E-ISSN: 2717-2937 | P-ISSN: 2783-1337

International Journal of Research in Industrial Engineering

www.riejournal.com

Int. J. Res. Ind. Eng. Vol. 12, No. 3 (2023) 273–286.

Paper Type: Research Paper

Designing an Innovative Closed-Loop Supply Chain Network Considering Economic and Environmental Aspects

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Citation:

Rahmaty, M. (2023). Designing an innovative closed-loop supply chain network considering economic and environmental aspects. *International journal of research in industrial engineering, 12*(3), 273-286.

Received: 03/01/2023 Reviewed: 06/02/2023 Revised: 19/03/2023 Accepted: 24/05/2023

Abstract

In this paper, the modeling of a closed-loop supply chain problem is discussed concerning economic and environmental aspects. The considered supply chain simultaneously makes strategic and tactical decisions, such as locating potential facilities, optimal allocation of product flow, and determining the optimal level of discount. Since the presented model is an NP-Hard model, MOPSO and SPEA II algorithms have been used to solve the problem. For this purpose, a priority-based encoding is presented, and the Pareto front resulting from solving different problems is compared. The results show that the MOPSO algorithm has obtained the most significant number of Pareto solutions in the large size. In contrast, the SPEA algorithm has included more Pareto solutions in the small and medium sizes. This is despite the fact that in different sizes, the MOPSO algorithm has the lowest calculation time among all algorithms. Also, according to the results obtained from the TOPSIS method, it was observed that the MOPSO algorithm in small and medium sizes and the SPEA2 algorithm in larger sizes have better performance than other proposed algorithms.

Keywords: Network design, Closed-loop supply chain, Economic and environmental aspects, Meta-heuristic algorithms.

1 | Introduction

Some of these organizations seek to achieve a competitive advantage by improving environmental performance by complying with environmental laws and standards, increasing customer knowledge, and reducing negative environmental effects. With the development of technology and the emergence of new technologies, companies need systematic integration in all production processes, from raw material to the final consumer. Supply chain management, as an integrated approach for the proper management of material and goods flow, information and money flow, can respond to these conditions and includes the coordination of production activities, inventory, positioning, and transportation among supply chain actors to achieve efficiency. More and meeting customer expectations [1], [2].

Due to the reduction of natural resources and reserves of raw materials, along with the increase in the cost of production of products and the problems caused by the landfilling of industrial waste and consumer goods, the cycle of products from the point of production to their final recovery has been taken into consideration, which has led to the emergence of new concepts such as the chain Closed-

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https://doi.org/10.22105/riej.2023.391773.1374

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loop provision has been made over the past decade [3]. Due to the economic, social, and environmental challenges that threatened organizations in the last decade, the customer-oriented approach and focusing on its demands and designing the organization's strategy based on this have lost its ability to create a competitive advantage. This attitude caused environmental pollution and the production of products and processes incompatible with the environment [4]. In this regard, organizations have survived in taking responsibility in three economic, social, and environmental fields. Greening the supply chain is the process of considering environmental criteria or considerations throughout the supply chain. Green supply chain management integrates supply chain management with environmental requirements at all stages of product design, raw material selection and procurement, manufacturing, distribution and transportation processes, delivery to the customer, and management of recycling and reuse in order to maximize the efficiency of energy and resource consumption along with improving the performance of the entire supply chain [5], [6]. In recent years, a few articles have focused on designing an integrated forward and reverse supply chain network, which can prevent suboptimality, increase efficiency and reactivity of the entire network, and coordinate between direct and reverse processes. For this reason, the closed-loop innovative supply chain network is presented in this paper, considering economic and environmental aspects.

The structure of this article is as follows; in the second part, the literature review is presented. In the third part, the problem definition and modeling are presented. The solution method is explained in the fourth part, and finally, the conclusion is presented in the last part.

2 | Literature Review

In recent years, several articles have been published in this field due to the increasing importance of closed and reverse supply chain design issues. Pishvaee et al. [7] designed a four-level model of a closed-loop supply chain network, considering the levels of reproduction, recycling, collection, and final customers of the first-hand and second-hand markets. In this model, reducing the costs of the entire chain is considered the main goal, and facility location and optimal flow allocation are considered secondary goals. Since demand parameters and transmission costs are non-deterministic, a stable optimization method controls the parameters. The results show an increase in system costs against an increase in the uncertainty rate. Khatami et al. [8] designed an integrated forward and reverse supply chain problem under demand uncertainty and product return rate in different scenarios. In this article, they considered two important strategic decisions, including facility location and tactical decisions, including the optimal amount of production, distribution, storage, shortage, and transportation. To simultaneously achieve the above objective function, they used the objective function of total cost minimization. The results obtained from Bandarz's analysis show that the number of problem scenarios can be reduced by using the K-means clustering algorithm. Saeedi et al. [9] modeled a robust closed-loop supply chain network under uncertainty by considering an M/M/1 queuing system. This model considers two objective functions of maximizing the profit of the entire supply chain network and minimizing the productivity costs of recycling centers. The Denovo method is used to form the Pareto front, and the stable method is used to control the non-deterministic demand parameter. The results show the high efficiency of the model in determining the facility capacity levels.

Mohammed et al. [10] used a robust method to control uncertainty conditions in the closed-loop supply chain network considering carbon policies. The main goal of this article is to reduce the fixed costs of construction, shortage, maintenance, operation, and transportation. In order to achieve the above objective function, location and allocation decisions must be taken. They also designed another model considering carbon emission policies and compared the results with the original one. Polo et al. [11] modeled an integrated forward and reverse supply chain network under uncertain environmental conditions. The model presented by them is a mixed integer non-linear programming model that pays attention to economic and risk aspects. Due to the indeterminacy of the problem's parameters, the stable optimization method has been used. The objective function of the problem is to maximize the total profit of the supply chain network design, which is obtained by subtracting the assumed value from the total costs of the network design (fixed, transportation, operational, maintenance, and shortage). They implemented their model in an electronic component manufacturing industry and obtained favorable results. Kim et al. [12] designed and developed a closed-loop supply chain network under conditions of demand uncertainty and product return rate. In this model, the stable method is used to increase the profit of the supply chain in conditions of uncertainty. The model results show a decrease in the profit of the supply chain network due to the increase in the uncertainty rate. Darestani and Hemmati [13] designed a closed-loop supply chain network under conditions of uncertainty of demand and transportation costs. In this model, a queue distribution system is used to distribute products. Since the problem's parameters are non-deterministic, the robust optimization method has been used. The objective functions of the problem are the simultaneous minimization of the total system costs and the minimization of greenhouse gas emissions. The solution of the two-objective model has been done by using three methods of comprehensive criteria, utility function, and TH, and the results show the high efficiency of the TH method in solving the two-objective model.

Ghahremani-Nahr et al. [14] designed a two-objective and 11-level closed-loop supply chain network under demand uncertainty and transportation costs. In this model, considering the discussion of discount, they measured the impact of this concept on the objective functions of minimizing network design costs and the amount of greenhouse gas emissions. They used the robust method to control their uncertain parameters. The results show an increase in model stability costs against an increase in uncertain demand. Gholizadeh et al. [15] designed a closed-loop supply chain model to apply it to the destruction of products, where the goal was to increase the return rate of returned products for recycling and destruction. The problem's objective function is the maximization of profit from product return and recycling and reproduction of products. In this model, location-allocation and routing decisions are taken together. n this research, they used a stable method to control non-deterministic parameters and used a priority-based genetic algorithm to solve the problem. The results show the high efficiency of the genetic algorithm in solving large-size problems. Vahdani and Mohammadi [16] presented a fuzzy/probabilistic hybrid optimization method to control the non-deterministic model of a multi-objective closed-loop supply chain network. This model considers four levels of production and reproduction centers, distribution and collection centers, final customers, and destruction centers. The objectives presented in this model are the simultaneous maximization of three objective functions of net present value, maximization of service level, and minimization of delivery time and collection of final products. Due to the indeterminacy of the demand parameter, the new fuzzy/probabilistic hybrid method is used to control the parameter, and the TH method is used to solve the three-objective model. The model results show the TH method's high efficiency in solving the problem. Fathollahi-Fard et al. [17] presented an integrated sustainable closed-loop supply chain network model for water supply and wastewater collection systems under uncertainty. They applied a case study in Iran to a new multi-objective stochastic optimization model. Kalantari Khalil Abad and Pasandideh [18] presented a model for designing a green closed-loop supply chain network with stochastic demand. To solve the model, they applied a new accelerated Benders decomposition algorithm together with the Pareto optimal cut method.

Pishvaee and Razmi [19] designed a multi-objective environmental supply chain model using fuzzy mathematical programming under uncertainty, which is able to consider and balance multiple environmental impacts along with cost minimization. An interactive fuzzy approach was developed to solve the problem. A real industrial case example was investigated to show the importance and application of the proposed model. Hamidieh et al. [20] modeled a bi-objective model of a closed-loop supply chain network by considering the minimization of total network design costs and the minimization of delivery time. They used a robust probabilistic programming method to control uncertain demand parameters and transmission costs.

Ghahremani-Nahr et al. [21] developed a single-objective closed-loop chain network model under the uncertainty of demand parameters, operational costs, and transportation costs. To control the model, they used the robust fuzzy programming method and concluded that the cost of the whole system increases with the increase of the uncertainty rate. They also used Wall's optimization algorithm to solve the problem by designing a priority-based chromosome. Liu et al. [22] modeled a green closed-loop supply chain network under demand uncertainty and used a fuzzy robust optimization method. They considered two objective functions of minimizing network design costs and minimizing greenhouse gas emissions and implemented their model in the Coca-Cola company. The results indicate the management of system costs under uncertainty. Boronoos et al. [23] modeled a closed-loop green supply chain multi-objective model under uncertain conditions. At the same time, in this model, they minimized the total costs of the Zanijare supply network and the amount of greenhouse gas emissions in the forward and reverse supply chain. Since transportation and operating costs are considered non-deterministic and triangular fuzzy numbers in this demand model, the fuzzy stable combination method controls these parameters. The results of the TH method in solving the two-objective model show that with the increase in system costs, greenhouse gas emissions increase under uncertainty. Sadrnia et al. [24] presented a multi-objective optimization model in an automotive supply chain network. The objective function presented in their model included the simultaneous minimization of the costs of the entire supply chain network and the amount of greenhouse gas emissions. They used the MOGSA algorithm to solve the problem.

According to the literature review, each article has built or expanded a supply chain network model by considering some limiting assumptions. So that in these articles, a comprehensive model that includes assumptions closer to the real world is less visible. Therefore, this article, which is a new model in the continuation of solving some of the limitations and assumptions of other articles, refers to a mixed integer non-linear programming model for the design of a multi-objective green supply chain network that seeks to locate potential facilities and optimize the amount of flow between the facility can be compensated by considering the discount factor and shortage, which has not been reviewed in other articles. Multi-objective meta-heuristic algorithms with a modified priority-based encoding have been used to solve the developed model.

3 | Problem Definition and Modeling

In this article, a multi-level green supply chain network is considered. The forward network includes levels of raw material suppliers, production centers, warehouses, product distribution centers, and final customers. The reverse network also includes levels of collection centers, repair centers, recycling centers, and destruction centers. According to *Fig. 1*, in the forward flow path, the supplier of raw materials sends the raw materials needed to produce products to the production centers. Raw materials are sent to the product warehouse after assembly in production centers and stored. After receiving the products from the warehouse, product distribution centers send them to the final customers. On the way back, a percentage of returned products is collected, and after product inspection, items that can be repaired are sent to repair centers and the rest to recycling centers. The repaired products in the repair center are finally sent to the distribution centers or potential warehouses. Recyclable products, if they are usable, are sent to production centers for reuse after disassembly in recycling centers. Otherwise, they are sent to destruction centers for disposal.

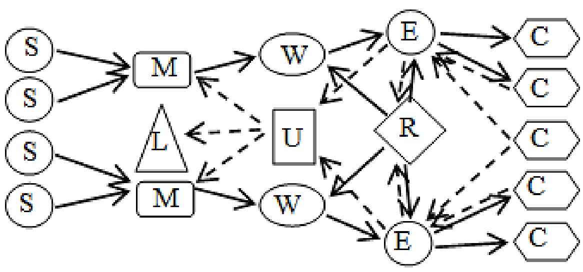

Fig. 1. Proposed green supply chain network.

To specify the study area, the following assumptions have been considered for the proposed model:

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I. Production centers provide the raw materials needed for the production of products with a discount from the suppliers of the products.
II. Production centers store part of the purchased raw materials in their warehouse.
III. The capacity of all centers is limited and specific.
IV. The location of all centers is potential and uncertain.
V. Customers' demands are fulfilled until the last period of time, taking into account the compensable deficiency.
VI. Distribution and collection centers are considered dual center.

For index modeling, the parameter and variables of the problem are defined as follows:

Sets

S	The set of potential points of raw material supply centers.
M	Set of potential points of manufacturing plants.
W	A set of potential storage points.
E	The set of potential points of distribution and collection centers.
C	Set of customer fixed points.
R	Set of potential points of repair centers.
U	Set of potential points of recycling centers.
L	Set of potential points of destruction centers.
I	Set of raw materials.
P	Set of final products.
H	Set of discount levels.
N	Cargo vehicle set.
T	Set of time periods.

Assuming $\vartheta^f = (G^1, A', A'')$ and $\vartheta^r = \; G^2, A''', A'''')$ where G is the nodes of the graph and A are the arcs of the graph according to the following definitions:

$$G^1 = \{S \cup M \cup W \cup E \cup C\}.$$

$$A' = \left\{(j,j')\middle|\; i \in M, j \in W) \cup \; i \in W, j \in E) \cup (i \in E, j \in C)\right\}.$$

$$A'' = \left\{(j,j')\middle|\; (i \in S, j \in M)\right\}.$$

$$G^2 = \{C \cup E \cup R \cup U \cup L\}.$$

$$A''' = \left\{(j,j')\middle|\begin{array}{c} i \in C, j \in E) \cup \; i \in E, j \in R) \cup \; i \in E, j \in U) \\ \cup \; i \in R, j \in E) \cup (i \in R, j \in W) \end{array}\right\}.$$

$$A'''' = \left\{(j,j')\middle|(i \in U, j \in L) \cup (i \in U, j \in M)\right\}.$$

$$G = \left\{G^1 \cup G^2\right\} - C.$$

$$A_1 = \{A'' \cup A''''\}.$$

$$A_2 = \{A' \cup A'''\}.$$

Parameters

fi_{jt}	Annual fixed cost of facility j in time period t.
op_{jt}	Establishment cost of facility j in time period t.
cl_{jt}	Closing cost of facility j in time period t.
$TC_{jj'in}$	The cost of transporting a unit of raw material i between facilities $(j, j') \in A_1$ by freight forwarder n
$TC_{jj'pn}$	The cost of transporting a unit of product p between facilities $(j, j') \in A_2$ by freight forwarder n.
$Co2_{jj'in}$	The amount of Co_2 gas emission per unit of raw material i between facilities $(j, j') \in A_1$ by cargo carrier n.
$Co2_{jj'pn}$	The amount of Co_2 gas emission per unit of product p between facilities $(j, j') \in A_2$ by cargo carrier n.
h_{mit}	The cost of keeping a unit of raw material i in the storage center m at period t's end.
h'_{wpt}	The cost of keeping a unit of product p in warehouse center w at the end of period t.

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Pr_{shit}	The purchase price of a unit of raw material i at discount level h from supplier s in period t.
VA_{shit}	The lower limit of the discount range for raw material i at discount level h from supplier s in period t.
$C_{1_{mpt}}$	The cost of producing a unit of product p in factory m in period t.
$C_{2_{ept}}$	The cost of distributing a unit of product p by distribution center e in period t.
$C_{3_{ept}}$	The cost of collecting a unit of returned product p by collection center e in period t.
$C_{4_{rpt}}$	The cost of repairing a unit of product p at repair center r in period t.
$C_{5_{upt}}$	The cost of recycling a unit of product p at the recycling center u in period t.
$C_{6_{lit}}$	Cost of destroying one unit of raw material i in destruction center l in period t.
π_{cpt}	Penalty cost of facing a shortage of one unit of product p from customer c in period t.
δ_{ip}	The number of raw material i needed to make a product p.
De_{cpt}	Customer c's demand for product p in period t.
α_{cpt}	Percentage of product p returned from customer c in period t.
β_{pt}	Percentage of product p that can be repaired in period t.
γ_{pt}	Percentage of product p transferred to the distribution center in period t.
θ_{it}	Percentage of usable raw materials i in period t.
cap_{si}	The supply capacity of raw material i from supplier s.
cap_{mi}	The storage capacity of raw material i in the raw material warehouse of the factory m.
cap_{mp}	Production capacity of product p in factory m.
cap_{wp}	The storage capacity of the final product p in the warehouse w.
cap_{ep}	Distribution capacity of product p in distribution center e.
cap'_{ep}	Return product capacity p in the collection center e.
cap_{rp}	Repair capacity of repairable product p in repair center r.
cap_{up}	The recycling capacity of the recyclable product p in the recycling center u.
cap_{li}	The destruction capacity of substance i in the center of destruction l.
M	A very large non-negative number.

Decision variables

$X_{jj'itn}$	The amount of raw material i that is transported by freight vehicle n between facilities $(j,j') \in A_1$ in period t.
$X_{jj'ptn}$	The amount of product p that is transported by freight vehicle n between facilities $(j,j') \in A_2$ in period t.
VQ_{mit}	The amount of inventory of raw material i in the raw material warehouse of factory m at the end of period t.
IQ_{wpt}	Inventory amount of product p in warehouse w at period t's end.
Q_{sit}	The total purchase amount of raw material i from supplier s in period t.
sh_{cpt}	The amount of shortage of product p from customer c in period t.
Y_{jt}	If the facilitation center $j \in G$ is established in period t, it takes the value 1 and otherwise 0.
A_{jhit}	If the discount level h is selected for the raw material i in the facilitation center $j \in S$ in the period t, the value is 1, and otherwise, it is 0.

$$
\begin{aligned}
\min z1 = {} & \sum_{j\in G}\sum_{t\in T}\begin{pmatrix} fi_{jt}Y_{jt} + op_{jt}Y_{jt}(1-Y_{j,t-1}) \\ +cl_{jt}Y_{jt}\left(1-Y_{j,t+1}\right)\end{pmatrix} \\
& + \sum_{j,j')\in A_1}\sum_{i\in I}\sum_{t\in T}\sum_{n\in N} tc_{jj'in}X_{jj'itn} + \sum_{j\in m}\sum_{i\in I}\sum_{t\in T} h_{jit}VQ_{jit} \\
& + \sum_{j,j')\in A_2}\sum_{p\in P}\sum_{t\in T}\sum_{n\in N} tc_{jj'pn}X_{jj'ptn} + \sum_{j\in W}\sum_{p\in P}\sum_{t\in T} h'_{jit}IQ_{jpt} \\
& + \sum_{j\in S}\sum_{j'\in M}\sum_{i\in I}\sum_{t\in T}\sum_{n\in N}\sum_{h\in H} pr_{jhit}A_{jhit}X_{jj'itn} \\
& + \sum_{j\in M}\sum_{j'\in W}\sum_{p\in P}\sum_{t\in T}\sum_{n\in N} C_{1_{jpt}}X_{jj'ptn} \\
& + \sum_{j\in E}\sum_{j'\in C}\sum_{p\in P}\sum_{t\in T}\sum_{n\in N}\left(C_{2_{jpt}}X_{jj'ptn} + C_{3_{jpt}}X_{j'jptn}\right) \\
& + \sum_{j\in E}\sum_{j'\in R}\sum_{p\in P}\sum_{t\in T}\sum_{n\in N} C_{4_{j'pt}}X_{jj'ptn} \\
& + \sum_{j\in E}\sum_{j'\in U}\sum_{p\in P}\sum_{t\in T}\sum_{n\in N} C_{5_{j'pt}}X_{jj'ptn} \\
& + \sum_{j\in U}\sum_{j'\in L}\sum_{i\in I}\sum_{t\in T}\sum_{n\in N} C_{6_{j'it}}X_{jj'itn} + \sum_{j\in C}\sum_{p\in P}\sum_{t\in T} \pi_{jpt}sh_{jpt}.
\end{aligned} \tag{1}
$$

$$
\min z2 = \sum_{j,j')\in A_1}\sum_{i\in I}\sum_{t\in T}\sum_{n\in N} co2_{jj'in}X_{jj'itn} + \sum_{j,j')\in A_2}\sum_{p\in P}\sum_{t\in T}\sum_{n\in N} co2_{jj'pn}X_{jj'ptn}. \tag{2}
$$

S. t.

$$
A_{jhit}VA_{jhit} \leq Q_{jit} \quad \text{for all } j \in S, h, i, t. \tag{3}
$$

$$
\sum_{h\in H} A_{jhit} = Y_{jt} \quad \text{for all } j \in S, i, t. \tag{4}
$$

$$
Q_{jit} = \sum_{j'\in M}\sum_{n\in N} X_{jj'itn} \quad \text{for all } j \in S, i, t. \tag{5}
$$

$$
\begin{aligned}
& \sum_{j\in S}\sum_{n\in N} X_{jj'itn} + \sum_{j\in U}\sum_{n\in N} X_{jj'itn} - VQ_{j'it} + VQ_{j'i,t-1} \\
& = \sum_{j\in W}\sum_{n\in N}\sum_{p\in P} X_{j'jptn}\delta_{ip} \quad \text{for all } j' \in M, i, t.
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
& \sum_{j\in M}\sum_{n\in N} X_{jj'ptn} + \sum_{j\in R}\sum_{n\in N} X_{jj'ptn} + IQ_{j'p,t-1} - \sum_{j\in E}\sum_{n\in N} X_{j'jptn} = IQ_{j'pt} \quad \text{for all } j' \\
& \in W, p, t
\end{aligned} \tag{7}
$$

$$
\sum_{j\in W}\sum_{n\in N} X_{jj'ptn} + \sum_{j\in R}\sum_{n\in N} X_{jj'ptn} = \sum_{j\in C}\sum_{n\in N} X_{j'jptn} \quad \text{for all } j' \in E, p, t. \tag{8}
$$

$$
De_{j'p,t} + sh_{j'p,t-1} - \underset{t<T}{sh_{j'pt}} = \sum_{j\in E}\sum_{n\in N} X_{jj'ptn} \quad \text{for all } j' \in C, p, t. \tag{9}
$$

$$
\alpha_{j'pt}\sum_{j\in E}\sum_{n\in N} X_{jj'p,t-1,n} = \sum_{j\in E}\sum_{n\in N} X_{j'jptn} \quad \text{for all } j' \in C, p, t. \tag{10}
$$

$$
\beta_{pt}\sum_{j\in C}\sum_{n\in N} X_{jj'ptn} = \sum_{j\in R}\sum_{n\in N} X_{j'jptn} \quad \text{for all } j' \in E, p, t. \tag{11}
$$

$$
(1-\beta_{pt})\sum_{j\in C}\sum_{n\in N} X_{jj'ptn} = \sum_{j\in U}\sum_{n\in N} X_{j'jptn} \quad \text{for all } j' \in E, p, t. \tag{12}
$$

$$
\gamma_{pt}\sum_{j\in E}\sum_{n\in N} X_{jj'ptn} = \sum_{j\in E}\sum_{n\in N} X_{j'jptn} \quad \text{for all } j' \in R, p, t. \tag{13}
$$

$$(1-\gamma_{pt})\sum_{j\in E}\sum_{n\in N}X_{jj'ptn}=\sum_{j\in W}\sum_{n\in N}X_{j'jptn} \quad \text{for all } j'\in R,p,t. \tag{14}$$

$$\theta_{it}\sum_{j\in E}\sum_{n\in N}\sum_{p\in P}X_{jj'ptn}\delta_{ip}=\sum_{j\in M}\sum_{n\in N}\sum_{p\in P}X_{j'jitn} \quad \text{for all } j'\in U,i,t. \tag{15}$$

$$(1-\theta_{it})\sum_{j\in E}\sum_{n\in N}\sum_{p\in P}X_{jj'ptn}\delta_{ip}=\sum_{j\in L}\sum_{n\in N}\sum_{p\in P}X_{j'jitn} \quad \text{for all} j'\in U,i,t. \tag{16}$$

$$\sum_{j\in M}\sum_{n\in N}X_{jj'itn}\le cap_{ji}Y_{jt} \quad \text{for all } j\in S,i,t. \tag{17}$$

$$VQ_{jit}\le cap_{ji}Y_{jt} \quad \text{for all } j\in M,i,t. \tag{18}$$

$$\sum_{j'\in W}\sum_{n\in N}X_{jj'ptn}\le cap_{jp}Y_{jt} \quad \text{for all } j\in M,p,t. \tag{19}$$

$$IQ_{jpt}\le cap_{jp}Y_{jt} \quad \text{for all } j\in W,p,t. \tag{20}$$

$$\sum_{j\in w}\sum_{n\in N}X_{jj'ptn}+\sum_{j\in R}\sum_{n\in N}X_{jj'ptn}\le cap_{j'p}Y_{j't} \quad \text{for all } j'\in E,p,t. \tag{21}$$

$$\sum_{j\in C}\sum_{n\in N}X_{jj'ptn}\le cap'_{j'p}Y_{j't} \quad \text{for all } j'\in E,p,t. \tag{22}$$

$$\sum_{j\in E}\sum_{n\in N}X_{jj'ptn}\le cap_{j'p}Y_{j't} \quad \text{for all } j'\in U,p,t. \tag{23}$$

$$\sum_{j\in E}\sum_{n\in N}X_{jj'ptn}\le cap_{j'p}Y_{j't} \text{ for all } j'\in R,p,t. \tag{24}$$

$$\sum_{j\in U}\sum_{n\in N}X_{jj'itn}\le cap_{j'i}Y_{j'i} \quad \text{for all } j'\in L,i,t. \tag{25}$$

$$Y_{j,t-1}=0 \quad \text{for all } j\in G,t=1. \tag{26}$$

$$Y_{j,t+1}=0 \quad \text{for all } j\in G,t=T. \tag{27}$$

$$X_{jj'itn},VQ_{mit},Q_{sit}\ge 0 \quad \text{for all } j,j')A_1,i,n,t,s,m. \tag{28}$$

$$X_{jj'ptn},IQ_{wpt},sh_{cpt}\ge 0 \quad \text{for all } j,j')\in A_2,p,n,t,w,c. \tag{29}$$

$$Y_{jt}\in\{0,1\} \quad \text{for all } j\in G,t. \tag{30}$$

The objective *Function (1)* seeks to minimize the costs of the entire supply chain network. These costs include: annual fixed costs, establishing and closing a facility, transportation costs of raw materials and products between facilities, storage costs of raw materials and finished products in the related warehouse, operational costs related to each facility (cost of production, distribution, collection, repair, recycling, destruction) and finally penalty costs are faced with product shortage. *Eq. (2)* shows the second objective function of the problem related to minimizing the amount of Co_2 gas released by moving cargo vehicles between facility centers. The constraint in *Inequality (3)* expresses the total amount of raw materials purchased from suppliers' discount levels. The constraint in *Eq. (4)* guarantees that if a potential supplier is selected, raw materials can be purchased from only one discount level in each period. The constraint in *Eq. (5)* sends suppliers' total raw material purchases to manufacturing plants. The limitation in *Eq. (6)* shows the volume of the raw material flow from the supplier and the recycling center to the factory; part of the raw material is stored in the factory warehouse after the production of the product. The restriction in *Eq. (7)* controls the volume of incoming and outgoing flow to the warehouse. *Eq. (8)* shows the equilibrium constraint on the distribution center and ensures that the volume of the incoming flow from the repair and warehouse center to the distribution center is equal to the volume of the outgoing flow from the distribution center to the customer. The constraint in *Eq. (9)* guarantees that the customer's demand must be satisfied until the last period of the time horizon. The constraint in *Eq. (10)* shows the percentage of the customer's discarded products in each period. Constraints in *Eqs. (11)* and *(12)* state the collection center, after inspecting the products, send a percentage of it that can be repaired to the repair center and the rest of the products to the recycling center. The constraints in *Eqs. (13)* and *(14)* show that, after repairing the returned products, the repair

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center sends a percentage of it to the distribution center and a percentage of the products to the warehouse. The constraints in *Eqs. (15)* and *(16)* also show that the recycling center, after inspecting the products and disassembling them products, sends a percentage of the raw materials that can be used to the manufacturing plant and the rest of the products to the destruction center for destruction. The constraints in *Inequalitys (17)* to *(25)* represent the constraints related to the capacity of the network facilities so that the constraint in the *Inequality (17)* shows the maximum capacity of the supplier in the provision of raw materials. Constraint in *Inequality (18)* limits the storage amount of each raw material in the factory warehouse. The constraint in *Inequality (19)* expresses the maximum production capacity of each product for the created factories. The constraint in *Inequality (20)* guarantees that the maximum amount of product storage cannot exceed the warehouse capacity if a warehouse is created. *Limitations (21)* and *(22)* states that if a dual collection and recycling center is established, the amount of distribution and collection will not exceed the capacity of this facility. The constraint in *Inequality (23)* shows the maximum amount of ability to recycle products in the recycling center. The constraint in *Inequality (24)* guarantees that if a repair center is established, the maximum number of repairable products does not exceed the repair capacity of the said center. The constraint in *Inequality (25)* also limits the capacity to destroy unusable raw materials. *Constraints (26)* and *(27)* make the value of the variable in the objective function zero for certain periods. *Constraints (28)* to *(30)* state the types of decision variables and their allowed values in the problem.

4 | Solution Method

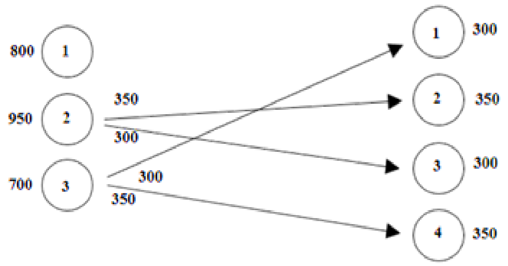
In this article, due to the high complexity of the proposed model, a new decoding based on modified priority is used. In this solution, the chromosome is a permutation of the number of facilities available at each level. Suppose a level of the supply chain includes 4 customers and 3 distributors according to *Fig. 2*. In this case, the initial solution will be a permutation of the number 7.

There are 2 main steps to decrypt this solution:

Step 1. First, the optimal number of centers (distributors) should be obtained. Therefore, for this purpose, the highest priority is selected among the distributors, and the capacity of that center is compared with the total demand of customers. If the center's capacity (centers) is less than the total demand, another distributor with the next highest priority is selected. This process continues until the selected centers' total capacity exceeds the total customer demand. Finally, the priority of not selected centers will be changed to zero.

Step 2. After determining the number of optimal centers, the number of goods should be allocated between the customers and the selected centers. For this, the highest priority among the customers (centers) is selected and connected to the centers (customers) with the lowest transportation cost. Then it is allocated according to the minimum capacity of the selected center and the customer's demand. If the amount of capacity or demand becomes zero, the corresponding priority will also change to zero. This continues until all requests are met.

This solution is described for one supply chain level and for one product and one period. To solve the proposed problem, chromosome should be considered in the total number of products, all periods, and all levels of the supply chain. Until the decoding of one level is done, the decoding of another level should not be done.



$v(K+J)$	node	1	2	3	1	2	3	4
	priority	2	5	3	7	4	1	6

⇩

$v(K+J)$	node	1	2	3	1	2	3	4
	priority	0	5	3	7	4	1	6

Fig. 2. Encoding and decoding of a supply chain level.

To compare meta-heuristic algorithms with each other, a series of numerical experiments are designed for the proposed multi-objective model. The nominal data were generated using the uniform distribution shown in *Table 1*. Also, the size of the designed sample problems is also shown in *Table 2*.

Table 1. Range of produced nominal data.

Fi_{Gt}	(40000,45000)~	VA_{shit}	(4000,10000)~	$C_{5_{upt}}$	(0.5,1.5)~
cl_{Gt}	(4000000,6000000)~	$C_{2_{ept}}$	(0.5,1.5)~	π_{cpt}	(150,200)~
op_{Gt}	(2500000,5000000)~	$C_{4_{rpt}}$	(0.5,1.5)~	δ_{ip}	(1,3)~
cap_{si}	(12000,15000)~	$C_{6_{lit}}$	(0.5,1)~	β_{pt}	(0.4,0.5)~
cap_{mp}	(1600,2200)~	De_{cpt}	(200,300)~	θ_{it}	(0.2,0.3)~
cap_{ep}	(1300,1500)~	α_{cpt}	(0.1,0.2)~	cap'_{ep}	(200,300)~
cap_{rp}	(200,250)~	γ_{pt}	(0.4,0.5)~	h_{mit}	(0.2,0.5)~
cap_{lp}	(1000,1600)~	$TC_{jj'in}$	(2.5,4)~	h'_{wpt}	(0.8,1.2)~
cap_{mi}	(4000,6000)~	$TC_{jj'pn}$	(5,15)~	Pr_{shit}	(1,1.5)~
cap_{p}	(2000,2500)~	$Co_{2_{jj'in}}$	(2.5,4)~	$C_{1_{mpt}}$	(0.5,1.5)~
cap_{up}	(200,250)~	$Co_{2_{jj'pn}}$	(5,15)~	$C_{3_{ept}}$	(0.5,1.5)~

Table 2. Dimension levels of designed sample problems.

Size	Problem	S*M*W*E*C*R*U*L*T*P*I*N*H
Small	1	6*6*6*6*10*4*4*4*6*2*2*3*3
	2	6*6*6*6*10*4*4*4*6*3*2*3*3
	3	6*6*6*6*10*4*4*4*8*2*3*3*3
	4	6*6*6*6*12*4*4*4*6*2*2*4*3
	5	6*6*6*6*12*4*4*4*8*3*3*4*3
Medium	6	10*10*10*10*15*6*6*6*10*3*3*3*3
	7	10*10*10*10*15*6*6*6*12*4*4*4*3
	8	10*10*10*10*15*6*6*6*14*4*3*5*3
	9	10*10*10*10*16*6*6*6*12*3*4*4*3
	10	10*10*10*10*15*6*6*6*10*3*4*5*3
Large	11	15*15*15*15*20*10*10*10*18*4*4*5*3
	12	15*15*15*15*20*10*10*10*18*4*5*5*3
	13	15*15*15*15*22*10*10*10*20*4*4*6*3
	14	15*15*15*15*22*10*10*10*20*3*4*5*3
	15	15*15*15*15*20*10*10*10*18*3*4*6*3

In this paper, Taguchi's methodology is used through the design of experiments to obtain all the optimal combinations of the factors (algorithm parameters) proposed. In this method, at first, the appropriate factors should be identified, then the levels of each factor should be selected, and then the appropriate test plan should be determined for these control factors. After the test plan is determined, the tests are performed, and the tests are analyzed to find the best combination of parameters. In this article, 3 levels are considered for each algorithm and each factor, and according to the number of factors and the number of their levels, the experiment's design and implementation are determined. It should be noted that each experiment was repeated 5 times on average and the average values obtained were evaluated in the final analysis. *Table 3* shows the parameter setting levels of the proposed algorithms. Bold data in *Table 3* shows the parameter set for each algorithm.

Table 3. Levels and adjusted parameters of the proposed algorithm.

Algorithm	Parameter	Low	Medium	High
NSGA II	Maximum number of iterations	200	300	500
	Number of population	100	150	200
	Composition rate	0.3	0.5	0.7
	Mutation rate	0.3	0.5	0.7
MOPSO	Maximum number of iterations	200	300	500
	Number of particles	100	150	200
	Number of archives	20	50	70
	Initial speed coefficient	0.1	0.5	0.8
	Secondary speed coefficient	0.3	0.5	0.7
SPEA2	Maximum number of iterations	200	300	500
	Number of population	100	150	200
	Arshid number	20	50	70
	Composition rate	0.3	0.5	0.7
	Mutation rate	0.3	0.5	0.7

5 | Test Results and Analysis of Results

For comparing and analyzing the results of meta-heuristic algorithms, 15 numerical examples in three sizes, small, medium, and large, were selected, and from each problem, a data sample was generated and solved according to *Table 1*. *Fig. 3* shows an example of the problem solved for problem 4 for the proposed algorithms.

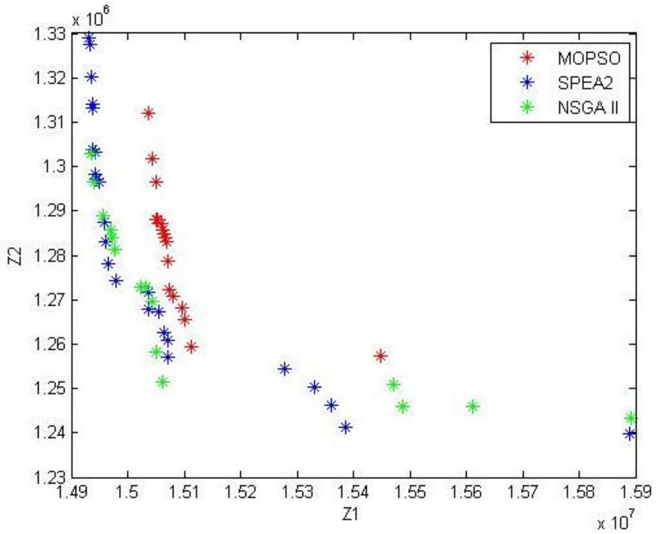


Fig. 3. An example of a problem solved by algorithms.

As seen in *Fig. 3*, the number of Pareto solutions obtained by the MOPSO algorithm is more than other algorithms. If the dispersion of efficient solutions of the NSGA II algorithm is better than other algorithms. *Table 4* shows the calculation results for all the designed problems; in this table, the number of efficient solutions (NPF), More Expansion Index (MSI), Spacing Index (SI), distance metric index (SM), and computing time (CPU-time) indicates each algorithm. According to *Table 4* and the obtained results, it can be seen that the average number of Pareto solutions obtained from the SPEA2 algorithm is more than other algorithms. On average, the calculation time of the MOPSO algorithm is lower than other algorithms.

Table 4. Computational results of sample problems.

Problem		NPF	MSI	SI	SM	CPU Time
1		14	433620.8	24356.12	0.44	130.1
2		20	835769.9	76533.37	0.6	149.45
3		14	853519.7	149878.5	0.7	138.54
4		15	956206.1	7562.21	0.83	150.23
5		13	783100	43304.24	0.73	171.55
6		13	1341179	78569.39	0.78	178.23
7		14	228346	8452.15	0.37	185.06
8		17	842071.7	75882.34	0.62	184.42
9		22	1650103	215436.1	0.69	193.65
10		8	472835.4	33311.04	0.58	218.94
11		15	1059873	71764.21	0.83	304.98
12		15	1786672	304626.1	0.79	291.61
13		15	1059873	59484.57	0.62	312.97
14	NSGA II	8	875864	129859.8	0.62	307.95
15		20	1292680	57939.01	0.73	320.56
1		9	512623.9	32258.58	0.46	34.12
2		31	849502.6	30198.74	0.81	40.23
3		12	327400.9	25311.65	0.84	38.56
4		17	414037	81921.48	0.74	41.21
5		5	234949.1	10020.79	0.23	51.17
6		16	954906.8	14201.89	0.65	86.45
7		7	892546	294427.1	0.79	87.65
8		21	1416885	59595.35	0.76	110.53
9		17	1286576	48061.21	0.70	84.25
10		20	1134990	31184.24	0.77	108.26
11		20	1254616	74754.02	0.97	239.86
12		23	1548515	38258.32	0.74	249.34
13		21	1882374	81827.01	0.85	259.59
14	MOPSO	23	1716464	28222.24	0.54	250.99
15		17	1538293	85243.26	0.52	262.53
1		18	587377.3	42644.47	0.98	98.1
2		17	745374.3	63967.08	0.66	97.81
3		14	568505.4	65360.28	0.68	110.24
4		25	963311.3	99913.29	0.71	113.37
5		18	506117.6	25790.64	0.7	119.01
6		15	1333088	64858.64	0.71	123.23
7		8	482408	70125.88	0.46	149.92
8		27	909092.2	28159.93	0.65	170.56
9		27	1153317	22505.3	0.56	161.16
10		19	810930.3	18806.11	0.73	177.2
11		15	493434.9	19606.03	0.42	311.74
12		19	955545.2	41922.03	0.7	313.29
13	SPEA 2	9	1139443	116988.5	0.71	314.94
14		17	1472409	163432	0.63	311.81
15		12	1316889	82819.48	0.85	326.99

Table 5. Average calculation indices in different sizes.

Algorithm	Size	NPF	MSI	SM	CPU Time
NSGA II	Small	15.2	772443.3	0.66	147.9
MOPSO		14.8	467702.7	0.61	41.05
SEPA2		18.4	674137.2	0.74	107.7
NSGA II	Medium	14.8	906906.9	0.6	192
MOPSO		16.2	1137181	0.73	95.4
SEPA2		19.2	937767.1	0.62	156.4
NSGA II	Large	14.6	1220063	0.73	307.6
MOPSO		20.8	1588052	0.72	252.4
SEPA2		14.4	1075544	0.66	315.7

According to *Table 5*, the MOPSO algorithm has obtained the largest number of Pareto solutions in the large size, while the SPEA algorithm has included more Pareto solutions in the small and medium sizes.

This is despite the fact that in different sizes, the MOPSO algorithm has the lowest calculation time among all algorithms. Therefore, the TOPSIS method has been used to compare algorithms to determine the best algorithm in each size. This method selects 4 indicators of the number of Pareto solutions, MSI, metric distance index, and computing time. It is more suitable if the first and second indexes have a larger value and the third and fourth indexes have a smaller value. *Table 6* shows the results obtained from the comparison of algorithms using the TOPSIS method. In this table, the weight of each index is obtained through the entropy method.

Table 6. The results were obtained from the TOPSIS method.

Size	Weight (Entropy Method)				Algorithm
	w1	w2	w3	w4	
Small	0.03	0.14	0.02	0.49	MOPSO>SPEA2>NSGA II
Medium	0.11	0.09	0.06	0.71	MOPSO >SPEA2>NSGA II
Large	0.03	0.95	0.002	0.01	SPEA2>MOPSO>NSGA II

According to the results obtained from the TOPSIS method according to *Table 6*, it can be seen that the MOPSO algorithm in small and medium sizes and the SPEA2 algorithm in larger sizes have better performance than other proposed algorithms.

5 | Conclusion

In this article, a dual-objective, multi-period, and multi-product green supply chain model was modeled and solved by considering tactical decisions, including the application of a quantity discount by the supplier and compensable shortage. The objectives of the proposed model included minimizing the cost of logistics and the number of CO_2 emissions by cargo vehicles. Multi-objective meta-heuristic algorithms, including NSGA II, MOPSO, and SEPA2 with new encryption based on modified priority, were used to solve the proposed model. After adjusting the parameters by the Taguchi method and calculating the results by the TOPSIS method, the aforementioned algorithms were compared with each other in different sizes, and the best algorithm was selected. Due to the high complexity of the proposed model, the SEPA2 algorithm was chosen as the most efficient algorithm in very large dimensions. Studies in the field of the supply chain are very extensive. However, it is possible to develop more supply chain models. In this article, the supply chain model is designed by considering the deterministic parameters. Therefore, it is suggested that in future studies, the developed model should be put on the agenda by considering non-deterministic parameters and using fuzzy or stable methods. Also, considering the development of meta-heuristic algorithms, it is suggested to design and solve the developed model with newer algorithms.

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