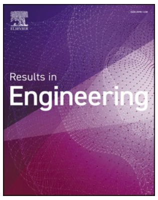
Results in Engineering 23 (2024) 102830

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering



Designing green logistics networks under carbon tax policy: Post-COVID condition

Sina Abbasi [a], Sasan Mazaheri [b], Hamid Reza Talaie [c], Peiman Ghasemi [d,*]

[a] Department of Industrial Engineering, Lahijan Branch, Islamic Azad University, Lahijan, Iran
[b] Department of Industrial Management, Management and Accounting Faculty, Shahid Beheshti University, Tehran, Iran
[c] Department of Industrial Management, Faculty of Administrative Sciences and Economics, Arak University, Arak, Iran
[d] University of Vienna, Department of Business Decisions and Analytics, Kolingasse 14-16, 1090 Vienna, Austria

ARTICLE INFO

Keywords:
Environmental engineering
Green logistics
Fuzzy method
Post-COVID era
Carbon tax

ABSTRACT

This paper proposes a fuzzy-based method for estimating demand in forward and reverse logistics networks (F&RLNs) subject to carbon pricing in the post-COVID era. We investigate the complex relationships between carbon prices, the reverse logistics network (RLN), and the ever-changing product demand by utilizing fuzzy inference systems (FIS) capabilities. The case study from Mexico confirms the effectiveness of the proposed technique. The findings demonstrate the precision and predictive power of our proposed FIS-based method and show how well it can predict the number of items in demand and the number of goods that will be returned and subject to carbon taxation in the post-COVID era. The results illustrate the significant impact that carbon pricing has on the RLN and the associated product demand. For logistics managers seeking to make informed decisions about the establishment and operation of forward and RLNs within the carbon pricing paradigm, this empirical data provides insightful information in the post-COVID era.

Abbreviations

Symbolism	Description
SC	Supply chain
RLN	Reverse logistics network
FLN	Forward logistics network
FIS	Fuzzy inference systems
RLND	Reverse logistics network design
FLND	Forward logistics network design
RL	Reverse logistics
FL	Forward logistics
MOMIP	Multi-objective mixed-integer programming
MILP	Mixed-integer linear program
RSCD	Reverse supply chain design
GSC	Green Supply Chain
GRSC	Green reverse supply chain
OFs	Objective functions
COP	Conference of parties
GHG	Greenhouse gas
LND	Logistics network design
LN	Logistics network
F&RLN	Forward and reverse logistics network
F&RLD	Forward and reverse logistics design
F&RL	Forward and reverse logistics
VRP	Vehicle routing problem
RLVRP	Reverse logistics vehicle routing problem
SCM	Supply chain management
CLSC	Closed-loop supply chain
ARIMA	Autoregressive integrated moving average
SCN	Supply chain network
SSCND	Sustainable supply chain network design
SSC	Sustainable supply chain
EOL	End-of-life

1. Introduction

To summarize, in the post-COVID context, logistics networks are being reshaped to be more adaptable, local, digital, and risk-aware. The epidemic has drawn attention to the need for increased resilience of logistics operations while accelerating current trends towards

---

* Corresponding author.
E-mail addresses: abbasisina170@gmail.com (S. Abbasi), Mazaheri.sasan@gmail.com (S. Mazaheri), H-talaie@araku.ac.ir (H.R. Talaie), peiman.ghasemi@univie.ac.at (P. Ghasemi).

https://doi.org/10.1016/j.rineng.2024.102830
Received 30 July 2024; Received in revised form 26 August 2024; Accepted 1 September 2024
Available online 4 September 2024

digitalization [47]. The importance of the logistics sector to the global economy is likely to increase during the next several years. Nevertheless, the sector also makes a sizable contribution to GHG emissions, which are a known cause of climate change. As a response, governments everywhere are putting regulations in place to lower emission levels of carbon, such as carbon taxes. These taxes increase the cost of emitting carbon to encourage businesses to lessen their carbon footprint [1]. During the background of commercial sustainability, environmental activities, and concerns have progressed from a localized focus on pollutants to a worldwide focus on universal sustainable development by efforts such as the United Nations Worldwide Compact [2]. Many worldwide meetings and accords have been held over the past thirty years, such as the current COP, highlighting the ought to reduce the global impacts of GHG emissions [3]. Global leaders agree on the need to limit GHG emissions. Given that a substantial portion of the economy significantly strains the natural resource base, which is constantly dwindling, global organizations understand the necessity to address intergenerational viability as a means of survival. Among many famous company environmental efforts, remanufacturing and its accompanying operations will play an important part [4]. Aside from the environmental advantage, there are also commercial benefits. Firms may differentiate themselves strategically from rivals by lowering costs, creating benefits to their SC and end consumers, and attaining sustainable development through RL and remanufacturing activities [5]. Furthermore, it is worthwhile for businesses to ignore the elements that impact the release produced by the RLN and its activities [6]. The size of refurbishing, collection, and testing center services, different kinds of vehicle loads, and the length of the route they travel are all factors that might affect emissions [7]. RLND has typically concentrated on the network, logistical operations, and effective return management [8]. Reverse flows of raw materials, in-process inventory, packaging, and finished goods from the point of manufacture and distribution or consumption to the point of recovery or proper disposal must be planned, implemented, and regulated for effective remanufacturing [9]. RL operations involve the essential duties: of creating examination and refurbishing centers, controlling center capacity to meet requests, and selecting among keeping as stocks or buying new items or disposing of returned items [10]. Vehicle kind choice is a crucial element of these RL operations that has received little attention in the literature but has been acknowledged as a topic for future study on vehicle allocation in SCs that are more environmentally friendly [11].

Finding the ideal number of cars of various types to satisfy customer needs while reducing the overall cost of transportation may be done by modifying the Vehicle type selection issue. These objectives have developed to include reducing carbon emissions and using fuel more efficiently. The nature of these issues can be significantly changed by factoring in the expenses associated with carbon emissions at different examination and remaking facilities and vehicle types [12]. As a result, the GRSC challenge should take into account RL, choosing the right vehicle type, and emissions of carbon dioxide [13]. The link between conventional F&RL has been extensively studied in early RLND research. The topological and methodological levels were the focus of this research. At the topological level, the goal was to examine how product recovery affected the structure of the network. It was emphasized that it is harder to manage the access of used products for recovery than it is to manage standard SC capabilities. As a result, there may be a significant mismatch between supply and demand in terms of time and quantity in a recovery network. Additionally, the accessibility and quality of secondhand goods are typically unknown before [14]. At the level of method, things are more challenging than in conventional forward LND since external supply and demand are coordinated through limitations. In the logistics network, the facility placement issue is mostly modeled using the MILP technique. A MILP technique has been modified by several scholars to simulate issues in RL contexts [15]. Khosravi Rastabi et al. [71] suggested model for a dynamic CLSCN using accelerated benders decomposition. Rastabi et al. [72] investigated benders decomposition for SCN.

Our contributions and motivations to the corpus of literature can be summarized as follows.

- Presenting a FIS for demand forecasting regarding both regular demands and returned products in F&RLN.
- Considering the influences of carbon pricing and carbon tax policy on the performance of F&RLN from both FLN and RLN points of view at the same time in the post-COVID era.
- Presenting a MOMIP model to obtain optimal solutions in the design of F&RLD under carbon pricing effects in the post-COVID era.
- We account for carbon emissions from cars and buildings in a real-world setting, to achieve a GSC, while attention is taken into account to select vehicle-type alternatives for transporting products between centers in F&RL in the post-COVID era.
- Making decisions to determine how the RSCD would affect the design of environmentally friendly SCs, with and without accounting for carbon emissions.

The remainder of this paper is organized as follows: Section 2 provides a literature review of previous research. The problem description for the study setting is introduced in Section 3. Section 4 offers details of mathematical modeling for FRL and RLN considering a carbon tax. In Section 6, the solution approach explained. In Section 6, we present a computational experiment and case study. Section 7 explains the sensitivity analysis of the model. The conclusions and remarkable outcomes, limitations, and future works are shown in Section 8.

2. Literature review

2.1. Related studies

In the post-COVID period, Dwivedi et al. [66] focused on the causes of freight transportation for SSC. Decarburization discussion in SC tweets during and after COVID-19 was studied by Shahzad et al. [67]. SC agility was viewed by Wang & Wang [68] as the prerequisite for firm sustainability in the post-COVID. Data mining approaches were used by Kalezhi et al. [51] to explain the modeling of COVID-19 infections in Zambia. Florida's state-wide evaluation of changes in air quality during the COVID-19 epidemic was conducted by Ghanim et al. [52]. Abbasi et al. [53] examined outsourcing logistics services. A sustainable nonlinear model that takes into account a piecewise function was created by Abbasi et al. [54] to address the danger of hazardous material routing-locating issues. The consequences and difficulties of the COVID-19 pandemic on global waste management for sustainable development were explored by Abbasi & Sıcakyüz [55]. In the post-COVID-19 period, Tian et al. [63] examined a worldwide low-carbon energy transition. The delivery network of necessary goods was created by Abbasi et al. [64] under the demanding circumstances of simultaneous COVID-19 and earthquakes.

Manufacturers are being pushed to incorporate RL into the SC by compelled legislation, societal perception, and creating competitive advantages in the market. Research on logistics and SC strategic planning is increasingly integrating RL into current logistics designs [17]. Manufacturers are being pushed to incorporate RL into the SC by compelled legislation, societal perception, and creating distinct advantages in the market. Research on logistics and SC strategic planning is increasingly integrating RL into current logistics designs [18].

Remarkably, economic concerns frequently took precedence over environmental concerns in many of these modeling studies [19]. For instance, Abbasi et al. [20] used combinatorial optimization to decide whether to recycle, refurbish, or remake products to maximize revenue. In certain studies, multi-period RLN models that emphasize long-term aspects enable more effective decision-making analysis [21].

This research also took into account the variable costs, like operational expenses, and the dynamic nature of location-allocation.

However, there is little scope for incorporating the quality of used goods into these models. Consideration of facility location analyses in an RL system with limitless capacity, among these has been used to gather EOL cars and provide more details [22]. Based on these findings, it was discovered that transportation costs are the determining factor for the RL network. Another line of study focuses on addressing product attributes and designs in the RL network, with MILP formulations appearing to be the preferred approach [23]. Abbasi et al. [24] built an RLN to recycle buildings and demolition debris while taking into account the social and environmental effects as well as cost in a multi-period situation. In their analysis of the SDGs, Danladi et al. [73] looked at financial inclusion and collaborative approaches to fintech uptake in poor nations.

Chen et al. [26] proposed and solved a VRP with simultaneous pickup and delivery utilizing a bacterial foraging efficiency method. Sangamithra et al. [27] provided an RLVRP with time windows where product return/pickup is permitted only during specified periods and attempted to handle the problem using heuristics and enhance the runtime of outcomes using a simulated heating process. Using green technology for material transportation and utilization at facilities helps to create an image of sustainability. Gonzalez et al. [25] designed a CLSC for recycling EOL automobiles in Turkey using a model with a finite planned window. Various phases of RL, such as the gathering of core returns, the recovery of items, and the generation of goods with varying levels of quality, have been deemed crucial modeling characteristics [28]. The cost of emissions from transportation and facility operations is an essential part of RLND. Recent growth and consideration of wide LND use both forward and reverse flows to minimize carbon footprint, and overall cost along the SC is beginning to become incorporated into the decision-making environment [29]. Babai et al. [30] provided a comprehensive review of fuzzy demand forecasting in SCM. It discusses various fuzzy forecasting techniques and their applications in different SC contexts [31].

Inventory has been a crucial choice feature in multi-period reverse LND, matching inventory and disposal expenses [32]. The level of new vs reused modules in manufacturing can additionally be considered when balancing LND considerations [33]. These characteristics are also included in this study, which broadens the decision environment by integrating more attainable difficulties [34]. Several papers have been published that address routing issues in reverse network design. Abbasi et al. [35] assessed and evaluated the impact of carbon emissions on forward and RSCs, and confirmed their findings for an Australian based corporation. Xu & Liao [36,37] prepossessed a fuzzy time series forecasting model to predict carbon emissions in China. The model takes into account the uncertainties and complexities of carbon emissions data and provides more accurate and reliable forecasts [38].

Inspired by such outcomes, this incorporated dynamic study represents the first endeavor in the literature to combine these features into a MILP model for RLND to assist the practitioner community by giving significant management ideas [39]. It also provides investigators with knowledge for predicting and evaluating outcomes in this setting. Furthermore, in today's environment, the transportation sector must change its focus from overall operational costs to sustainability [40]. The study that is now available has developed rather complicated algorithms, such as different analytical modeling and pricing models with a clear focus on industrial and price issues [41]. Carbon footprint-based RL solutions also featured transportation-specific technologies [42]. Abbasi et al. [43] created a model for integrated F&RLNs and the planning of routes. Li & Zhang [44] developed a fuzzy time series forecasting model for carbon emissions in China. The model incorporates the fuzzy set theory and the ARIMA model to capture the uncertainties and complexities of carbon emissions data.

The agroforestry as residual biomass SC was improved by Bastos et al. [48] by taking into account a novel method to improve forest management and reduce logistical expenses. Lotfi et al.'s study [49] looked into a SC that took into account vendor-managed inventory together with a learning method and consignment stock policy. El Hafdaoui et al. [50] examined potential futures and energy-related initiatives for Morocco's long-term low-carbon policy.

SCN was created with the economy and environmental sustainability in mind during the crisis by Abbasi et al. [56]. In uncertain settings, Shahparvari et al. [57] revised the sustainable closed-loop RLN. A CLSC model under uncertainty based on carbon footprint and risk analysis [58]. In light of COVID-19 rehabilitation efforts, Koley [59] outlined the social value possibilities of Australia's construction sector for the Aboriginal people. In light of the factors that led to the transition from crop production to mining operations, Wongnaa et al. [60] proposed sustainable food crop cultivation. Jiang and colleagues [61] proposed an SSCND for China based on its carbon footprint. The use of trash electrical and electronic equipment in China was investigated by Wang et al. [62]. The fast impact assessment matrix approach was employed by Abbasi et al. [65] to evaluate the environmental effect of catastrophe situations.

2.2. Research Gaps and contributions

In their prior study, the researchers solely addressed CO_2 emissions from shipping or analyzing at facilities. However, the carbon emissions from both activities are evaluated in this work. The prior studies described above evaluated either vehicle type selection or the release of carbon dioxide, but not both simultaneously. Logistics is crucial in logistics and supply networks. Vehicle type selection is included in the model to save costs and regulate emissions caused by transportation.

In this study, we provide a strategy for predicting demand in F&RLNs under a carbon price using a FIS during the post-COVID ear. We concentrate on a recent carbon price that was put into place in Mexico as a case study. Our approach employs fuzzy logic and takes into consideration how the carbon price will affect demand to estimate demand accurately. In light of carbon prices and other environmental laws, we think that our strategy can assist logistics firms in Mexico and other nations in making wiser decisions. For a more accurate study, we are evaluating two models. The RLN was investigated in model A, and F&RLNs were considered in model B.

It is now necessary to describe our contributions to overcome the limitations.

- Proposed a MOMIP was given to discover optimal solutions.
- Assessed the effects of the carbon tax policy on FLN and RLN at the same time in the post-COVID era.
- Included the selection of appropriate vehicle-type alternatives for transporting products between centers in F&RLN in the post-COVID era.
- To have a better image of the green issue, we accounted for carbon emissions from cars and buildings in a real-world setting.
- Examined the managerial implications of the mathematical model in the post-COVID era.
- Decisions made both with and without accounting for carbon emissions are included in the study to determine how the RSCD research would affect environmental design.
- Forecasting demand with the FIS method.

3. Description of the problem

3.1. Problem statement

The efficiency of F&RNL in this mathematical framework is influenced by environmental performance metrics and economic performance indicators. We will assess the model's performance using a common carbon price scheme.

The mathematical model A mentioned above takes into account five different sorts of facilities.

1. Potential Customer Centers (c)
2. Potential Collection Centers (p)
3. Potential Remanufacturing Centers (r)
4. Potential Secondary Markets (s)
5. Potential Disposal Centers (d)

Within the mathematical model B mentioned above, four sorts of facilities are taken into consideration.

1. Potential Customer Centers (c)
2. Potential Distribution/Collection Centers (p')
3. Potential Manufacturing/Remanufacturing Centers (r')
4. Potential Disposal Centers (d)

The network schematic for forward and reverse logistics, which can be explained as up, is presented in Fig. 1(a and b).

3.2. Network structure

The initial stage in designing an RLN is to ascertain the network's general structure. The network's design is examined in this section. Based on the various network structure features of the articles, we grouped them into the following two groups.

3.2.1. General network structure (model A)

Customers, collecting, remanufacturing, secondary markets, and disposal facilities are seen in RLNs. The first stage, shown in Fig. 1 (a), is the client zone, where utilized goods are produced. The second step is the collection center, where used goods are gathered from consumer zones before being examined and dismantled. After collecting them, some of them are sent to the disposal centers and others are sent to the repair centers for repair. Finally, second-hand items are sent to secondary markets.

3.2.2. Hybrid facility network structure (model B)

This part discusses the structure of hybrid model network. A hybrid facility, as depicted in Fig. 1 (b), refers to a customer, hibrid centers, remanufacturing/manufacturing centers and disposal centers. This model has two distinct purposes and a mix of forward and backward logistics simultaneously. The creation of these sorts of hybrid facilities enables the use of existing forward logistics network nodes to optimize the architecture of the RLN for remanufacturing. Furthermore, this strategy can remove the requirement for a RLN, thereby lowering expenses.

Some assumptions suggested in the two models include.

- ✓ The locations of all facilities in models A and B are potential.
- ✓ The amount of returned products is determined in two models.
- ✓ CO_2 emissions for all activities in the two models are determined.
- ✓ CO_2 emissions for all transfers in the two models are determined.
- ✓ The problem in the post-COVID era.
- ✓ There are several possibilities for transferring for every node, and the sorts of transportation options have no restriction on capacity.
- ✓ The distances between network nodes of two models must be feasible.

4. Mathematical modeling

In this section, a MOMIP model was proposed to design a multi-echelon F&RLN. The model includes many practical significant features such as carbon emissions, with five facilities for model A and four facilities for model B and vehicle type selection for transportation. The model notations including sets, parameters, and decision variables are presented below. Mathematics models are formulated using OFs and constraints. Tables 1 and 2 provide the notations of models A and B, respectively.

4.1. Model formulation without carbon emission consideration (cost-only model)

A multi-echelon F&RLN were proposed to be designed using this paper during the post-COVID era. Numerous important and useful aspects are included in the model, including vehicle type choices, carbon emissions, and five facilities for model A and four facilities for model B.

4.1.1. Model A

For strategic and operational choices, cost-only approaches rely entirely on financial results. A cost-only approach is going to be used to reduce the overall estimated cost of RLN.

$$\text{MinZ}_{\left(\substack{\text{Cost-only}\\ \text{model A}}\right)} = TF + TV + TT \tag{1}$$

Total Cost = Fixed costs (TF) + Variable costs (TV (+ Transportations costs (TT)

$$TF = \sum_{c=1}^{C} F_c x_c + \sum_{p=1}^{P} F_p x_p + \sum_{r=1}^{R} F_r x_r + \sum_{s=1}^{S} F_s x_s + \sum_{d=1}^{D} F_d x_d$$

$$TV = \sum_{c=1}^{C}\sum_{p=1}^{P}\sum_{tc=1}^{TC} v_c^{tc} y_{cp}^{tc} + \sum_{c=1}^{C}\sum_{p=1}^{P}\sum_{tc=1}^{TC} v_p^{tc} y_{cp}^{tc} + \sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{tp=1}^{TP} v_r^{tp} y_{pr}^{tp} + \sum_{r=1}^{R}\sum_{s=1}^{S} \times \sum_{tr=1}^{TR} v_s^{tr} y_{rs}^{tr} + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{tp=1}^{TP} v_d^{tp} y_{pd}^{tp} TV = \sum_{c=1}^{C}\sum_{p=1}^{P}\sum_{tc=1}^{TC} \omega_c^{tc} y_{cp}^{tc} + \sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{tp=1}^{TP} \omega_r^{tp} y_{pr}^{tp} + \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{tr=1}^{TR} \omega_s^{tr} y_{rs}^{tr} + \sum_{p=1}^{P}\sum_{d=1}^{D} \times \sum_{tp=1}^{TP} \omega_d^{tp} y_{pd}^{tp}$$

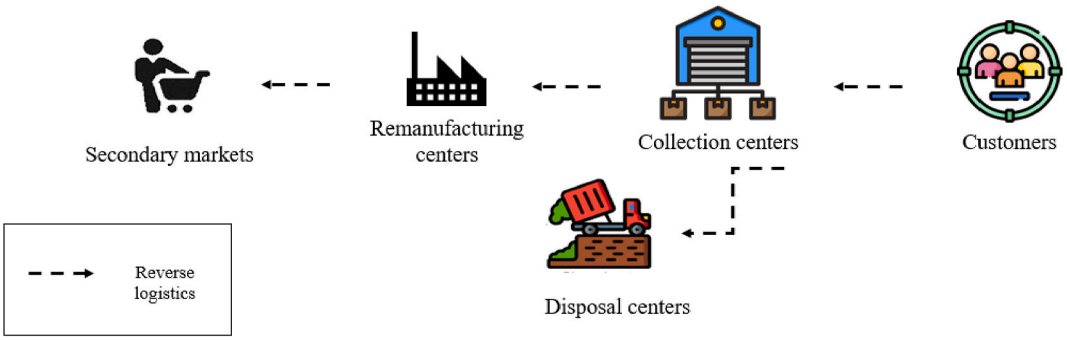


Fig. 1(a). The framework of general RLN (Model A).

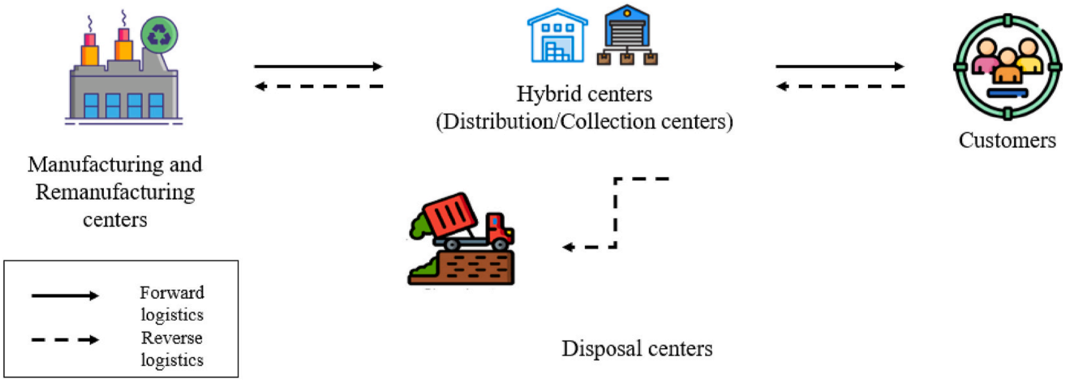


Fig. 1 (b). The framework of hybrid facility F&RLN (Model B).

Subject to:

$$\sum_{p=1}^{p}\sum_{tc=1}^{TC} Y_{cp}^{tc} \le dem_c \ \forall c \in C \tag{2}$$

$$\sum_{c\in C}\sum_{tc\in Tc} y_{cp}^{tc} \le \Gamma_p x_p \ \forall p \in P \tag{3}$$

$$\sum_{p\in P}\sum_{tr\in TR} y_{pr}^{tr} \le \Gamma_r x_r \ \forall r \in R \tag{4}$$

$$\sum_{r\in R}\sum_{tr\in TR} y_{rs}^{tr} \le \Gamma_s x_s \ \forall s \in S \tag{5}$$

$$\sum_{p\in P}\sum_{tp\in TP} y_{pd}^{tp} \le \Gamma_d x_d \ \forall d \in D \tag{6}$$

$$\sum_{p\in P}\sum_{tp\in TP} y_{pr}^{tp} \le \sum_{c\in C}\sum_{tc\in TC} y_{cp}^{tc} \ \forall p \in P \tag{7}$$

$$\sum_{d\in D}\sum_{tp\in TP} y_{pd}^{tp} \le \sum_{c\in C}\sum_{tc\in TC} y_{cp}^{tc} \ \forall p \in P \tag{8}$$

$$\sum_{s\in S}\sum_{tr\in TR} y_{rs}^{tr} \le \sum_{p\in P}\sum_{tp\in TP} y_{pr}^{tp} \ \forall r \in R \tag{9}$$

$$\sum_{s\in S}\sum_{tr\in TR} y_{rs}^{tr} \le \sum_{c\in C}\sum_{tc\in TC} y_{cp}^{tc} \ \forall p \in P, \forall r \in R \tag{10}$$

$$y_{cp}^{tc}, y_{pr}^{tp}, y_{pd}^{tp}, y_{rs}^{tr} \ge 0 \ \forall c \in C, \forall p \in P, \forall r \in R, \forall s \in S, \forall d \in D \tag{11}$$

$$x_c, x_p, x_r, x_s, x_d \in \{0,1\} \forall c \in C, \forall p \in P, \forall r \in R, \forall s \in S, \forall d \in D \tag{12}$$

4.1.2. *Model B*

MinZ $_{\text{(Cost-only model B)}}$ = TF + TV + TT.

Total Cost = Fixed costs (TF) + Variable costs (TV)+ Transportations costs (TT)

$$TF = \sum_{c=1}^{C} F_c x_c + \sum_{p'=1}^{P'} F_{p'} x_{p'} + \sum_{r'=1}^{R'} F_{r'} x_{r'} + \sum_{d=1}^{D} F_d x_d \tag{13}$$

$$TV = \sum_{c=1}^{C}\sum_{p'=1}^{P'}\sum_{tc=1}^{TC} v_c^{tc} y_{cp'}^{tc} + \sum_{c=1}^{C}\sum_{p'=1}^{P'}\sum_{tc=1}^{TC} v_{p'}^{tc} y_{cp'}^{tc} + \sum_{p'=1}^{P'}\sum_{r'=1}^{R'}\sum_{tp'=1}^{TP'} v_{r'}^{tp'} y_{p'r'}^{tp'} + \sum_{p'=1}^{P'}\sum_{d=1}^{D}\sum_{tp'=1}^{TP'} v_d^{tp'} y_{p'd}^{tp'} + \sum_{r'=1}^{R'}\sum_{p'=1}^{P'}\sum_{tr'=1}^{TR'} v_{p'}^{tp'} y_{r'p'}^{tr'} + \sum_{p'=1}^{P'}\sum_{c=1}^{C}\sum_{tc=1}^{TC} v_c^{tp'} y_{p'c}^{tp'}$$

$$TT = \sum_{c=1}^{C}\sum_{p'=1}^{P'}\sum_{tc=1}^{TC} \omega_c^{tc} y_{cp'}^{tc} + \sum_{p'=1}^{P'}\sum_{r'=1}^{R'}\sum_{tp'=1}^{TP'} \omega_{r'}^{tp'} y_{p'r'}^{tp'} + \sum_{p'=1}^{P'}\sum_{d=1}^{D}\sum_{tp'=1}^{TP'} \omega_d^{tp'} y_{p'd}^{tp'} + \sum_{r'=1}^{R'}\sum_{p'=1}^{P'}\sum_{tr'=1}^{TR'} \omega_{p'}^{tp'} y_{r'p'}^{tr'} + \sum_{p'=1}^{P'}\sum_{c=1}^{C}\sum_{tc=1}^{TC} \omega_c^{tp'} y_{p'c}^{tp'}$$

Subject to:

$$\tilde{dem_c} \le \sum_{p'=1}^{P'}\sum_{tp'=1}^{TP'} Y_{p'c}^{tp'} \ \forall c \in C \tag{14}$$

$$\sum_{p=1}^{p}\sum_{tc=1}^{TC} Y_{cp}^{tc} \le \tilde{dem_c} \ \forall c \in C \tag{15}$$

$$\sum_{c\in C}\sum_{tc\in Tc} y_{cp'}^{tc} \le \Gamma_{p'} x_{p'} \ \forall p' \in P' \tag{16}$$

$$\sum_{p'\in P'}\sum_{tr'\in TR'} y_{p'r'}^{tr'} \le \Gamma_{r'} x_{r'} \ \forall r' \in R' \tag{17}$$

$$\sum_{p'\in P'}\sum_{tp'\in TP'} y_{p'd}^{tp'} \le \Gamma_d x_d \ \forall d \in D \tag{18}$$

$$\sum_{p'\in P'}\sum_{tp'\in TP'} y_{p'r'}^{tp'} \le \sum_{c\in C}\sum_{tc\in TC} y_{cp'}^{tc} \ \forall p' \in P' \tag{19}$$

$$\sum_{p'\in P'}\sum_{tp'\in TP'} y_{p'd}^{tp'} \le \sum_{c\in C}\sum_{tc\in TC} y_{cp'}^{tc} \ \forall p' \in P' \tag{20}$$

$$\sum_{s\in S}\sum_{tr\in TR} y_{rs}^{tr} \le \sum_{p\in P}\sum_{tp\in TP} y_{pr}^{tp} \ \forall r \in R \tag{21}$$

$$\sum_{s\in S}\sum_{tr\in TR} y_{rs}^{tr} \le \sum_{c\in C}\sum_{tc\in TC} y_{cp}^{tc} \ \forall p \in P, \forall r \in R \tag{22}$$

$$y_{cp'}^{tc}, y_{p'r'}^{tp'}, y_{p'd}^{tp'} \ge 0 \ \forall c \in C, \forall p \in P, \forall r \in R, \forall d \in D \tag{23}$$

$$x_c, x_{p'}, x_{r'}, x_d \in \{0,1\} \ \forall c \in C, \forall p' \in P', \forall r' \in R', \forall d \in D \tag{24}$$

The OFs are mathematically formulated in Equations (1) and (13) in models A and B respectively. The total cost is the sum of the fixed, variable, and transportation costs. Equations (2)–(12) and (14)-(24) present the constraints for models A and B. Constraints (2), (-14) and (15) explain the demand of customers for models A and B. Constraints (3)-(6) explain the capacity of facilities in model A and Constraints (16)-(18) does the same for model B. Constraints (7)–(10) explain the flow balance in model A and Constraints (19)–(22) do the same for model B.

Table 1
Notations of model A.

Sets of model A		
c	Potential Customer Centers	$c = 1, 2, \ldots, C$
p	Potential Collection Centers	$P = 1, 2, \ldots, P$
r	Potential Remanufacturing Centers	$r = 1, 2, \ldots, R$
s	Potential Secondary Markets	$s = 1, 2, \ldots, S$
d	Potential Disposal Centers	$d = 1, 2, \ldots, D$
tc	Transportation type from Customer Centers	$tc = 1, 2, \ldots, TC$
tp	Transportation type from Collection Centers	$tp = 1, 2, \ldots, TP$
tr	Transportation type from Remanufacturing Centers	$\mathrm{tr} = 1, 2, \ldots, TR$
Parameters of model A		
$dem^{\sim}{}_{c}$	The demand of customer center c during the post-COVID condition	
Γ_p	The capacity of the collection center p during the post-COVID condition	
Γ_r	The capacity of the remanufacturing center r during the post-COVID condition	
Γ_s	The capacity of the secondary market s during the post-COVID condition	
Γ_d	The capacity of the disposal center d during the post-COVID condition	
dis_{cp}	Distance between customer center c and collection center p	
dis_{pr}	Distance between collection center p and remanufacturing center r	
dis_{rs}	Distance between remanufacturing center r and secondary market s	
dis_{pd}	Distance between collection center p and disposal center d	
F_c	Fixed costs for founding the customer center c	
F_p	Fixed costs for founding the collection center p	
F_r	Fixed costs for founding the remanufacturing center r	
F_s	Fixed costs for founding the secondary market s	
F_d	Fixed costs for founding the disposal center d	
V_c	Variable costs in the customer center c	
V_p	Variable costs in the collection center p	
V_r	Variable costs in the remanufacturing center r	
V_s	Variable costs in the secondary market s	
V_d	Variable costs in the disposal center d	
ψ_{cp}^{tc}	Transfer costs between the customer center c to collection center p with transportation tc	
ψ_{pr}^{tp}	Transfer costs between the collection center p to remanufacturing center r with transportation tp	
ψ_{rs}^{tr}	Transfer costs between the remanufacturing center r to secondary market s with transportation t	
ψ_{pd}^{td}	Transfer costs between the collection center p to disposal center d with transportation tp	
em_c	The CO_2 emissions caused by activities in customer center c during the post-COVID condition	
em_p	The CO_2 emissions caused by activities in collection center p during the post-COVID condition	
em_r	The CO_2 emissions caused by activities in remanufacturing center r during the post-COVID condition	
em_s	The CO_2 emissions caused by activities in secondary market s during the post-COVID condition	
em_d	The CO_2 emissions caused by activities in disposal center d during the post-COVID condition	
emt_{cp}^{tc}	The CO_2 emissions caused by the transfer of the goods between customer center c and collection center p by transportation type tc during the post-COVID condition	
emt_{pr}^{tp}	The CO_2 emissions caused by the transfer of the goods between collection center p and remanufacturing center r by transportation type tp during the post-COVID condition	
emt_{rs}^{tr}	The CO_2 emissions caused by the transfer of the goods between remanufacturing center r and secondary market s by transportation type tr during the post-COVID condition	
emt_{pd}^{tp}	The CO_2 emissions caused by the transfer of the waste between collection center p and disposal d by transportation type tp during the post-COVID condition	
δ	The carbon tax rate per unit (Amount of tax paid per unit emitted) during the post-COVID condition	
Decision (Binary & Continuous) variables of model A		
x_c	If potential customer center c is founded, equal 1; otherwise 0	
x_p	If potential collection center p is founded, equal 1; otherwise 0	
x_r	If potential remanufacturing center r is founded, equal 1; otherwise 0	
x_s	If potential secondary market s is founded, equal 1; otherwise 0	
x_d	If potential disposal center d is founded, equal 1; otherwise 0	
y_{cp}^{tc}	The number of goods transferred from customer center c to collection center p with the method of transportation tc	
y_{pr}^{tp}	The number of goods transferred from collection center p to remanufacturing center r with the method of transportation tp	
y_{rs}^{tr}	The number of goods transferred from the remanufacturing center r to secondary market s with the method of transportation tr	
y_{pd}^{tp}	The number of goods transferred from collection center p to disposal center d with the method of transportation t	

Note: For model B, all common components remained except new sets, parameters, and decision variables.

Constraints (11)&(12) and (23&24) express the non-negative and integer of the decision variables, respectively for models A and B.

4.2. *Model formulation of carbon tax policy (M_A & M_B)*

The rule in question provides options for stringent carbon limitations. This policy does not impose any emission restrictions or limitations on emissions, as do carbon cap regimes. Nonetheless, emissions are punished by a carbon price. The tax is a monetary penalty (δ) in which emissions are linked to taxes on carbon.

$$\begin{aligned} z_1' = & \sum_{c=1}^{C}\sum_{p'=1}^{P'}\sum_{tc=1}^{TC} em_c^{tc} y_{cp'}^{tc} + \sum_{c=1}^{C}\sum_{p'=1}^{P'}\sum_{tc=1}^{TC} em_{p'}^{tc} y_{cp'}^{tc} + \sum_{p'=1}^{P'}\sum_{r'=1}^{R'}\sum_{tp'=1}^{TP'} em_{r'}^{tp'} y_{p'r'}^{tp'} \\ & + \sum_{p'=1}^{P'}\sum_{d=1}^{D}\sum_{tp'=1}^{TP'} em_d^{tp'} y_{p'd}^{tp'} \\ & + \sum_{r'=1}^{R'}\sum_{p'=1}^{P'}\sum_{tr'=1}^{TR'} em_{p'}^{tp'} y_{r'p'}^{tr'} + \sum_{p'=1}^{P'}\sum_{c=1}^{C}\sum_{tp'=1}^{TP'} em_c^{tp'} y_{p'c}^{tp'} + \sum_{p'=1}^{P'}\sum_{d=1}^{D}\sum_{tp'=1}^{TP'} em_d^{tp'} y_{p'd}^{tp'} \end{aligned} \tag{25}$$

Table 2
Notations of model B.

New Sets of model B		
P'	Potential Collection/Distribution Centers	$p' = 1, 2, \ldots, P'$
r'	Potential Remanufacturing/Manufacturing Centers	$r' = 1, 2, \ldots, R'$
tp'	Transportation type from Collection/Distribution Centers	$tp' = 1, 2, \ldots, TP'$
tr'	Transportation type from Remanufacturing/ Manufacturing Centers	$tr' = 1, 2, \ldots, TR'$
New Parameters of model B		
$\Gamma p'$	The capacity of the collection/distribution center p' during the post-COVID condition	
$\Gamma r'$	The capacity of the remanufacturing/manufacturing center r' during the post-COVID condition	
$dis_{cp'}$	Distance between customer center c and collection/distribution center p'	
$dis_{p'r'}$	Distance between collection/distribution center p' and remanufacturing/ manufacturing center r'	
$dis_{p'd}$	Distance between collection/distribution center p' and disposal center d	
$F_{p'}$	Fixed costs for founding the collection/distribution center p'	
$F_{r'}$	Fixed costs for founding the remanufacturing/manufacturing center r'	
$V_{p'}$	Variable costs in the collection/distribution center p'	
$V_{r'}$	Variable costs in the remanufacturing/manufacturing center r'	
$\psi^{tc}_{cp'}$	Transfer costs between the customer center c to collection/distribution center p' with transportation tc	
$\psi^{tp'}_{p'r'}$	Transfer costs between the collection/distribution center p' to remanufacturing/manufacturing center r' with transportation tp'	
$\psi^{tr'}_{r'p'}$	Transfer costs between the remanufacturing/manufacturing center r' to collection/distribution center p' with transportation tr'	
$\psi^{tp'}_{p'c}$	Transfer costs between the collection/distribution center p' to customer center c with transportation tp'	
$em_{p'}$	The CO_2 emissions caused by activities in collection/distribution center p' during the post-COVID condition	
$em_{r'}$	The CO_2 emissions caused by activities in remanufacturing/manufacturing center r' during the post-COVID condition	
$emt^{tc}_{cp'}$	The CO_2 emissions caused by the transfer of the goods between customer center c and collection/distribution center p' by transportation type tc during the post-COVID condition	
$emt^{tp'}_{pr'}$	The CO_2 emissions caused by the transfer of the goods between collection/ distribution center p' and remanufacturing/manufacturing center r' by transportation type tp' during the post-COVID condition	
$emt^{tr'}_{r'p'}$	The CO_2 emissions caused by the transfer of the goods between remanufacturing/manufacturing center r' and the collection/distribution center p' by transportation type tr' during the post-COVID condition	
$emt^{tp'}_{p'\ c}$	The CO_2 emissions caused by the transfer of the goods between collection/ distribution center p' and customer center c by transportation type tp' during the post-COVID condition	
$emt^{tp'}_{p'\ d}$	The CO_2 emissions caused by the transfer of the goods between collection/ distribution center p' and disposal center d by transportation type tp' during the post-COVID condition	
New Decision (Binary & Continuous) Variables of model B		
$x_{p'}$	If potential collection/distribution center p' is established, equal 1; otherwise 0;	
$x_{r'}$	If potential remanufacturing/manufacturing center r' is established, equal 1; otherwise 0;	
$y^{tc}_{cp'}$	The number of goods transferred from customer center c to collection/ distribution center p' with the method of transportation tc	
$y^{tp'}_{p'r'}$	The number of goods transferred from the collection/distribution center p' to the remanufacturing/manufacturing center r' with the method of transportation tp'	
$y^{tr'}_{r'p'}$	The number of goods transferred from remanufacturing/manufacturing center r' to the collection/distribution center p' with the method of transportation tr'	
$y^{tp'}_{p'c}$	The number of goods transferred from collection/distribution center p' to customer center c with the method of transportation tp'	
$y^{tp'}_{p'd}$	The number of waste transferred from collection/distribution center p' to disposal center d with the method of transportation tp'	

$$z'_2 = \sum_{c=1}^{C}\sum_{p=1}^{P}\sum_{tc=1}^{TC} emt^{tc}_{c} y^{tc}_{cp} dis_{cp} + \sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{tp=1}^{TP} emt^{tp}_{r} y^{tp}_{pr} dis_{pr} + \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{tr=1}^{TR} emt^{tr}_{s} y^{tr}_{rs} dis_{rs} + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{tp=1}^{TP} emt^{tp}_{d} y^{tp}_{pd} dis_{pd} \tag{26}$$

4.2.1. Model A (M_A)

$$\text{MinZ}_{(\text{Tax model A})} = \text{MinZ}_{(\text{Cost-only model A})} + \delta\,(Z_1 + Z_2) \tag{27}$$

Subject to:
Constraints (2)–(11)
Therefore, Equations 25–27is made the formulation of the Tax model for M_A.

4.2.2. Model B (M_B)

$$\text{MinZ}_{(\text{Tax model B})} = \text{MinZ}_{(\text{Cost-only model B})} + \delta\,(Z'_1 + Z'_2) \tag{28}$$

Subject to:
Constraints (13)–(21)

$$z_1 = \sum_{c=1}^{C}\sum_{p=1}^{P}\sum_{tc=1}^{TC} em^{tc}_{c} y^{tc}_{cp} + \sum_{c=1}^{C}\sum_{p=1}^{P}\sum_{tc=1}^{TC} em^{tc}_{p} y^{tc}_{cp} + \sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{tp=1}^{TP} em^{tp}_{r} y^{tp}_{pr} + \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{tr=1}^{TR} em^{tr}_{s} y^{tr}_{rs} + \sum_{p=1}^{P}\sum_{d=1}^{D}\sum_{tp=1}^{TP} em^{tp}_{d} y^{tp}_{pd} \tag{29}$$

$$z'_2 = \sum_{c=1}^{C}\sum_{p'=1}^{P'}\sum_{tc=1}^{TC} emt^{tc}_{c} y^{tc}_{cp'} dis_{cp'} + \sum_{p'=1}^{P'}\sum_{r'=1}^{R'}\sum_{tp'=1}^{TP'} emt^{tp'}_{r'} y^{tp'}_{p'r'} dis_{p'r'} + \sum_{p'=1}^{P'}\sum_{d=1}^{D}\sum_{tp'=1}^{TP'} emt^{tp'}_{d} y^{tp'}_{p'd} dis_{p'd} + \sum_{r'=1}^{R'}\sum_{p'=1}^{P'}\sum_{tr'=1}^{TR'} emt^{tp'}_{p'} y^{tr'}_{r'p'} dis_{r'p'} + \sum_{p'=1}^{P'}\sum_{c=1}^{C}\sum_{tc=1}^{TC} emt^{tp'}_{c} y^{tp'}_{p'c} dis_{p'c} \tag{30}$$

Therefore, Equations 28–30 is made the formulation of the Tax model for M_B.

5. Solution approach

5.1. Fuzzy inferences system (FIS)

The utilization of fuzzy systems is progressively growing with each passing day. These systems find application across diverse domains, including fuzzy expert systems, decision support systems, risk analysis, control systems, image processing, communication, commerce, medicine, military, education, robotics, power systems, nuclear reactors, and automobile engineering [45]. In this article, FIS is employed for the purpose of predicting demand. Initially, the criteria necessary for fulfilling the demand are acquired through a review of existing literature and insights from experts. These identified criteria then undergo the process of fuzzification. Subsequently, membership functions for the fuzzy criteria are established. For each criterion, a corresponding fuzzy operator is designated, followed by a customization of these operators.

Experts define the fuzzy rules that govern the system. The rules outlined here are organized according to the designated operators, and then they are combined in a specific order. Ultimately, the output is presented in the form of the defined demand. The fuzzy inference engine employed in this research aligns with the model introduced by Mamdani & Asilian [16].

5.2. Identifying criteria

In this research, 29 experts who have worked in the field of the electronic equipment industry were selected. All the experts had academic degrees, including master's degrees and doctorates, and had more than 5 years of experience. Initially, 30 criteria were chosen by the experts, and screening was performed using the fuzzy Delphi approach. Finally, 9 criteria were selected. Based on the opinion of experts and the literature review, the following criteria that affect the demand for electronic devices have been selected [69,70].

- **C1:** Technological Advancements: Consumers often seek the latest technology and features in their electronic devices. Innovations such as smart home integration, energy efficiency, voice control, and improved connectivity can significantly impact demand.
- **C2:** Energy Efficiency: With growing concerns about environmental sustainability and energy costs, energy-efficient devices are in high demand. Energy-efficient appliances not only reduce utility bills but also contribute to a greener lifestyle.
- **C3:** Cost: Price is a major factor affecting demand. Consumers will assess whether the benefits and features offered by a device justify its price tag. Lower-cost alternatives or discounts can stimulate demand, especially during economic downturns.
- **C4:** Ease of Use: Devices that are user-friendly and intuitive tend to have higher demand. Consumers are more likely to opt for products that do not require a steep learning curve.
- **C5:** Brand Reputation: Established and trusted brands often have a higher demand due to their reputation for quality and reliability. Consumers are more likely to invest in devices from brands they know and trust.
- **C6:** Lifecycle and Durability: Consumers consider the expected lifespan of a device and its potential for repairs or upgrades. Devices that are built to last or have upgradeable components can attract higher demand.
- **C7:** Health and Wellness: Devices that contribute to health and wellness, such as air purifiers, fitness trackers, and smart scales, are gaining popularity as consumers become more health-conscious.
- **C8:** Cultural and Lifestyle Trends: Socio-cultural factors, such as the trend toward remote work or the desire for a connected lifestyle, can impact demand for devices that facilitate these trends.
- **C9:** Replacement and Upgrading Cycles: As technology evolves, consumers may replace or upgrade their devices to stay current with the latest features and capabilities.

5.3. Fuzzification and membership functions

The membership functions for each input and output are defined by the selected criteria. The fuzzy weights are assigned to the chosen criteria. In this study, triangular fuzzy values are utilized, denoted as Moderate Significance (MS), Limited Significance (LS), and High Significance (HS). The proposed linguistic weighting terms are as follows.

Linguistic Terms	Fuzzy weights
Limited Significance (LS)	(0.1,0.2,0.3)
Moderate Significance (MS)	(0.4,0.5,0.6)
High Significance (HS)	(0.7,0.8,0.9)

5.4. Applying fuzzy operators

In this research, two operators proposed by the Mamdani & Asilian [16] FIS have been used. The operators used include 'min' and 'multiplication.' These operators are employed based on related equations in the FIS (Equation (31)&(32).

$$R(x,y) = \min \left[\mu_i(x), \mu_j(y)\right] \tag{31}$$

$$R(x,y) = \mu_i(x).\mu_j(y) \tag{32}$$

6. Computational experiments

6.1. Input parameters

This section tests the applicability of the suggested models using a numerical example. Consider five customer centers ($|C| = 5$), two collection centers ($|P| = 2$), four remanufacturing centers ($|R| = 4$), three Secondary Markets ($|S| = 3$), one disposal centers ($|D| = 1$), three distribution/collection centers ($|p'| = 3$), two manufacturing/remanufacturing centers ($|r'| = 2$), two transportation type from customer centers ($|TC| = 2$), one transportation type from collection centers ($|TP| = 1$), two transportation type from remanufacturing centers ($|TR| = 2$), two transportation type from collection/distribution centers ($|TP'| = 2$), one transportation type from remanufacturing/manufacturing centers ($|TR'| = 1$). In general, it is acknowledged that CO_2 emissions from various facilities and modes of transportation vary significantly. The rule parameters are chosen as δ (carbon tax) = 0.7 $/kg to highlight differences in selling and purchasing prices in a market after accounting for transaction expenses after the post COVID-19. The additional parameters reported in two models are solved using LINGO19 and on a notebook with an Intel core i7 CPU running at 2.40 GHz and 8.0 GB of RAM. Table 3 shows the optimal value solution of objective functions for models A & B under no carbon policy and carbon tax policy. The carbon tax scheme increases the RL's expenses. Figs. 2 and 3 provides a comparison of optimization values for models A and B in cost-only and tax scenarios.

The numerical example's outcomes provide light on the possible advantages of employing fuzzy-based demand forecasting models in forward and RLNs in the context of carbon tax laws. The study also emphasizes how crucial it is to take into account the uncertainty surrounding carbon tax laws when designing and operating logistics networks, and how crucial it is to have reliable demand forecasting models to assist in making decisions in this situation.

6.2. Case study

A real-world case study setting has been used to assess the model's results. The location of the case study is Puebla state in Mexico The model's accuracy and usefulness are assessed using the case study data. Last but not least, the proposed model should be referred to as FLN and RLN, as well as being trustworthy and adaptable. The facilities, based on this report, consist of consider two customer centers ($|C| = 2$), one collection centers ($|P| = 1$), two Remanufacturing centers ($|R| = 2$),

Table 3
Optimal value solution of objective functions under no carbon policy and carbon tax policy for models A and B.

Optimization value of the objective function	No Carbon Policy (M_A)	No Carbon Policy (M_B)	Carbon Tax Policy (M_A)	Carbon Tax Policy (M_B)
P1	3950	5432	3560	4000
P2	2653	4721	2020	4500
P3	2320	1830	1980	1900
P4	1680	910	1001	750
P5	925	804	320	500

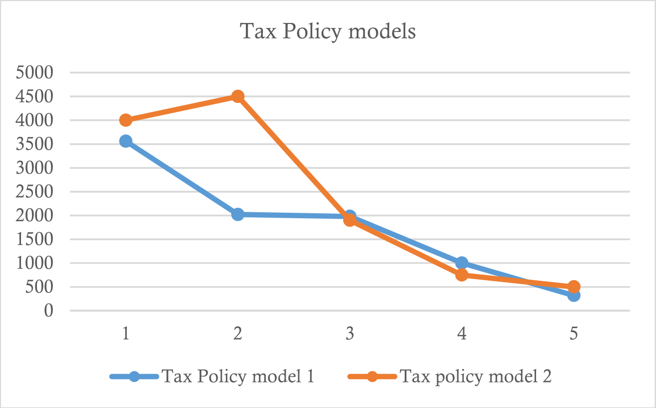


Fig. 2. The comparison optimization value for cost-only situations between model A and model B.

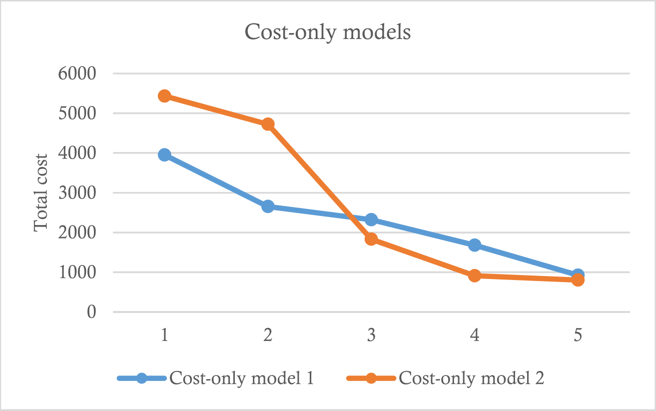


Fig. 3. The comparison optimization value for tax policy situations between model A and model B.

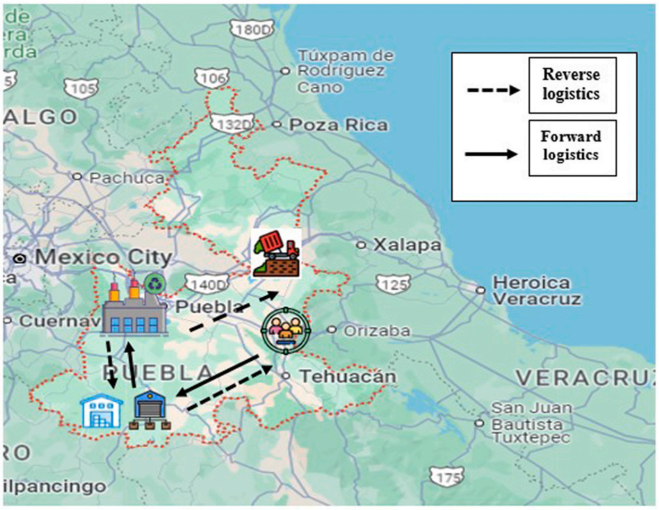


Fig. 4 (a). A schematic of the general network structure in the post-COVID era (Model A) [46].

three secondary markets ($|S| = 3$),one disposal centers ($|D| = 1$), four distribution/collection centers ($|p'| = 4$), for manufacturing/remanufacturing centers ($|r'| = 4$), one Transportation type from Customer Centers ($|TC| = 1$), two Transportation type from Collection Centers ($|TP| = 2$), three transportation type from remanufacturing centers ($|TR| = 3$), one transportation type from collection/distribution centers ($|TP'| = 1$), one transportation type from remanufacturing/manufacturing centers ($|TR'| = 1$).

Fig. 4 (b). A schematic of the hybrid facilities network structure in the post-COVID era (Model B) [46].

In general, it is acknowledged that CO_2 emissions from various facilities and modes of transportation vary significantly. The rule parameters are chosen as δ (carbon tax) $= 0.5$ \$/kg to highlight differences in selling and purchasing prices in a market after accounting for transaction expenses.

The carbon tax scheme increases the RL’s expenses. Fig. 4(a and b) provide a comparison of optimization values for models A and B in cost-only and tax scenarios. Fig. 5 displays the optimization value comparison between Model A and Model B in a real-world scenario, just focusing on costs. The comparative optimization value between Model A and Model B in a real-world scenario, taking into account the tax policy conditions, is displayed in Fig. 6.

In the framework of Mexico’s carbon tax legislation, this case study focuses on demand forecasting in forward and RLNs. The goal of the project is to create a fuzzy-based demand forecasting model that may assist in decision-making regarding the design and operation of logistics networks while also successfully incorporating the uncertainties related to carbon tax regulations.

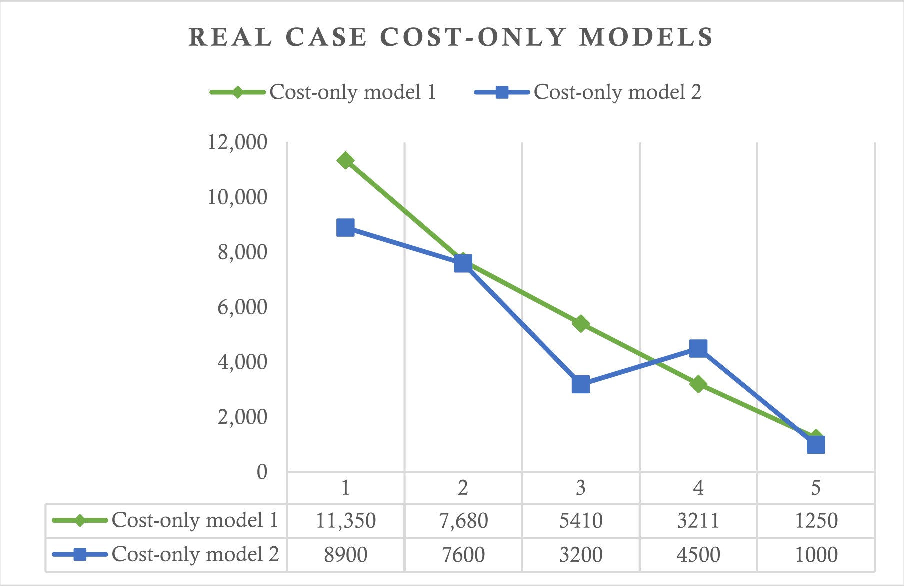
The following goals are particularly addressed in the case study.

1. Creating a demand forecasting model with a fuzzy foundation in the post-COVID era.
2. Designing logistics networks with carbon price plans in mind in the post-COVID era.
3. Examining how carbon tax laws affect the efficiency of logistics networks in the post-COVID era.

The case study’s findings shed light on the possible advantages of employing demand forecasting models with fuzzy logic in forward and RLNs in the context of carbon tax laws. The study also emphasizes how crucial it is to take into account the uncertainty surrounding carbon tax laws when designing and operating logistics networks, and how crucial it is to have reliable demand forecasting models to assist in making decisions in this situation.

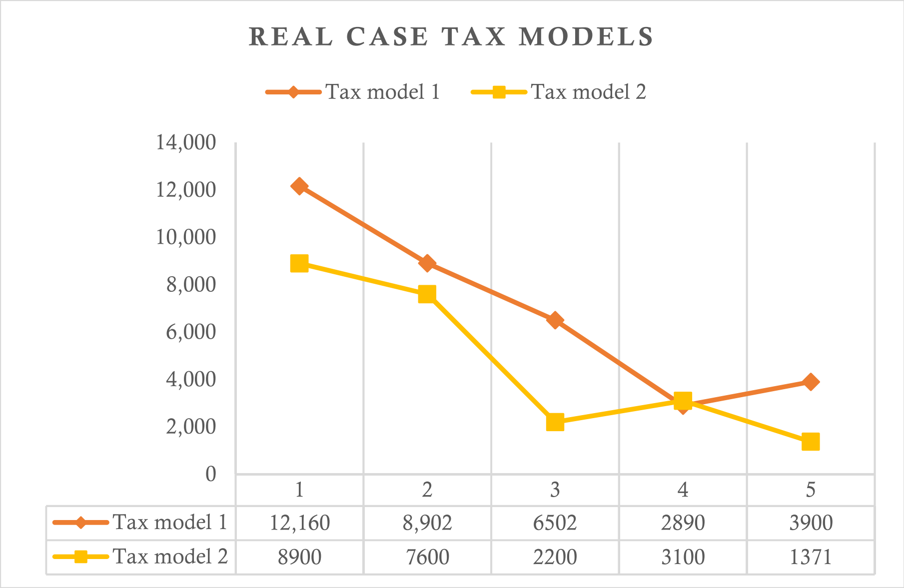
7. Sensitivity analysis

In this section, we look at how objective function two changed when the carbon tax parameter was adjusted. A base value is regarded as the



	1	2	3	4	5
Cost-only model 1	11,350	7,680	5410	3211	1250
Cost-only model 2	8900	7600	3200	4500	1000

Fig. 5. Comparing optimization value considering the cost-only situations between model A and model B in real case in the post-COVID era.



	1	2	3	4	5
Tax model 1	12,160	8,902	6502	2890	3900
Tax model 2	8900	7600	2200	3100	1371

Fig. 6. Comparing optimization value considering the tax policy situations between model A and model B in real case in the post-COVID era.

same as the current value and is progressively enhanced. As you can see, RL expenses will rise as a result of the increased carbon price. We provide sensitivity calculations for several carbon pricing regimes in Fig. 7 (a and b).

Table 4 presents the optimal value of the third objective function achieved by increasing the carbon price. Table 5 presents the optimal value of the third objective function achieved by increasing the carbon price.

The considered rules amount to 445 unique laws, as per the expert opinions. Here, 15 rules are presented as examples. For instance, in rule one, if all criteria except the price (which is low) are deemed high, the demand is assessed as high. The formulation of the rules was established following the if-then rule structure. if y_1 is a_1 andy_2 is b_1 then z is c_1," the variables y_1, y_2, and z are interpreted as fuzzy terms represented by the respective variables a_1, b_1, and c_1.

8. Conclusions and outlook

The method used in this study is to predict demand in a logistics network affected by a carbon price in the post-COVID era. The study intends to inform decision-makers in the sector on possible carbon price effects on logistics operations and assist them in making plans for a more sustainable future. The research focuses on the Mexican logistics network and takes into account both forward and reverse logistics, dealing with the transit of products from producers to consumers and, accordingly, the return of products from consumers to manufacturers in the post-COVID era. To predict demand in this network, the authors create a FIS model that takes into consideration several variables, including the carbon tax, transportation expenses, and consumer preferences. Two models were proposed to assess the impact of RL strategic and functional actions on the optimization process in the post-COVID era. For one of the most well-liked carbon policies (Carbon tax), the implications of forward and reverse logistics are investigated. A

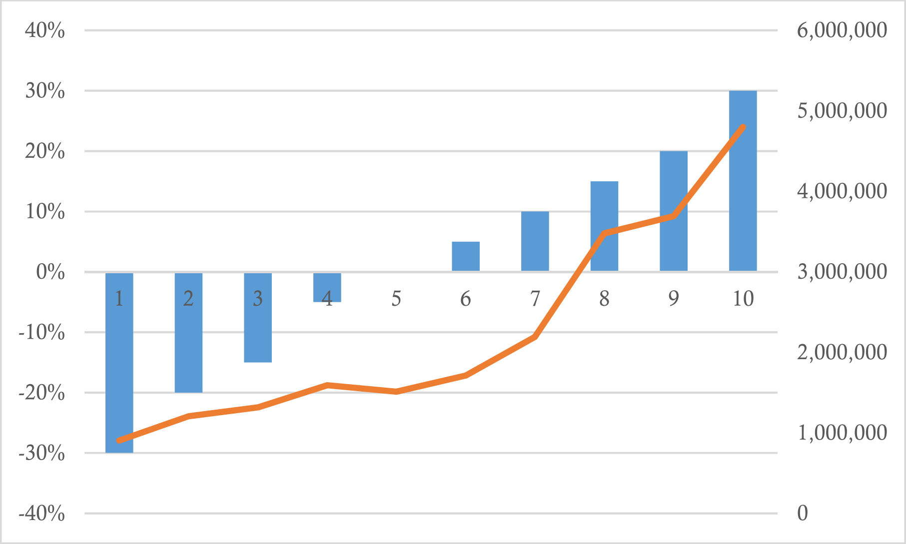


Fig. 7(a). Sensitivity analysis for different carbon tax policies for model A.

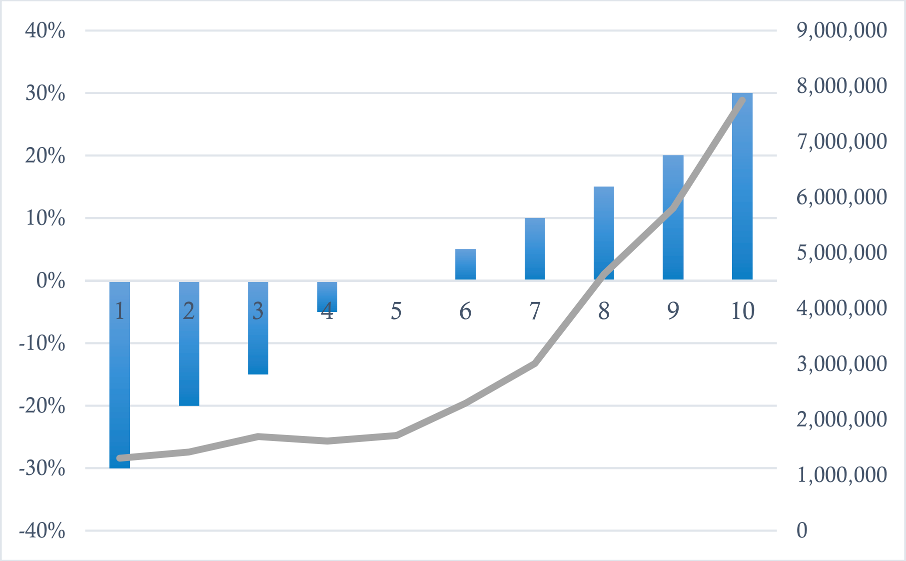


Fig. 7 (b). Sensitivity analysis for different carbon tax policies for model B.

Table 4
The third objective function's value as optimized via raising the carbon tax.

The optimization value of the objective function (M_A)	Increased/decreased change in carbon tax %
905,033	−30 %
1,205,000	−20 %
1,315,044	−15 %
1,591,035	−5%
1,512,000	0
1,712,129	5 %
2,193,330	10 %
3,477,898	15 %
3,692,255	20 %
4,799,819	30 %

Table 5
The third objective function's value as optimized via raising the carbon tax.

The optimization value of the objective function (M_B)	Increased/decreased change in carbon tax %
1,305,000	−30 %
1,415,011	−20 %
1,691,088	−15 %
1,612,099	−5%
1,710,120	0
2,293,430	5 %
3,007,811	10 %
4,611,288	15 %
5,799,010	20 %
7,744,888	30 %

statistical evaluation of the model is performed, and the implications of various regulations on the total cost and CO_2 emissions of the RL are examined. Although carbon pricing regimes offer more freedom, firms are under enormous financial pressure to meet carbon reduction targets.

To attain the mandated emission levels, businesses and politicians must regain their RLs about operational and strategic decisions.

The research yields several remarkable outcomes and conclusions.

- Under the impact of a carbon price, the FIS model appears to be a useful tool for demand forecasting in a logistics network. Using actual data from a Mexican corporation, the model's accuracy is assessed, and the findings demonstrate that it surpasses conventional forecasting techniques like linear regression and artificial neural networks in the post-COVID era.
- The study shows that the installation of a carbon tax can result in major modifications to the logistics network, such as modifications to the modes of transportation, the quantity of inventory, and the methods of production and distribution. The requirement to reduce carbon emissions and adhere to tax laws is what motivates these reforms in the post-COVID era.
- The carbon tax directly influences the price of transportation, which in turn has an impact on the logistics network's overall cost. They suggest a two-step optimization strategy to reduce the network's overall cost while taking the carbon tax and consumer preferences into account in the post-COVID era.
- The study emphasizes how crucial it is to take into account both forward and reverse logistics when designing and organizing a sustainable logistics network. The authors contend that more effective and ecologically friendly operations might result from a holistic strategy that considers the complete product life cycle in the post-COVID era.
- The study offers useful information for decision-makers in the logistics sector, assisting them in comprehending the possible effects of carbon taxes and formulating plans to prepare for a more sustainable future.
- By contrasting models, A and B, research was carried out to determine the impact of the carbon price on RLN and FLN in the post-COVID era.
- We employed a MOMIP model to evaluate these problems.
- To better explain the impacts of carbon tax policy on the RLN and FLN framework in 2023 and assess the effectiveness of this project, this research offered a genuine case study in Mexico.

This paper has some limitations as follows.

* The availability and quality of the input data have a considerable influence on the FIS model's correctness, and the findings' probable lack of direct transfer to other regions or sectors of the economy may restrict the results' generalizability.
* This study's historical data may not be typical of other industries or regions due to the author's use of historical information from a Mexican company. Furthermore, the lack of a clear explanation of the data used for training and testing the FIS model makes it difficult to assess the reliability of the results.
* The performance of the model in diverse contexts or its sensitivity to input parameters is not thoroughly examined. The benefits and drawbacks of the FIS model as well as its application in diverse settings may be clarified through a comparative study.
* The FIS model favors internal factors like transportation costs and carbon levies above external factors like competition and market demand. The inclusion of these external factors in the model may lead to better decision-making in the logistics network and more precise demand estimations.

The Perspectives on the future of research are as follows.

- Although the paper's main focus is on the Mexican industry, the FIS method may be used by various companies and countries. The effectiveness and applicability of the FIS approach in various contexts may be examined in further studies, supporting the assertion that it is resilient and universal.
- The research looks at how the carbon price has a big influence on the demand in the F&RLNs. However, demand may also be influenced by other factors such as consumer preferences, governmental policies, and monetary conditions. The incorporation of these additional factors into the FIS approach may be the subject of future research to improve the accuracy and applicability of its predictions.
- The FIS technique presented in the article, which focuses on demand forecasting, may be integrated with other tools for decision-making to provide a more comprehensive approach to achieving better logistics.
- The paper acknowledges that demand forecasting involves uncertainty in the setting of a carbon price. To help those in charge make more reliable and informed decisions, future research may look at methods for evaluating and managing this ambiguity and possible risk.
- Although long-term forecasting may be useful for decision-making and strategic planning, the research concentrates on projecting short-term demand. Further study may look at methods for long-term demand forecasting in the context of a carbon tax and other factors, to aid decision-makers in predicting and planning for future changes in demand.

CRediT authorship contribution statement

Sina Abbasi: Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Sasan Mazaheri:** Visualization, Software, Investigation, Conceptualization. **Hamid Reza Talaie:** Writing – review & editing, Validation, Funding acquisition. **Peiman Ghasemi:** Validation, Supervision, Funding acquisition, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was partially supported by the FWF Austrian Science Fund (Peiman Ghasemi): I 5908-G.

References

[1] A. Kumar, P. Singh, P. Raizada, C.M. Hussain, Impact of COVID-19 on greenhouse gases emissions: a critical review, Sci. Total Environ. 806 (2022) 150349.
[2] N. Fallah Shayan, N. Mohabbati-Kalejahi, S. Alavi, M.A. Zahed, Sustainable development goals (SDGs) as a framework for corporate social responsibility (CSR), Sustainability 14 (3) (2022) 1222.
[3] M.A. Maslin, J. Lang, F. Harvey, A short history of the successes and failures of the international climate change negotiations, UCL Open Environment 5 (2023).
[4] F.D. Santos, P.L. Ferreira, J.S.T. Pedersen, The climate change challenge: a review of the barriers and solutions to deliver a Paris solution, Climate 10 (5) (2022) 75.
[5] J. Kirchherr, N.H.N. Yang, F. Schulze-Spüntrup, M.J. Heerink, K. Hartley, Conceptualizing the circular economy (revisited): an analysis of 221 definitions, Resour. Conserv. Recycl. 194 (2023) 107001.
[6] N. Zarrinpoor, M.S. Pishvaee, Designing a municipal solid waste management system under disruptions using an enhanced L-shaped method, J. Clean. Prod. 299 (2021) 126672.
[7] S. Aminzadegan, M. Shahriari, F. Mehranfar, B. Abramović, Factors affecting the emission of pollutants in different types of transportation: a literature review, Energy Rep. 8 (2022) 2508–2529.
[8] V. Jayaraman, Y. Luo, Creating competitive advantages through new value creation: a reverse logistics perspective, Acad. Manag. Perspect. 21 (2) (2007) 56–73.

[9] S. Agrawal, R.K. Singh, Q. Murtaza, A literature review and perspectives in reverse logistics, Resour. Conserv. Recycl. 97 (2015) 76–92.

[10] S. Lambert, D. Riopel, W. Abdul-Kader, A reverse logistics decisions conceptual framework, Comput. Ind. Eng. 61 (3) (2011) 561–581.

[11] C.J. Yuik, M.Z. Mat Saman, N.H.A. Ngadiman, H.S. Hamzah, Supply chain optimisation for recycling and remanufacturing sustainable management in end-of-life vehicles: a mini-review and classification, Waste Manag. Res. 41 (3) (2023) 554–565.

[12] F. Alanazi, Electric vehicles: benefits, challenges, and potential solutions for widespread adaptation, Appl. Sci. 13 (10) (2023) 6016.

[13] S. Aghakhani, P. Pourmand, M. Zarreh, A mathematical optimization model for the pharmaceutical waste location-routing problem using genetic algorithm and particle swarm optimization, Math. Probl Eng. 2023 (2023).

[14] K.N. Reddy, A. Kumar, J. Sarkis, M.K. Tiwari, Effect of carbon tax on reverse logistics network design, Comput. Ind. Eng. 139 (2020) 106184.

[15] A. Baghestani, M. Abbasi, S. Rastegar, A.R. Mamdoohi, A. Afaghpoor, M. Saffarzadeh, Logistics village location with capacity planning problem, an MILP model approach, Sustainability 15 (5) (2023) 4633.

[16] E.H. Mamdani, S. Assilian, An experiment in linguistic synthesis with a fuzzy logic controller, Int. J. Man Mach. Stud. 7 (1975) 1–13, https://doi.org/10.1016/S0020-7373(75)80002-2.

[17] C.M. U-Dominic, I.J. Orji, M. Okwu, Analyzing the barriers to reverse logistics (RL) implementation: a hybrid model based on IF-DEMATEL-EDAS, Sustainability 13 (19) (2021) 10876.

[18] M. Varsei, C. Soosay, B. Fahimnia, J. Sarkis, Framing sustainability performance of supply chains with multidimensional indicators, Supply Chain Manag.: Int. J. 19 (3) (2014) 242–257.

[19] M. Kirby, Modeling the fall and rise in the importance of the environment to the British public: 2006–2019, Br. J. Polit. Int. Relat. 25 (2) (2023) 199–218.

[20] S. Abbasi, S. Zahmatkesh, A. Bokhari, M. Hajiaghaei-Keshteli, Designing a vaccine supply chain network considering environmental aspects, J. Clean. Prod. 417 (2023) 137935.

[21] H.S. Kilic, Z.T. Kalender, B. Solmaz, D. Iseri, A two-stage MCDM model for reverse logistics network design of waste batteries in Turkey, Appl. Soft Comput. 143 (2023) 110373.

[22] R. Turkeš, K. Sörensen, D.P. Cuervo, Design of experiments in humanitarian logistics: facility decision making in disaster preparedness, Int. Trans. Oper. Res. 30 (6) (2023) 4078–4106.

[23] A. Al-Refaie, T. Kokash, Optimization of sustainable reverse logistics network with multi-objectives under uncertainty, Journal of Remanufacturing 13 (1) (2023) 1–23.

[24] S. Abbasi, M. Daneshmand-Mehr, A. Ghane Kanafi, Designing sustainable recovery network of end-of-life product during the COVID-19 pandemic: a real and applied case study, Discrete Dynam Nat. Soc. 2022 (2022), https://doi.org/10.1155/2022/6967088.

[25] E.D.S. Gonzalez, S. Abbasi, M. Azhdarifard, Designing a reliable aggregate production planning problem during the disaster period, Sustainable Operations and Computers (2023), https://doi.org/10.1016/j.susoc.2023.08.004.

[26] X. Chen, H.F. Yan, Y.J. Zheng, M. Karatas, Integration of machine learning prediction and heuristic optimization for mask delivery in COVID-19, Swarm Evol. Comput. 76 (2023) 101208.

[27] B. Sangamithra, P. Neelima, M.S. Kumar, A memetic algorithm for multi objective vehicle routing problem with time windows, in: 2017 IEEE International Conference on Electrical, Instrumentation and Communication Engineering (ICEICE), IEEE, 2017, April, pp. 1–8.

[28] M. Muzafar Ali, D.A. Siddiqui, How reverse logistic product disposition affects business performance in Pakistan: the mediatory role of reverse logistic innovation and resource commitment, in: Ahmed Danish (Ed.), How Reverse Logistic Product Disposition Affects Business Performance in Pakistan: the Mediatory Role of Reverse Logistic Innovation and Resource Commitment, 2023. (Accessed 28 April 2023).

[29] M. Bathaee, H. Nozari, A. Szmelter-Jarosz, Designing a new location-allocation and routing model with simultaneous pick-up and delivery in a closed-loop supply chain network under uncertainty, Logistics 7 (1) (2023) 3.

[30] M.Z. Babai, J.E. Boylan, B. Rostami-Tabar, Demand forecasting in supply chains: a review of aggregation and hierarchical approaches, Int. J. Prod. Res. 60 (1) (2022) 324–348.

[31] S. Fawzy, A.I. Osman, J. Doran, D.W. Rooney, Strategies for mitigation of climate change: a review, Environ. Chem. Lett. 18 (2020) 2069–2094.

[32] S.T. John, R. Sridharan, P.R. Kumar, Multi-period reverse logistics network design with emission cost, Int. J. Logist. Manag. 28 (1) (2017) 127–149.

[33] A. Mutha, S. Pokharel, Strategic network design for reverse logistics and remanufacturing using new and old product modules, Comput. Ind. Eng. 56 (1) (2009) 334–346.

[34] J.U. Siebert, R.E. Kunz, P. Rolf, Effects of decision training on individuals' decision-making proactivity, Eur. J. Oper. Res. 294 (1) (2021) 264–282.

[35] S. Abbasi, Ç. Sıcakyüz, B. Erdebilli, Designing the home healthcare supply chain during a health crisis, Journal of Engineering Research 100098 (2023), https://doi.org/10.1016/j.jer.2023.100098.

[36] Z. Xu, H. Liao, Intuitionistic fuzzy analytic hierarchy process, IEEE Trans. Fuzzy Syst. 22 (4) (2013) 749–761.

[37] X. Xu, M. Liao, Prediction of carbon emissions in China's power industry based on the mixed-data sampling (MIDAS) regression model, Atmosphere 13 (3) (2022) 423.

[38] C.Y. Zhang, L. Zhao, H. Zhang, M.N. Chen, R.Y. Fang, Y. Yao, Q. Wang, Spatial-temporal characteristics of carbon emissions from land use change in Yellow River Delta region, China, Ecol. Indicat. 136 (2022) 108623.

[39] S.H.D. Ghayour, M. Solimanpur, R. Babazadeh, An integrated mixed-integer linear programming (MILP) model for urban water supply chain optimization, Journal of Applied Research in Water and Wastewater 14 (2020) 102–110.

[40] Y.K. Dwivedi, L. Hughes, A.K. Kar, A.M. Baabdullah, P. Grover, R. Abbas, M. Wade, Climate change and COP26: are digital technologies and information management part of the problem or the solution? An editorial reflection and call to action, Int. J. Inf. Manag. 63 (2022) 102456.

[41] I.H. Sarker, Machine learning: algorithms, real-world applications and research directions, SN computer science 2 (3) (2021) 160.

[42] S. Abbasi, M. Daneshmand-Mehr, A.G. Kanafi, Designing a tri-objective, sustainable, closed-loop, and multi-echelon supply chain during the COVID-19 and lockdowns, Found. Comput. Decis. Sci. 48 (3) (2023) 269–312.

[43] S. Abbasi, M. Daneshmand-Mehr, A. Ghane Kanafi, Green closed-loop supply chain network design during the coronavirus (COVID-19) pandemic: a case study in the Iranian Automotive Industry, Environ. Model. Assess. 28 (1) (2023) 69–103, https://doi.org/10.1007/s10666-022-09863-0.

[44] X. Li, X. Zhang, A comparative study of statistical and machine learning models on carbon dioxide emissions prediction of China, Environ. Sci. Pollut. Control Ser. (2023) 1–18.

[45] S.A. Ahmadi, P. Ghasemi, Pricing strategies for online hotel searching: a fuzzy inference system procedure, Kybernetes 52 (11) (2023) 4913–4936.

[46] https://www.google.com/maps/place/Puebla,+Mexico/@19.3980472,-98.1132304,7z/data=!4m6!3m5!1s0x85cf8cb0ddc0a765:0xe25cae5bd60220ad!8m2!3d19.0412894!4d-98.2062013!16zL20vMDI1ZGp0?entry=ttu&g_ep=EgoyMDI0MDgyMS4wIKXMDSoASAFQAw%3D%3D.

[47] M. Wang, B. Wang, Supply chain agility as the antecedent to firm sustainability in the post COVID-19, Int. J. Logist. Manag. 35 (1) (2024) 281–303.

[48] T. Bastos, L.C. Teixeira, J.C.O. Matias, L.J. Nunes, Optimizing the agroforestry residual biomass supply chain: a disruptive tool for mitigating logistic costs and enhancing forest management, Results in Engineering 20 (2023) 101500.

[49] R. Lotfi, P. MohajerAnsari, M.M.S. Nevisi, M. Afshar, S.M.R. Davoodi, S.S. Ali, A viable supply chain by considering vendor-managed-inventory with a consignment stock policy and learning approach, Results in Engineering 21 (2024) 101609.

[50] H. El Hafdaoui, A. Khallaayoun, K. Ouazzani, Long-term low carbon strategy of Morocco: a review of future scenarios and energy measures, Results in Engineering (2023) 101724.

[51] J. Kalezhi, M. Chibuluma, C. Chembe, V. Chama, F. Lungo, D. Kunda, Modeling Covid-19 infections in Zambia using data mining techniques, Results in Engineering 13 (2022) 100363.

[52] M.S. Ghanim, D. Muley, P. Kianmehr, M. Kharbeche, Statewide assessment of air quality changes in Florida during the COVID-19 pandemic, Results in Engineering 20 (2023) 101622.

[53] S. Abbasi, Ç. Sıcakyüz, E.D.S. Gonzalez, P. Ghasemi, A systematic literature review of logistics services outsourcing, Heliyon 10 (13) (2024) 100363 e33374.

[54] S. Abbasi, M. Ardeshir Nasabi, I. Vlachos, F. Eshghi, M. Hazrati, S. Piryaei, Designing a sustainable nonlinear model considering a piecewise function for solving the risk of hazardous material routing-locating problem, Sustainability 16 (10) (2024) 4112.

[55] S. Abbasi, Ç. Sıcakyüz, A review of the COVID-19 pandemic's effects and challenges on worldwide waste management for sustainable development, Int. J. Environ. Sci. Technol. (2024) 1–30.

[56] S. Abbasi, S. Abbaspour, M.E.N. Siahkoohi, M.Y. Sorkhi, P. Ghasemi, Supply chain network design concerning economy and environmental sustainability: crisis perspective, Results in Engineering 22 (2024) 102291.

[57] S. Shahparvari, H. Soleimani, K. Govindan, B. Bodaghi, M.T. Fard, H. Jafari, Closing the loop: redesigning sustainable reverse logistics network in uncertain supply chains, Comput. Ind. Eng. 157 (2021) 107093.

[58] A. Mohajeri, M. Fallah, A carbon footprint-based closed-loop supply chain model under uncertainty with risk analysis: a case study, Transport. Res. Transport Environ. 48 (2016) 425–450.

[59] S. Koley, Exploring social value prospects of Australia's construction industry towards the aboriginal communities, under COVID-19 recovery efforts, Int. J. Eng. Trends Technol. 70 (12) (2022) 227–251.

[60] C.A. Wongnaa, E.K. Nti, P.P. Acheampong, R.K. Bannor, S. Prah, S. Babu, Towards sustainable food crop production: drivers of shift from crop production to mining activities in Ghana's Arable Lands, Environmental Challenges 14 (2024) 100835.

[61] Y. Jiang, Y. Zhao, M. Dong, S. Han, Sustainable supply chain network design with carbon footprint consideration: a case study in China, Math. Probl Eng. 2019 (1) (2019) 3162471.

[62] R. Wang, Y. Deng, S. Li, K. Yu, Y. Liu, M. Shang, Q. Liang, Waste electrical and electronic equipment reutilization in China, Sustainability 13 (20) (2021) 11433.

[63] J. Tian, L. Yu, R. Xue, S. Zhuang, Y. Shan, Global low-carbon energy transition in the post-COVID-19 era, Appl. Energy 307 (2022) 1.

[64] S. Abbasi, I. Vlachos, S. Rekabi, M. Talooni, Designing the distribution network of essential items in the critical conditions of earthquakes and COVID-19 simultaneously, Sustainability 15 (22) (2023) 15900.

[65] S. Abbasi, U.M. Modibbo, H. Jafari Kolashlou, I. Ali, N. Kavousi, Environmental impact assessment with rapid impact assessment matrix method: during disaster conditions, Frontiers in Applied Mathematics and Statistics 10 (2024) 1344158.

[66] A. Dwivedi, S. Pratap, F. Zhou, Antecedents of freight transportation for sustainable supply chain in the post-COVID era: an emerging market study, Int. J. Emerg. Mark. 18 (6) (2023) 1453–1471.

[67] U. Shahzad, T. Sengupta, A. Rao, G.D. Sharma, Energy in the backseat? Investigating decarburization dialogue in supply chain tweets during and after COVID-19, Ann. Oper. Res. (2024) 1–33.

[68] M. Wang, B. Wang, Supply chain agility as the antecedent to firm sustainability in the post COVID-19, Int. J. Logist. Manag. 35 (1) (2024) 281–303.

[69] M. Shavandi, A. Taghavi, Non-linear triple product A* B-B* A derivations on*-algebras, Surv. Math. Appl. 19 (2024) 67–78.

[70] M. Shavandi, A. Taghavi, Maps preserving n-tuple A* B− B* A derivations on factor von Neumann algebras, Publ. Inst. Math. (Beogr.) 113 (127) (2023) 131–140.

[71] A. Khosravi Rastabi, S.R. Hejazi Taghanaki, S. Sadri, A. Kumar, H. Arshad, A robust optimization model for a dynamic closed-loop supply chain network redesign using accelerated Benders decomposition, Journal of applied research on industrial engineering 9 (1) (2022) 1–31, https://doi.org/10.22105/jarie.2021.304879.1380.

[72] A.K. Rastabi, S.R. Hejazi, S. Sadri, Benders decomposition for supply chain network redesign with capacity planning and multi-period pricing, International Journal of Industrial Engineering and Production Research 28 (4) (2017) 351–365, https://doi.org/10.22068/ijiepr.28.4.351.

[73] S. Danladi, M.S.V. Prasad, U.M. Modibbo, S.A. Ahmadi, P. Ghasemi, Attaining sustainable development goals through financial inclusion: exploring collaborative approaches to Fintech adoption in developing economies, Sustainability 15 (17) (2023) 13039.