International Journal of Applied Operational Research
Vol. 12, No. 2, pp. 43-58, Spring 2024

Journal homepage: ijorlu.liau.ac.ir

A novel attitude of robust optimization and risk management for network designing of closed-loop green supply chain

A. Taherinezhad*, A. Alinezhad, S. Gholami

Received: 3 January 2024 ; **Accepted:** 16 March 2024

Abstract A very important factor which needs to be considered in the process of designing an efficient supply chain is cost reduction. Meanwhile, to tackle climate change and to fight the increase in environmental pollution, the managers of organizations as well as scholars active in the field of designing supply chains, have started to adopt measures, which, on top of economic optimization, are also focused on environmental factors aimed at reducing pollutants in all sectors of the economy. Apart from the mentioned two variables, another factor influencing the supply chain is the delivery time. In the present paper, an integrated forward/reverse logistics network has been studied considering three objective functions including "minimizing environmental effects", "minimizing costs", and "minimizing delivery time", which are in fact the innovations of this research study. Model uncertainty has been dealt with through robustness of solutions. Scenario-based risk assessment methods have been applied to identifying and assessing potential risks. Then, taking into consideration the uncertain parameters, the robust scenario-based model of the problem has been submitted. Replacing the outputs of risk analysis (normalized risk priority number (RPN)) in the model for scenario occurrence, the authors have completed the model. Meanwhile, using the General Algebraic Modeling System (GAMS) software and the LP metric method, the model is transformed into a single-objective model and the problem is solved. The findings indicate that with the combination of risk assessment and robust optimization techniques, an efficient supply chain design will be realized, which is the study's another innovative aspect.

Keyword: Closed-loop Supply Chain (CLSC), Green Supply Chain, Robust Optimization, Risk Management.

1 Introduction

Considering technology advancements and the competitive nature of today's markets, effective, efficient, and strong supply chains have gained significance as they have the potential to give companies a sustainable competitive edge over their competitors and to help

* **Corresponding Author.** (✉)
E-mail: atqiau@gmail.com (A. Taherinezhad)

A. Taherinezhad
Department of Industrial Engineering, Qazvin branch, Islamic Azad University, Qazvin, Iran

A. Alinezhad
Department of Industrial Engineering, Qazvin branch, Islamic Azad University, Qazvin, Iran

S. Gholami
Caspian Higher Education Institute, Qazvin, Iran

[DOI: 10.71885/ijorlu-2024-1-667]

them in overcoming market turbulence and intensified competitive pressures [1]. Consequently, the appropriate designing of an efficient and optimal supply chain has turned into a major concern for managers and decision-makers. The effective and competitive management of a supply chain could be realized once an optimal structure has been designed. The concept of closed-loop supply chains has nowadays absorbed a lot of attention. As forward and reverse supply chains need to be simultaneously managed, a combination of forward and reverse supply chains will be a performance booster. Therefore, in order to avoid sub-optimization resulting from designing regardless of the whole, forward and reverse supply chain networks need to be combined [2]. Furthermore, the world nowadays deals with issues like global warming, different types of pollution, and greenhouse gases each may potentially lead to human extinction. Thus, protecting the environment and the devising of relevant strategies have been urgently put on the top of the priority list of innovative organizations. On the one hand, the organization needs to care for profitability and the competitive edge and on the other, it has to take action to eliminate or at least minimize waste (energy, hazardous chemicals, and solid). This has raised concerns about the concept of green supply chains [3, 4]. The emergence of factors leading to uncertainty in the supply chain causes a reduction in the risk tolerance of supply chains and a rise in their vulnerability. The management of the supply chain risk is essential for encountering these uncertainties. For the management of the supply chain uncertainties, it is necessary that reliable and robust planning be put on the organizations' agenda so that the managers could trust the results and take decisions at minimum risk. Using the optimization approach in a closed-loop supply chain under uncertain conditions is the topic dealt with in this article for the expansion of the existing models. In robust optimization, knowing the type of data distribution function is not required and a robust solution is feasible for all possible scenarios. In fact, under robust optimization, the best answer is selected among answers suitable to all scenarios [5]. Considering the importance of this topic, the authors decided to combine robust optimization and risk management techniques to design an innovative green closed-loop supply chain.

In the present study, an integrated forward/reverse logistics network model in the form of the environmental closed-loop supply chain (ECLSC) has been studied. The model includes multiple production centers, collection centers, demand zones, and various products. The recommended model consists of a forward supply chain and a reverse supply chain. Costs, demand, and delivery time are supposed to be the uncertain parameters of the model. Initially, a three-objective Mixed-Integer Nonlinear Programming (MINLP) model is presented. The first objective function is formulated for the minimization of economic costs, the second is formulated for the minimization of environmental costs, and the third aims at minimizing delivery delays. In the next stage, for the transformation of the rendered certain model to the scenario-based robust model, the model introduced in 1995 by Mulvey et al. [6] (later revised in 2000 by Yu and Li [7]) is used. Then, the model rendered by the LP metric method (a method of optimizing the transformation of multiple-objective functions to single-objective functions) is turned into a single-objective mixed-integer programming model. Meanwhile, supply chain risks are identified using conventional risk identification and assessment methods and the scores thereby received are entered into the robust model of the problem replacing the scenarios. Finally, the model is solved using the General Algebraic Modeling System (GAMS) software [8].

The research questions are as follows:

- How can forward and reverse trends in a green closed-loop supply chain be considered simultaneously?
- How can *cost*- and *demand*-related risks be managed in a green closed-loop supply chain?

[DOI: 10.71885/ijorlu-2024-1-667]

- How could risk management and robust optimization techniques be combined for the design of a green closed-loop supply chain including forward and reverse processes?

The research hypotheses are as follows:

- The model is designed for a single period.
- All products returned from the demand nodes are shipped to collection centers.
- Plants are considered as production, distribution, and recycling centers with fixed capacities. For relocation purposes, plants and collection centers are considered as potential centers.
- The demand location is fixed.
- For simplification purposes, inventory and ordering costs are ignored.

2 Theoretical Foundation and Literature Review

In recent years, decision-making tools and uncertainty theories have grown significantly in solving a wide range of engineering problems [9-16]. One of the most important engineering issues is the design of supply chains, which is of particular importance in today's world. Today, considering the significance of environmental criteria and the organizations' efforts for the effective and efficient use of products as well as the protection of consumers, researchers have paid a special attention to the design of reverse and closed-loop supply chains. The primary target for this cause is the minimization of waste through reuse, recycling, and remanufacturing of used and worn-out materials, reduction of various types of pollution, and realization of profitability along with other social and commercial considerations. In the following, some of the researches conducted in this field have been reviewed.

Pan and Nagi [17] put on their agenda the integrated optimization of logistics and production costs related to the members of the supply chain. They came up with a robust optimization model with three components in the objective function including expected total costs, cost variability as a result of demand uncertainty, and expected penalty for unmet demand. They also applied two types of decision variables including *binary* variables for the selection of companies to build supply chain and *continuous* variables related to production planning. Pishvaee et al. [18] applied the concept of supply chain robustness to their studies. They considered demand uncertainty, costs, and product returns of their closed-loop supply chain network in the form of a box uncertainty set. Vahdani et al. [19] introduced a new model for the design of a closed-loop supply chain network under uncertainty. To this end, a double-objective mathematical programming model was developed with the aim of minimizing total as well as expected transportation costs upon equipment failure in the logistics network. In order to solve the problem, a hybrid model consisting of robust optimization, queueing theory, and the fuzzy multiple-objective programming (FMOP) techniques was used. Hassanzadeh Amin and Zhang [20] investigated a closed-loop supply chain (CLSC) network consisting of forward and reverse supply chains, which included multiple plants, collection centers, demand markets, and products. For this purpose, a mixed-integer linear programming model was proposed which would minimize total costs. This model was extended to consider environmental factors via ε-constraint methods and weighted sums. They also studied the effect of demand and return uncertainties on the network by scenario-based stochastic programming. Their findings indicated that the model could simultaneously handle demand and return uncertainties. Ramezani et al. [21] considered a multiple-objective model for the design of a logistics network under uncertain conditions

[DOI: 10.71885/ijorlu-2024-1-667]

including 3 forward levels (suppliers, plants, and distribution centers) and 2 reverse levels (collection and disposal centers) with the aim of maximizing profit, satisfying customers, and raising quality. Altmann and Bogaschewsky [22] presented a multi-objective closed-loop supply chain model based on robust optimization, aimed at minimizing expected costs and carbon dioxide equivalents. In this model, demand and product returns are considered as uncertain. Ma et al. [23] investigated a robust environmental closed-loop supply chain (ECLSC) network including multiple plants, collection centers, demand zones, and products by first introducing a robust multi-objective mixed-integer nonlinear programming model, which was supposed to deal with the uncertain nature of the supply chain. The first objective function was aiming at minimizing the economic cost and the second objective function was related to minimizing environmental effects. The results pointed to the fact that the recommended model was practically applicable. Talaei et al. [24] studied a multi-product green closed-loop supply chain network including production/recycling centers, supervision and control centers, disposal centers, and the market, and proposed a mixed linear programming model, thereby minimizing costs and environmental effects. They also considered uncertainty of variable costs and demand for network design and solved the model through the constraint approach. Safaei et al. [25] studied a closed-loop supply chain for the recycling network with multiple suppliers and production stages. They recommended a mixed linear programming model for the optimization of the recycling network. The robust optimization approach was used to solve the demand uncertainty problem in this network. This model maximizes total profit. Soleimani et al. [26] rendered a closed-loop supply chain network including suppliers, producers, distribution centers, customers, warehouses, reuse, and recycling. This necessitated three selections regarding recycling of products, recycling of components, and/or raw materials. The objectives of the model included the optimization of total profit and the reduction of the working days of parties disabled due to workplace accidents. To solve the problem, the genetic algorithm was used and several scenarios were studied. Solving the model facilitates decision-making in terms of the opening or closing of the network components and the product's optimal flow.

Today, supply chain risks have turned into one of the most talked about topics in the world. Many risks of this type have the potential to adversely affect the performance of the supply chain. Therefore, organizations need to utilize appropriate strategies to manage these risks. Accordingly, extensive research has been conducted to identify supply chain risks; however, a consensus has not yet been reached on the nature of such risks as they can be studied from various angles.

Tang [27] classifies supply chain risks into operational and disruption risks. Operational risks refer to intrinsic uncertainties such as uncertain customer demand and uncertain costs. Disruption risks refer to major disruptions in the chain resulted from natural disasters like earthquakes, man-made disasters like terrorist attacks, and economic crises like strikes. In most cases, the impact of disruption risks on businesses is much greater than that of operational risks. Tuncel and Alpan [28] tried to show how a timed-Petri nets framework can be used to model and analyze a supply chain network subject to various risks. To this end, they investigated the disruption factors of the supply chain network through a Failure Mode, Effects and Criticality Analysis (FMECA) technique. The results of their study were indicative of the fact that the system performance could be improved through the adoption of risk management measures and the overall costs may be reduced via mitigation scenarios. Thun and Hoenig [29] have analyzed supply chain risk management practices from an experimental point of view. They studied 67 manufacturing plants active in the German automotive industry. Upon analyzing the key factors, supply chain risks were identified

[DOI: 10.71885/ijorlu-2024-1-667]

through surveying their likelihood and potential impact on the supply chain. The findings were depicted in the form of a probability-impact-matrix. Later, instruments for encountering risks were investigated and the effects of supply chain risk management on organizational performance were tested. Some other scholars have suggested a stochastic model for the multi-stage global supply chain network problem with the aim of maximizing profit and minimizing risks. The model incorporates a set of related risks including supply, demand, exchange, and disruption risks [30]. Hasani et al. [31] proposed a comprehensive optimization model aimed at maximizing the after-tax profit of a closed-loop supply chain for medical devices under uncertainty. The uncertainty of the decision-making environment was modelled using the budget of uncertainty concept in interval robust optimization. Bashiri et al. [32] rendered a robust approach for the relocation of three-level supply chain warehouses under uncertainty. The uncertainty of parameters was studied in the form of discrete random variables under different scenarios. Finally, the applied robust approach has been described through an example. Rozenblit et al. [33] utilized an interval-based robust model for the correction of a multi-period and single-product programming model, with demand factor as the only uncertain parameter.

To date, no study is available that takes into account the environmental factors, costs, delivery time, and risks simultaneously for the design of the supply chain. This gap prompted the formation of the present study which is an innovation of its kind. Combining risk assessment and robust optimization techniques, the authors managed to design an efficient supply chain. It is believed that the model thereby created could be a good guidance for managers, helping them with taking more logical and pragmatic decisions.

3 Research methodology

The network under study is a closed-loop supply chain including forward and reverse processes. In the forward closed-loop supply chain, the produced goods are shipped from the production centers to demand markets. Under the reverse closed-loop supply chain, product returns are classified as either *recyclable* or *disposable*. The general structure of the forward/reverse integrated logistics network is shown in Figure 1. The network includes production, demand, collection, and disposal centers. Solid lines represent the forward process whereas the dotted lines indicate the reverse trend. The production centers include multiple plants wherein several types of goods are produced. These products are later sent to demand nodes based on customer demand. Demand zones will in turn ship faulty products back to collection centers. The products thereby collected are sent back to the plants for recycling, remanufacturing, and disposal.

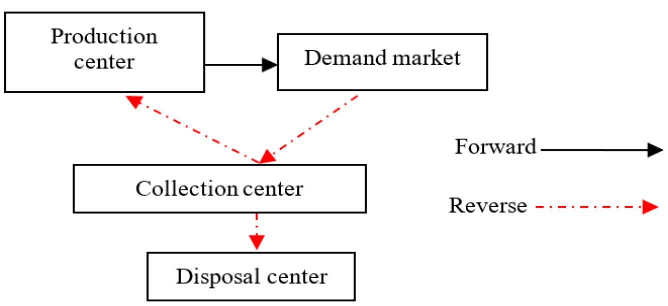

Fig. 1 Structure of A Closed-loop Supply Chain (Ma et al. [23])

[DOI: 10.71885/ijorlu-2024-1-667]

In the present study, a closed-loop supply chain network is studied with due consideration of environmental effects, including multiple production centers, collection centers, demand zones, and various products. The recommended model is composed of a forward/reverse supply chain.

The stages for solving the problem are as follows:

- First, a three-objective mixed-integer nonlinear programming model is proposed with the first objective function being the minimization of economic costs, the second function being the minimization of environmental costs, and the third function being the minimization of the delay in delivery time.
- Second, to transform the recommended certain model to a scenario-based robust model, the model introduced by Mulvey et al. [6] (later revised by Yu and Li [7]) has been used.
- Third, the rendered model is transformed into a single-objective mixed-integer programming model through the LP metric method (a method of optimizing the transformation of multiple-objective functions to single-objective functions).
- Fourth, supply chain risks are identified using the conventional methods of risk identification and assessment.
- Finally, the scores of risk assessment thereby received are replaced in the problem's robust model for the scenarios and the model is solved using the GAMS software [8].

In the present study, costs, demand, and delivery time are considered as the model's uncertain parameters. The base model in this article has been extracted from the study by Ma et al. [23], which has been rather adjusted. The model used in the study conducted by Ma et al. [23] was a double-objective one covering economic and environmental costs whereas the model rendered in the present study is a three-objective one, adding the objective function of minimizing the delay in delivery time. Meanwhile, in the objective function related to the economic costs, *repair and maintenance* as well as *supervision and control* costs are also included, which comprise the other innovative aspects of the model.

3.1 Developing Scenarios Using Risk Rating Methodologies

Risks may affect the objectives of the supply chain including costs, time, quality, limit, and credit either positively or negatively. Risks with negative effects (threats) and risks with positive effects (opportunities) are identified and rated via the Failure Mode and Effects Analysis (FMEA) methodology. The FMEA is a risk assessment tool that mitigates maximally the potential failures in systems, processes, designs, and services, used in a wide range of industries. The risk priority number (RPN) is calculated by multiplying three parameters including the severity of the effect of failure (S), the probability of occurrence (P), and the ease of detection for each failure mode (D).

3.2 Determining Sets, Parameters, and Mathematical Decision Variables

3.2.1 Sets

M: Set of potential manufacturing plants locations $(1 \ldots m \ldots M)$.
K: Set of demand zones locations $(1 \ldots k \ldots K)$.

[DOI: 10.71885/ijorlu-2024-1-667]

J: Set of products $(1 \dots j \dots J)$.
I: Set of potential collection centers locations $(1 \dots i \dots I)$.

3.2.2 Parameters

ε: Scenarios.
P_j^ε: Production cost of product j.
G_j^ε: Collection cost of product j.
A_j^ε: Transportation cost of product j per kilometer (from the plant to demand zones).
B_j^ε: Transportation cost of product j per kilometer (from demand zones to collection centers).
C_j^ε: Transportation cost of product j per kilometer (from collection centers to the plant).
D_j^ε: Transportation cost of product j per kilometer (from collection centers to disposal centers).
F_m^ε: Fixed cost of the construction of plant m.
$\bar{F}_i^\varepsilon$: Fixed cost of the construction of collection center i.
S_j^ε: Savings cost of product j (due to recycling).
H_j^ε: Disposal cost of product j.
e_{mj}^ε: Environmental cost of the manufacturing of one unit of product j in plant m.
ec_{ij}^ε: Environmental cost of the collection of one unit of product j in collection center i.
ed_j^ε: Environmental cost of one unit of product j in the disposal center.
etc_j^ε: Environmental cost of the transportation of one unit of product j per kilometer.
V_{mj}: Capacity of plant m for product j.
$\bar{V}_{ij}$: Capacity of collection center i for product j.
T_{mk}: Distance between collection center i and demand zone k (T_{ki} and T_{im} have similar definitions).
d_{kj}^ε: Demand by customer k for product j.
r_{kj}^ε: Return of customer k for product j.
dt_{jmk}: Delivery time for the j^{th} product from the m^{th} manufacturing center to the k^{th} customer.
$edt_{jk}{}^\varepsilon$: Expected delivery time of the k^{th} customer for the j^{th} product.
$GT_{mj}{}^\varepsilon$: Repair and maintenance costs for the m^{th} manufacturing center per unit of the j^{th} product.
$GB_{ij}{}^\varepsilon$: Supervision and control costs in the i^{th} collection center per unit of the j^{th} product.
$M = \{m | dt_{jmk} \geq edt_{jk}\}$: Total production centers with delay in delivery time.
α_j: The average disposal fraction of product j.
λ: Adjustable coefficient for trade-off between risks and costs.
ω**:** This parameter is added to the model for preservation. In fact, ω is the weight of penalty for deficit or surplus, determined based on the decision-maker's views.

3.2.3 Decision Variables

X_{mkj}^ε: The number of products of type j, manufactured by factory m for the demand node k.
Y_{kij}^ε: The number of returned products of type j, shipped from the demand node k to the collection center i.

[DOI: 10.71885/ijorlu-2024-1-667]

Z_{imj}^{ε}: The number of returned products of type j, returned from the collection center i to plant m.
Q_{ij}^{ε}: The number of returned products of type j, returned from the collection center i to the disposal center.
$Q_m = 1$: This variable equal one if the plant is constructed.
$W_i = 1$: This variable equal one if the collection center is constructed.

3.3 Limitations of the Problem's Certain Model

Limitation (1) is concerned with demand, specifying that the sum total of different types of products in the manufacturing center must meet the customer demand. Limitation (2) deals with the capacity of manufacturing centers, which indicates that the sum total of product returns from the collection centers to the plant as well as the number of the manufactured products should not exceed the capacity of the plant. Limitation (3) indicates the capacity limitation per collection center, stipulating that the number of returned products from the demand zones should not exceed the capacity of the collection center they are shipped to. Limitation (4) indicates that the forward trend in the model must be larger than the reverse trend i.e., the number of returned products from any demand zone is constantly *lower than* or *equal to* the number of incoming products. Limitation (5) shows that the number of products sent to the disposal center is *lower than* or *equal to* the number of products returned from the demand zones to the collection centers. Limitation (6) indicates that all types of products returned from the demand zones to the collection centers are either recyclable and, therefore, sent to the manufacturing or recycling centers, or need to be sent to disposal centers. Limitation (7) specifies that the number of all types of products returned from the demand node to the collection centers should equal the total number of product returns from that node (balance at demand zone). Limitation (8) explains the nature of decision variables (limitations (1) through (8) are extracted from the study conducted by Ma et al. [23]):

$$\sum_m X_{mkj}^{\varepsilon} \geq d_{kj}^{\varepsilon}, \qquad \forall k, j, \tag{1}$$

$$\sum_i \sum_j Z_{imj}^{\varepsilon} + \sum_k \sum_j X_{mkj}^{\varepsilon} \leq O_m \sum_j V_{mj}^{\varepsilon} \qquad \forall m, \tag{2}$$

$$\sum_k \sum_i Y_{kij}^{\varepsilon} \leq W_i \sum_i \bar{V}_{ij,} \qquad \forall i, \tag{3}$$

$$\sum_i Y_{kij}^{\varepsilon} \leq \sum_m X_{mkj}^{\varepsilon}, \qquad \forall k, j \tag{4}$$

$$\alpha_j \sum_k Y_{kij}^{\varepsilon} \leq Q_{ij}^{\varepsilon}, \qquad \forall i, j \tag{5}$$

$$\sum_k Y_{kij}^{\varepsilon} = \sum_m Z_{imj}^{\varepsilon} + Q_{ij}^{\varepsilon}, \qquad \forall i, j \tag{6}$$

$$\sum_i Y_{kij}^{\varepsilon} = r_{kj}^{\varepsilon}, \qquad \forall k, j \tag{7}$$

$$O_m, W_i \in \{0,1\}, X_{mkj}^{\varepsilon}, Y_{kij}^{\varepsilon}, Z_{imj}^{\varepsilon}, Q_{ij}^{\varepsilon} \geq 0 \quad \forall m, k, j, i \tag{8}$$

3.4 Objective Functions

Equation (9) indicates total fixed cost resulted from the sum total of fixed costs for the construction of the plant and collection centers. Equation (10) refers to total transportation costs resulted from the sum total of costs of transporting products between the plant and the demand zones, between the demand zones and the collection centers, between the collection centers and the plant, and finally between the collection centers and the disposal centers.

[DOI: 10.71885/ijorlu-2024-1-667]

Equation (11) refers to total manufacturing costs including production, collection, savings (due to recycling) and disposal costs (Equations (9) through (11) are extracted from the study conducted by Ma et al. [23]).
Equation (12) indicates the manufacturing centers' repair and maintenance costs. Equation (13) shows the control and supervision costs in the collection center (Equations (12) and (13) are added to the model by the authors).

$$FC^{\varepsilon} = \sum_m F_m^{\varepsilon} O_m + \sum_i \bar{F}_i^{\varepsilon} W_i \tag{9}$$

$$TRC^{\varepsilon} = \sum_m \sum_j \sum_k A_j^{\varepsilon} T_{mk} X_{mkj}^{\varepsilon} + \sum_k \sum_j \sum_i B_j^{\varepsilon} T_{ki} Y_{kij}^{\varepsilon} + \sum_i \sum_j \sum_m C_j^{\varepsilon} T_{im} Z_{imj}^{\varepsilon} + \sum_i \sum_j D_j^{\varepsilon} T_i Q_{ij}^{\varepsilon} \tag{10}$$

$$PC^{\varepsilon} = \sum_m \sum_k \sum_j P_j^{\varepsilon} X_{mkj}^{\varepsilon} + \sum_k \sum_i \sum_j G_j^{\varepsilon} Y_{kij}^{\varepsilon} - \sum_i \sum_m \sum_j S_j^{\varepsilon} Z_{imj}^{\varepsilon} + \sum_i \sum_j H_j^{\varepsilon} Q_{ij}^{\varepsilon} \tag{11}$$

$$NC^{\varepsilon} = \sum_m {GT_{mj}}^{\varepsilon} * V_{mj} \tag{12}$$

$$BC^{\varepsilon} = \sum_i \sum_k {GB_{ij}}^{\varepsilon} * {y_{kij}}^{\varepsilon} \tag{13}$$

3.4.1 Total Economic Cost

Equation (14) indicates the total economic cost, which is the sum total of Equations (9) through (13), pointing to the fixed cost (FC^{ε}), transportation cost (TRC^{ε}), production cost (PC^{ε}), the production center's repair and maintenance cost (NC^{ε}), and the collection center's supervision and control cost (BC^{ε}):

$$f_1^{\varepsilon} = FC^{\varepsilon} + TRC^{\varepsilon} + PC^{\varepsilon} + NC^{\varepsilon} + BC^{\varepsilon} = \sum_m F_m^{\varepsilon} O_m + \sum_i \bar{F}_i^{\varepsilon} W_i + \sum_m \sum_k \sum_j \left(P_j^{\varepsilon} + A_j^{\varepsilon} T_{mk}\right) X_{mkj}^{\varepsilon} + \sum_k \sum_j \sum_i \left(G_j^{\varepsilon} + B_j^{\varepsilon} T_{ki}\right) Y_{kij}^{\varepsilon} + \sum_i \sum_j \sum_m (C_j^{\varepsilon} T_{im} - S_i^{\varepsilon}) Z_{imj}^{\varepsilon} + \sum_i \sum_j \left(H_j^{\varepsilon} + D_j^{\varepsilon} T_i\right) Q_{ij}^{\varepsilon} + \sum_m {GT_{mj}}^{\varepsilon} * V_{mj} + \sum_i \sum_k {GB_{ij}}^{\varepsilon} * {y_{kij}}^{\varepsilon} \tag{14}$$

3.4.2 Total Environmental Cost

Equation (15), extracted from the study conducted by Ma et al. [23], indicates the total environmental cost of the supply chain:

$$f_2^{\varepsilon} = \sum_m \sum_k \sum_j (e_{mj}^{\varepsilon} + etc_j^{\varepsilon} T_{mk}) X_{mkj}^{\varepsilon} + \sum_k \sum_j \sum_i \left(ec_{ij}^{\varepsilon} + etc_j^{\varepsilon} T_{ki}\right) Y_{kij}^{\varepsilon} + \sum_i \sum_j \sum_m etc_j^{\varepsilon} T_{im} Z_{imj}^{\varepsilon} + \sum_i \sum_j \left(ed_j^{\varepsilon} + etc_j^{\varepsilon} T_i\right) Q_{ij}^{\varepsilon} \tag{15}$$

3.4.3 Delay in Delivery Time

Equation (16), added to the model by the authors, refers to the delay in the delivery of products sent from the production center to the demand zone:

$$f_3^{\varepsilon} = \sum_n \sum_j \sum_{m \in M} \left({dt_{jmk}}^{\varepsilon} - {edt_{jk}}^{\varepsilon}\right) {X_{mkj}}^{\varepsilon} \tag{16}$$

3.5 Robust Optimization Approach to Model Uncertainty

To transform the rendered certain model to a scenario-based robust model, the model introduced by Mulvey et al. [6] (later revised by Yu and Li [7]) has been used:

$$\min \quad \sum_{\varepsilon} \rho_{\varepsilon} f^{\varepsilon} + \lambda \sum_{\varepsilon} \rho_{\varepsilon} [(f^{\varepsilon} - \sum_{\varepsilon} \rho_{\varepsilon} f^{\varepsilon}) + 2\theta] + \omega \sum_{\varepsilon} \rho_{\varepsilon} \delta_{\varepsilon} \quad (17)$$

$$S.t. \quad f^{\varepsilon} - \sum_{\varepsilon} \rho_{\varepsilon} f^{\varepsilon} + \theta_{\varepsilon} \geq 0, \quad \forall \varepsilon \quad (18)$$

$$\theta_{\varepsilon} \geq 0, \quad \forall \varepsilon \quad (19)$$

Considering the robust model introduced above, the model's robust objective functions are as follows:

$$min f_1 = \sum_{\varepsilon} \rho_{\varepsilon} f_1^{\varepsilon} + \lambda_1 \sum_{\varepsilon} \rho_{\varepsilon} [(f_1^{\varepsilon} - \sum_{\varepsilon} \rho_{\varepsilon} f_1^{\varepsilon}) + 2\theta_{1\varepsilon}] + \omega \sum_{\varepsilon} \rho_{\varepsilon} (X_{mkj}^{\varepsilon} - d_{kj}^{\varepsilon}) \quad (20)$$

$$min f_2 = \sum_{\varepsilon} \rho_{\varepsilon} f_2^{\varepsilon} + \lambda_2 \sum_{\varepsilon} \rho_{\varepsilon} [(f_2^{\varepsilon} - \sum_{\varepsilon} \rho_{\varepsilon} f_2^{\varepsilon}) + 2\theta_{2\varepsilon}] \quad (21)$$

$$min f_3 = \sum_{\varepsilon} \rho_{\varepsilon} f_3^{\varepsilon} + \lambda_3 \sum_{\varepsilon} \rho_{\varepsilon} [(f_3^{\varepsilon} - \sum_{\varepsilon} \rho_{\varepsilon} f_3^{\varepsilon}) + 2\theta_{1\varepsilon}] + \omega' \sum_{\varepsilon} \rho_{\varepsilon} (dt_{jmk}{}^{\varepsilon} - edt_{jk}{}^{\varepsilon}) \quad (22)$$

Limitations (1) through (8) related to the rendered certain model, along with Limitations (18) and (19), are added to these robust objective functions. Equations (17) through (21) are extracted from the study conducted by Ma et al. [23], and limitation Equation (22) is added to the base model by the authors. Finally, with the replacement of the scores resulted from the normalized risk for the scenarios in the robust model, the model is solved using the GAMS software [8].

4 Findings

For further understanding, the problem is solved for an automobile parts manufacturing company with 5 production centers, 3 types of products, 4 demand zones, and 3 collection centers, under 3 scenarios. The model is solved considering the scores of assessment risk extracted from Table 5, using GAMS. For risk assessment, figures related to impact and occurrence are extracted from Tables 1 and 2.

Table 1 Risk impact on objectives (expert views)

Objectives	**Measure**				
	Very low	Low	Average	High	Very high
	1	3	5	7	9
Cost	Insignificant impact on cost	Deviation of less than 10%	Deviation of 10% to 20%	Deviation of 20% to 40%	Deviation of more than 40%
Environmental factors	Insignificant impact	Low impact	Average impact	High impact	Very high impact
Delay in delivery time	Deviation of less than 20%	Deviation of 20% to 40%	Deviation of 40% to 60%	Deviation of 60% to 80%	Deviation of 80% to 100%

[DOI: 10.71885/ijorlu-2024-1-667]

Table 2 Risk occurrence/probability (expert views)

Measure		Occurrence/Probability (%)	Frequency (based on past experience)
Very low	1	Less than 20%	Never happened before
Low	3	More than 20% and less than 40%	Happens once in several years
Average	5	More than 40% and less than 60%	Happens once a year
High	7	More than 60% and less than 80%	Happens once in several months
Very high	9	More than 80%	Always happens

Table 3 depicts the risk assessment matrix, based on which the risk priority number (RPN) extracted from Table 4 will point to the risk level.

Table 3 Risk assessment matrix (expert views)

Risk occurrence/ probability	Negative risks (threats)					Positive risks (opportunities)				
9	9	27	45	63	81	81	63	45	27	9
7	7	21	35	49	63	63	49	35	21	7
5	5	15	25	35	45	45	35	25	15	5
3	3	9	15	21	27	27	21	15	9	3
1	1	3	5	7	9	9	7	5	3	1
	1	3	5	7	9	9	7	5	3	1
	Risk impact									

The details of the recommended measures in Table 4 are as follows:

1) It is advised that the marginal and overhead costs be reduced and prediction on price rises be considered in price analysis. This is concerned with the government policies. The only measure to be adopted by the customer is the provision of raw materials (sheets and tubes).
2) It is recommended that the operators' awareness on waste reduction be raised and a bonus system should be planned for those employees who produce the least amount of waste in a month. It is also suggested that experienced and trained personnel in this regard be employed.
3) It is highly recommended that the required raw materials be provided by domestic manufacturers.
4) The overhaul period for old equipment or those with higher capacities should be shortened as confirmed by the managers of the "technical and engineering" and the "repair and maintenance" departments. The use of the PDCA cycle for continuous improvement is highly recommended.

[DOI: 10.71885/ijorlu-2024-1-667]

Table 4 Risk assessment

Risk Analysis									
No.	Risk	Cause	Objectives	Potential impact on achieving objectives			RPN	Normalized RPN	Recommended Measure
				1st objective	2nd objective	3rd objective			
			Weight of objectives/P	40%	20%	40%			
1	Rise in production costs	Rise in price of raw materials	9	7	3	7	55.80	0.43	(1)
		Rise in wastes	3	5	5	5	15	0.11	(2)
2	Untimely provision of imported goods	Sanctions	5	5	7	7	31	0.24	(3)
3	Stopping the production line	Unplanned stoppage of machinery	7	5	5	3	29.40	0.22	(4)
							131.20		

4.1 Risk Level

In the risk management plan, the risk level can be:
1- High: first-level risks shown in red
2- Moderate: second-level risks shown in yellow
3- Low: third-level risks shown in green

Table 5 Classification of risk/opportunity (expert views)

Risk level	Color	Impact
1		Risk with high significance (high)
2		Risk with medium significance (moderate)
3		Risk with low significance (low)

[DOI: 10.71885/ijorlu-2024-1-667]

4.2 Prioritizing Risks/Opportunities

Prioritizing the assessed risks/opportunities is done based on Table 5. A risk priority number of *higher than* or *equal to* 45 is located in the unacceptable area, which indicates "high risk" shown in red. The RPNs of less than 45 and more than 15 are located in the "as low as reasonably practicable" (ALARP) area, indicating "moderate risk" shown in yellow. Finally, the RPNs of less than 15 are located in the acceptable area, pointing to "low risk" shown in green (Table 6).

4.3 Determination of Control Measures and Implementation

Based on Table 6, it is essential that control measures be adopted against unacceptable risks. This needs to be done along with the determination of an executive as well as a deadline.

Table 6 Risk control measures

Risk Priority Number (RPN)	How to tackle
Unacceptable (higher than or equal to 45)	Adoption of new control and supervision measures is essential
As Low as Reasonably Practicable (ALARP) (higher than 15 and less than 45)	New control and supervision measures need to be considered in view of regulations, employer issues, costs, impact on other procedures, facilitation, speed, and beneficiaries' attitudes
Acceptable (less than or equal to 15)	Currently, further control and supervision measures are not necessary. Existing supervisory measures need to continue.

With the replacement of the outputs of risk assessment (normalized RPNs) resulted from Table (4) in the scenario-based robust model for p_ε and the solving of the model via the GAMS software [8], the following is resulted:

- Out of 5 potential production centers, centers 4, 1 and 5 could be active and operating.
- Out of 3 potential collection centers, centers 2 and 3 could be active and operating.

5 Concluding Remarks

The model rendered in the present study is a forward/reverse supply chain, for which the identification and assessment of risks and scenarios have been fulfilled using the Failure Mode and Effects Analysis (FMEA) method. Considering the issue of uncertainty in some parameters, the application of a robust model will be a good solution as it could optimize costs, environmental effects, and delivery time. In robust models, problems normally associated with uncertain models, which lead to unresponsiveness and non-optimization, do not exist. Therefore, robust models are good options when it comes to dealing with real-life problems.

[DOI: 10.71885/ijorlu-2024-1-667]

6 Recommendations for Future Research

We encourage researchers to provide the following ideas for future studies:

- A shortcoming of scenario-based robust models is the high volume of calculations which makes problem-solving for large scenarios difficult. It is recommended that in future studies, problems with large dimensions should be optimized through innovative approaches like the genetic algorithm (GA) or the particle swarm optimization (PSO) in reasonable time.
- The model is designed for a single period. In future studies, it is advised that the model should be designed for multiple periods.
- To simplify the problem, the inventory maintenance as well as ordering costs have been ignored. In future studies, such parameters could also be taken into account.
- Risk assessment and analysis could be done via alternative methods.
- FMEA calculation factors may not be fully and accurately measurable. To overcome the shortcomings of the RPN calculation methods, the fuzzy and grey set theories could be applied.
- In the present study, the relative weights of risk impact, probability of occurrence, and probability of identification have been ignored and hypothesized to be the same. As this is not in effect in the real world, it could lead to risk assessment errors. It is suggested that the weighted FMEA method should be used wherein each of the mentioned parameters has a distinct weight, with a sum total of 1. For instance, the arrangement of the scenarios could be something like this: in one scenario, the probability of occurrence could be given the most weight, indicating that the officials accept no risks. In the following scenarios, the most weight could be allocated to impact and identification.
- Alternative risk assessment techniques could be helpful. These techniques include: Linear Discriminant Analysis, hazard and operability (HAZOP) technique, success and effect diagram, truth table technique, Markov chain/process technique, event tree analysis (ETA), Monte Carlo methods/experiments, security audit, and fault tree analysis (FTA).

References

1. Amiri, A. (2006). Designing a distribution network in a supply chain system: Formulation and efficient solution procedure. *European journal of operational research, 171*(2), 567-576. https://doi.org/10.1016/j.ejor.2004.09.018
2. Fleischmann, M., Beullens, P., BLOEMHOF‐ RUWAARD, J. M., & Van Wassenhove, L. N. (2001). The impact of product recovery on logistics network design. *Production and operations management, 10*(2), 156-173. https://doi.org/10.1111/j.1937-5956.2001.tb00076.x
3. Sarrafha, K., Kazemi, A., & Alinezhad, A. (2014). A multi-objective evolutionary approach for integrated production-distribution planning problem in a supply chain network. *Journal of Optimization in Industrial Engineering, 7*(14), 89-102. https://dorl.net/dor/20.1001.1.22519904.2014.7.14.8.6
4. Khalili, J., & Alinezhad, A. (2018). Performance evaluation in green supply chain using BSC, DEA and data mining. *International journal of supply and operations management, 5*(2), 182-191. https://dx.doi.org/10.22034/2018.2.6
5. Ben-Tal, A., El Ghaoui, L., & Nemirovski, A. (2009). *Robust optimization* (Vol. 28). Princeton university press.
6. Mulvey, J. M., Vanderbei, R. J., & Zenios, S. A. (1995). Robust optimization of large-scale systems. *Operations research, 43*(2), 264-281. https://doi.org/10.1287/opre.43.2.264
7. Yu, C. S., & Li, H. L. (2000). A robust optimization model for stochastic logistic problems. *International journal of production economics, 64*(1-3), 385-397. https://doi.org/10.1016/S0925-5273(99)00074-2

[DOI: 10.71885/ijorlu-2024-1-667]

8. GAMS Development Corporation. General Algebraic Modeling System (GAMS) Release 36.1.0, Fairfax, VA, USA, 2021. Available for download at https://www.gams.com/download/
9. Alinezhad, A., Makui, A., & Mavi, R. K. (2007). An inverse DEA model for inputs/outputs estimation with respect to decision maker's preferences: The case of Refah bank of IRAN. *Mathematical Sciences, 1*(1-2), 61-70.
10. Kiani Mavi, R., Makui, A., Fazli, S., & Alinezhad, A. (2010). A forecasting method in data envelopment analysis with group decision making. *International Journal of Applied Management Science, 2*(2), 152-168. https://doi.org/10.1504/IJAMS.2010.031084
11. Alinezhad, A., Khalili, J., Alinezhad, A., & Khalili, J. (2019). SMART method. *New methods and applications in multiple attribute decision making (MADM),* 1-7. https://doi.org/10.1007/978-3-030-15009-9_1
12. Alinezhad, A., & Taherinezhad, A. (2020). Control Chart Recognition Patterns Using Fuzzy Rule-Based System. *Iranian Journal of Optimization, 12*(2), 149-160. https://dorl.net/dor/20.1001.1.25885723.2020.12.2.2.0
13. Alinezhad, A., & Taherinezhad, A. (2021). Performance Evaluation of Production Chain using Two-Stage DEA Method (Case Study: Iranian Poultry Industry). *new economy and trade, 16*(3), 105-130. https://doi.org/10.30465/jnet.2022.36849.1741
14. Taherinezhad, A., & Alinezhad, A. (2022). COVID-19 crisis management: Global appraisal using two-stage DEA and ensemble learning algorithms. *Scientia Iranica,* Article in Press. https://doi.org/10.24200/sci.2022.58911.5962
15. Alinezhad, A., Heidaryan, L., & Taherinezhad, A. (2023). Ranking the Measurement System of Auto Parts Companies via MSA–MADM Combinatorial Method under Fuzzy Conditions. *Sharif Journal of Industrial Engineering & Management, 38*(2), 15-27. https://doi.org/10.24200/j65.2022.56897.2176
16. Taherinezhad, A., & Alinezhad, A. (2023). Nations performance evaluation during SARS-CoV-2 outbreak handling via data envelopment analysis and machine learning methods. *International Journal of Systems Science: Operations & Logistics, 10*(1), 2022243. https://doi.org/10.1080/23302674.2021.2022243
17. Pan, F., & Nagi, R. (2010). Robust supply chain design under uncertain demand in agile manufacturing. Computers & operations research, 37(4), 668-683. https://doi.org/10.1016/j.cor.2009.06.017
18. Pishvaee, M. S., Rabbani, M., & Torabi, S. A. (2011). A robust optimization approach to closed-loop supply chain network design under uncertainty. *Applied mathematical modelling, 35*(2), 637-649. https://doi.org/10.1016/j.apm.2010.07.013
19. Vahdani, B., Razmi, J., & Tavakkoli-Moghaddam, R. (2012). Fuzzy possibilistic modeling for closed loop recycling collection networks. *Environmental Modeling & Assessment, 17*, 623-637. https://doi.org/10.1007/s10666-012-9313-7
20. Amin, S. H., & Zhang, G. (2013). A multi-objective facility location model for closed-loop supply chain network under uncertain demand and return. *Applied Mathematical Modelling, 37*(6), 4165-4176. https://doi.org/10.1016/j.apm.2012.09.039
21. Ramezani, M., Bashiri, M., & Tavakkoli-Moghaddam, R. (2013). A new multi-objective stochastic model for a forward/reverse logistic network design with responsiveness and quality level. *Applied mathematical modelling, 37*(1-2), 328-344. https://doi.org/10.1016/j.apm.2012.02.032
22. Altmann, M., & Bogaschewsky, R. (2014). An environmentally conscious robust closed-loop supply chain design. *Journal of Business Economics, 84*, 613-637. https://doi.org/10.1007/s11573-014-0726-4
23. Ma, R., Lifei, Y. A. O., Maozhu, J. I. N., Peiyu, R. E. N., & Zhihan, L. V. (2016). Robust environmental closed-loop supply chain design under uncertainty. Chaos, Solitons & Fractals, 89, 195-202. https://doi.org/10.1016/j.chaos.2015.10.028
24. Talaei, M., Moghaddam, B. F., Pishvaee, M. S., Bozorgi-Amiri, A., & Gholamnejad, S. (2016). A robust fuzzy optimization model for carbon-efficient closed-loop supply chain network design problem: a numerical illustration in electronics industry. *Journal of cleaner production, 113*, 662-673. https://doi.org/10.1016/j.jclepro.2015.10.074
25. Safaei, A. S., Roozbeh, A., & Paydar, M. M. (2017). A robust optimization model for the design of a cardboard closed-loop supply chain. *Journal of cleaner production, 166*, 1154-1168. https://doi.org/10.1016/j.jclepro.2017.08.085
26. Soleimani, H., Govindan, K., Saghafi, H., & Jafari, H. (2017). Fuzzy multi-objective sustainable and green closed-loop supply chain network design. *Computers & industrial engineering, 109*, 191-203. https://doi.org/10.1016/j.cie.2017.04.038
27. Tang, C. S. (2006). Perspectives in supply chain risk management. *International journal of production*

[DOI: 10.71885/ijorlu-2024-1-667]

economics, 103(2), 451-488. https://doi.org/10.1016/j.ijpe.2005.12.006

28. Tuncel, G., & Alpan, G. (2010). Risk assessment and management for supply chain networks: A case study. *Computers in industry, 61*(3), 250-259. https://doi.org/10.1016/j.compind.2009.09.008
29. Thun, J. H., & Hoenig, D. (2011). An empirical analysis of supply chain risk management in the German automotive industry. *International journal of production economics, 131*(1), 242-249. https://doi.org/10.1016/j.ijpe.2009.10.010
30. Goh, M., Lim, J. Y., & Meng, F. (2007). A stochastic model for risk management in global supply chain networks. *European Journal of Operational Research, 182*(1), 164-173. https://doi.org/10.1016/j.ejor.2006.08.028
31. Hasani, A., Zegordi, S. H., & Nikbakhsh, E. (2015). Robust closed-loop global supply chain network design under uncertainty: the case of the medical device industry. *International Journal of Production Research, 53*(5), 1596-1624. https://doi.org/10.1080/00207543.2014.965349
32. Bashiri, M., REZVANI, H., & Moslemi, A. (2012). A Robust Approach for Redesigning Three Level Supply Chain Warehouses in Uncertain Condition. *Research in Production and Operations Management, 3*(1), 117-132.
33. Rozenblit, M., Ben-Taly, A., & Golany, B. (2008). *Robust Optimization of Multi-Period Production Planning Under Demand Uncertainty* (Doctoral dissertation, thesis submitted for the degree of master of science, Faculty of Industrial Engineering and Management).