (15)$$
$$\sum_b \sum_m \widetilde{QB}_{bm} \le \widetilde{Db} \quad (16)$$
$$\text{All of variables} \ge \tilde{0} \quad (17)$$

The first objective function maximizes the profits of all supply chain components. In fact, this function considers the economic aspect of sustainable development. To do that, total income is subtracted from total cost. The income involves summation of income of forward ($T\widetilde{R}F$) and reverse flow ($T\widetilde{R}R$).

$$\mathbf{T\widetilde{R}F} = \left(\sum_b \sum_m \widetilde{PS}_{bm} \otimes \widetilde{QB}_{bm}\right) \oplus \left(\sum_m \sum_k \widetilde{PS}_{mk} \otimes \widetilde{QB}_{mk}\right) \oplus \left(\sum_k \sum_c \widetilde{PS}_{kc} \otimes \widetilde{QB}_{kc}\right) \quad (18)$$

$$\mathbf{T\tilde{R}R} = \sum_{e}\sum_{s} \widetilde{PS}_{es} \otimes \widetilde{QB}_{es} \qquad (19)$$

The cost is calculated from summation of cost of purchase of raw material ($T\tilde{C}R$), processing ($T\tilde{C}P$), transportation ($T\tilde{C}T$), and shortage ($T\tilde{C}S$).

$$\mathbf{T\tilde{C}R} = \left(\sum_{i}\sum_{b} \tilde{P}_{ib} \otimes \widetilde{QR}_{ib}\right) \oplus \left(\sum_{r}\sum_{b} \tilde{P}_{rb} \otimes \widetilde{QR}_{rb}\right) \qquad (20)$$

$$\begin{aligned}\mathbf{T\tilde{C}P} = {} & \left(\sum_{i} \widetilde{Pr}_{i} \otimes \sum_{b} \widetilde{QR}_{ib}\right) \oplus \left(\sum_{b} \widetilde{Pr}_{b} \otimes \sum_{m} \widetilde{QB}_{bm}\right) \oplus \left(\sum_{m} \widetilde{Pr}_{m} \otimes \sum_{k} \widetilde{QB}_{mk}\right) \\ & \oplus \left(\sum_{k} \widetilde{Pr}_{k} \otimes \sum_{c} \widetilde{QB}_{kc}\right) \oplus \left(\sum_{f} \widetilde{Pr}_{f} \otimes \left(\tilde{R} \otimes \sum_{c} \widetilde{QB}_{kc}\right)\right) \\ & \oplus \left(\sum_{e} \widetilde{Pr}_{e} \otimes \left(\sum_{f} \widetilde{QB}_{fe} \oplus \sum_{s} \widetilde{Rs} \otimes \widetilde{QB}_{es}\right)\right) \\ & \oplus \left(\sum_{r} \widetilde{Pr}_{r} \otimes \left(\sum_{b} \widetilde{QR}_{rb} \oplus \sum_{d} \widetilde{QC}_{rd}\right)\right) \\ & \oplus \left(\sum_{d} \widetilde{Pr}_{d} \otimes \left(\sum_{f} \widetilde{QB}_{fd} \oplus \sum_{e} \widetilde{QB}_{ed} \oplus \sum_{r} \widetilde{QC}_{rd}\right)\right) \qquad (21)\end{aligned}$$

$$\begin{aligned}\mathbf{T\tilde{C}S} = {} & \left(\widetilde{Sh}b \otimes \left(\tilde{D}b - \sum_{b}\sum_{m} \widetilde{QB}_{bm}\right)\right) \oplus \left(\widetilde{Sh}m \otimes \left(\tilde{D}EV - \sum_{m}\sum_{k} \widetilde{QB}_{mk}\right)\right) \\ & \oplus \left(\widetilde{Sh}k \otimes \left(\tilde{D}EV - \sum_{k}\sum_{c} \widetilde{QB}_{kc}\right)\right) \qquad (22)\end{aligned}$$

$$\begin{aligned}\mathbf{T\tilde{C}T} = {} & \left(\sum_{i}\sum_{b} \tilde{T}_{ib} \otimes \widetilde{QR}_{ib}\right) \oplus \left(\sum_{r}\sum_{b} \tilde{T}_{rb} \otimes \widetilde{QR}_{rb}\right) \oplus \left(\sum_{r}\sum_{b} \tilde{T}_{rb} \otimes \widetilde{Qc}_{rd}\right) \\ & \oplus \left(\sum_{b}\sum_{m} \tilde{T}_{bm} \otimes \widetilde{QB}_{bm}\right) \oplus \left(\sum_{m}\sum_{k} \tilde{T}_{mk} \otimes \widetilde{QB}_{mk}\right) \\ & \oplus \left(\sum_{f}\sum_{e} \tilde{T}_{fe} \otimes \widetilde{QB}_{fe}\right) \oplus \left(\sum_{f}\sum_{r} \tilde{T}_{fr} \otimes \widetilde{QB}_{fr}\right) \\ & \oplus \left(\sum_{f}\sum_{d} \tilde{T}_{fd} \otimes \widetilde{QB}_{fd}\right) \oplus \left(\sum_{e}\sum_{s} \tilde{T}_{es} \otimes \widetilde{QB}_{es}\right) \oplus \left(\sum_{e}\sum_{r} \tilde{T}_{er} \otimes \widetilde{QB}_{er}\right) \\ & \oplus \left(\sum_{e}\sum_{d} \tilde{T}_{ed} \otimes \widetilde{QB}_{ed}\right) \qquad (23)\end{aligned}$$

Function 2 minimizes the negative impacts of the supply chain on the environment by reducing energy consumption in processing the facilities.

Function 3 maximizes the social impacts of sustainable development via increasing the service level. The service level defined as is a ratio between satisfied demand to total demand. Constraint 10 shows facilities' capacities.

Constraints 11 and 12 in the order are related to collection centers and echelon utilization centers and show that the total amount of their input produces is equal to the outputs. Constraint 13 indicates that the quantity of battery production determines the amount of purchase of raw materials. Constrains 14 shows that the amount of EVs that retailers supply to the market should be equal to or less than market demand. Constrains 15 persists that the quantity of the EVs that manufacturers supply to retailers should be equal to or less than k retailer demands. and constraint 16 demonstrates that the amount of battery demand should always be more significant than battery production. Finally, constrain (17) all variables are non-negative.

3.4 Solutions approaches

There are various techniques to solve FFMOP problems. The present study employs the technique (Sharma and Aggarwal, 2018) to solve the proposed FFMOP model because its computation complexity is less than other techniques, solves problems with triangular and trapezoidal fuzzy numbers, and can be used for other LR flat fuzzy numbers. According to this method, the proposed FFMOP model is converted into a CLP model (for more information, see (Sharma and Aggarwal, 2018)); then, by solving the CLP model, the optimal values of the decision variable are obtained.

The main advantage of the proposed model is that the optimal values of decision variables and objective functions are calculated as fuzzy values. It means decision makers and practitioners can consider the real-world uncertainties in their decision-making processes. For example, when the outputs are shown via triangular fuzzy numbers the optimal values are three values lower boundary, upper boundary, and mean, while previous studies determined only one value as an optimal result.

4 Conclusion

This research initially contributes to considering uncertainty in optimizing the closed-loop supply chain of EV batteries. In addition, designing the developed model was based on the principles of sustainable development.

The three objective models were designed. To make the generated model more realistic fuzzy logic was utilized, and a fully fuzzy multi-objective was developed. The model includes three objective functions. The first maximize profits, while the second and third functions minimize negative environmental impacts of the supply chain and maximize social benefits, respectively.

Performing the model on real datasets provides opportunities for scholars and practitioners to investigate the outcomes of various scenarios and improve electric battery supply chain management. In addition, Applying the model in a real case study in Canada is the agenda of the authors.

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