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Research Paper

An Approach Utilizing Epsilon-Constraint and NSGA-II for Circular Manufacturing Supply Chain Networks

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Abstract

Circular manufacturing supply chains offer a novel and compelling perspective within the realm of supply chain sustainability. Consequently, the development of a suitable solution approach for circular manufacturing supply chains holds significant value. This study presents appropriate solution approaches for a mathematical model that has been formulated for a circular supply chain. To address the small-sized problem, the epsilon-constraint method is proposed. This method aids in obtaining a Pareto set of optimal solutions, facilitating the evaluation of trade-offs among three objectives. Given the NP-hard nature of the problem, the non-dominated sorting genetic algorithm (NSGA-II) is employed to approximate the Pareto front for larger problem sizes. A comparative analysis is conducted between the outcomes achieved in smaller dimensions using the epsilon-constraint method and those generated by the metaheuristic algorithm. The results indicate that the error percentage of the objective function, when compared to the epsilon method, remains consistently below 1%, underscoring the effectiveness of the proposed algorithm. These methodologies empower decision-makers to offer efficient, optimal solutions, enabling them to select the most suitable alternative based on budgetary considerations and organizational policies.

Keywords

Circular Manufacturing Supply Chain, Optimization, Epsilon-constraint, NSGA-II Algorithm

1. Introduction

Over the past two decades, environmental studies have received considerable attention because of their potential to improve sustainability effectively. Meanwhile, increased laws, regulations, and public pressure have forced companies to pay special attention to environmental issues.

Instead of working as individuals, companies have been forced to work as supply chain members due to intense competition in today’s market, quick changes in customer preferences, rapid technology development, and globalization. Properly integrating and coordinating all supply chain members is critical to its success and making an efficient network structure. This can lead to cost savings and faster response to customer needs throughout the supply chain [1]. Supply chain network design is a systematic approach that aims to determine an ideal combination of products, suppliers, and facilities through mathematical modeling [2]. However, the current Supply chain networks should be efficiently redesigned by integrating circular economy concepts to achieve sustainable development goals [3, 4]. For this reason, a closed-loop supply chain that originates from the circular economy concept aims to increase efficiency and profitability by reducing waste and energy consumption [5]. The circular economy is composed of technical and biological cycles. In technical cycles, geosphere-derived technical nutrients can be designed for recovery (i.e., refurbishing, remanufacturing, and recycling) so that they can be kept within the techno sphere by circulating in the economy with the least possible wastage. In a biological cycle, biological ingredients or nutrients can be safely returned to the biosphere, enhancing natural capital. The circular economy aims to continuously keep materials, components, and products at their highest value in both technical and biological cycles [6, 7].

This study investigates a circular supply chain model where the model has been solved just in small size using the weighted sum method. However, the proposed problem is of NP-hard category in large dimensions, and it is impossible to solve it in large sizes with exact solution methods. Therefore, this study aims to provide the optimal solution for the circular manufacturing supply chain mathematical model in small and large dimensions (as an NP-hard problem) with effective methods. Therefore, the contributions of this study are as follows:

- Considering the appropriate solution method for the mathematical planning model of circular closed-loop supply chain network in small dimensions;
- Presenting the appropriate solution method for the problem in large dimensions considering that the problem is NP-hard in large dimensions;
- Developing solution approaches for a multi-objective mathematical planning model that simultaneously considers minimizing total supply chain costs, minimizing unusable products that are buried, minimizing environmental pollution, and maximizing the number of jobs created to optimize, which is in the NP-hard category problem;

2. Literature review

In the following, some papers that used mathematical programming to design supply chain network and their solution approaches are reviewed. Some researchers have proposed a step further and examined closed-loop supply chain networks (CLSCN), focusing on the circular economy.

Nasr et al. [6] have used the circular economy concepts to design a CLSCN for digital devices and clothing industries, respectively. In this regard, MahmoumGonbadi et al. [7] to transition towards circular economy presented a systematic review of the applications and methods of CLSCN articles. Erdoğan et al. [8] provided a hydrogen supply chain (HSC) which is modeled using a mixed integer linear programming (MILP) for Turkey. Its objective was to minimize cost, carbon emission, and security risk. As much importance has been given to the network costs, attention has also been paid to reducing the harmful effects caused by the network on the environment and the security risks in the design of this network. They implemented the epsilon constraint method and weighted sum method to solve the model. Ten different demand scenarios showed that the HSC has a decentralized structure under almost all scenarios.

Govindan et al. [5] to design a circular closed-loop supply chain network and achieve a circular economy studied a location-inventory-routing problem with carbon tax policy. They presented an integrated bi-objective mixed-integer linear programming model. Optimizing both strategic and operational decisions was the aim of this model in a closed-loop supply chain network. The model considered a vehicle scheduling and carbon tax policy problem to reduce vehicle waiting time and emissions, respectively. The proposed model benefits the location-inventory-routing problem to structure the network. To deal with demand uncertainty a stochastic scenario-based approach is used, and to solve the proposed bi-objective model an augmented epsilon-constraint method is employed.

Goudarzi et al. [9] formulated a mathematical model for a closed-loop supply chain. This model was multi-objective and multi-echelon and was designed to maximize routes considering the joint assembly center and the reliability of facilities and minimize total supply chain costs. Two methods that have been used to solve the problem are multi-choice goal programming and the epsilon constraint method. Dastani et al. [1] for a green closed-loop supply chain presented a multi-objective mathematical model. They have considered the environmental and economic objectives. To simultaneously optimize them, two methods of multi-objective gray wolf optimization (MOGWO) algorithm and epsilon constraint have been implemented. The results show that the average solving time is decreased by applying the MOGWO algorithm. Govindan et al. [10] for medical waste management provided a circular economy transition model which was multi-product, multi-period, and bi-objective mixed-integer linear programming. They considered the uncertainty in the amount of waste generated to design a green reverse network and to deal with the uncertainty a stochastic scenario-based approach was used. An improved augmented epsilon-constraint method implied minimizing total cost and population risk.

Ghasemi et al. [11] proposed a bio-objective mathematical location-routing model for location-routing problems in the supply chain. The supply chain was based on the customer’s time window. To solve the mathematical model Epsilon-constraint and NSGA-II approaches have been used. Two objectives include cost minimization and reliability maximization. The assessment metric results indicate the proper performance of their proposed model. Pahlevan et al. [12] presented a model for the sustainable aluminum closed-loop supply chain in Iran. To estimate the environmental impacts, they used the life cycle assessment and to optimize the proposed mathematical model implied two novel meta-heuristic algorithms. The multi-objective red deer algorithm (MORDA), the multi-objective gray wolf optimizer (MOGWO), and the augmented epsilon constraint (AEC) are used to achieve Pareto optimal solutions.

Lahri et al. [13] for a sustainable supply chain network, designed a two-level multi-objective integer linear programming, and green image factors for suppliers were introduced. They used Epsilon (ε) constraint method to generate distinct Pareto-optimal solutions, which provided a variety of combinations of the trade-off between objectives. Moslehi et al. [14] studied a reverse logistics supply chain and formulated a multi-objective stochastic model. An SSP approach via the epsilon constraint was implemented to solve the model. Fasihi et al. [18] proposed a two-objective mathematical model to design the fish closed-loop supply chain. A novel mathematical model has been presented to maximize customer demand responsiveness and minimize network costs. The epsilon-constraint method and Lp-metric were employed to solve this model. The comparison between the solution methods was based on the performance metrics and a statistical hypothesis. Bal and Badurdeen [16] presented a multi-objective programming model for optimizing the locations of end-of-life product recovery facilities and implementing Product Service Systems (PSS). The model considers the lead time of reusable products and covered social, environmental, and economic criteria as objectives. To obtain Pareto optimal results the epsilon constraint method is used.

Franco and Alfonso-Lizarazo [17] studied the pharmaceutical supply chain and for optimizing tactical and operative decisions conducted a simulation-optimization approach based on the stochastic counterpart or sample-path method. They formulated two mixed integer programming (MIP) models. Expiration dates, the service level required, perishability, aged-based inventory levels, and emergency purchases are considered in the first model. The simulation-optimization approach was used to solve this. A bi-objective optimization model solved with the epsilon-constraint method is the second model. In this model by determining the maximum acceptable expiration date, the total amount of expired medicines will be minimized. Orjuela-Castro et al. [18] formulated a deterministic multi-objective linear programming model for food security dimensions of the biodiesel supply chain (BSC) in Colombia. Their model considered economic and environmental aspects. The model aims to minimize total cost, emissions of greenhouse gases, and impact on food security. To solve the multi-objective model Epsilon-constraint method is employed. This solution approach offered a Pareto set of optimal solutions to get trade-offs between the three objectives. Tavana et al. [19] developed an integrated location-inventory-routing humanitarian logistic supply chain network and included pre- and post-disaster management considerations. The multi-echelon model was designed for the location of central warehouses, managing the perishable products inventory, and routing the relief vehicles. To solve this mixed integer linear programming problem an epsilon-constraint method and a non-dominated sorting genetic algorithm (NSGA-II) are proposed. Fakhrzad and Lotfi [20] addressed the issue of green backorder vendor-managed inventory in the supply chain. They introduced a model which is non-convex and non-linear and has two objective functions. To solve the small size of the problem epsilon-constraint and for large scale, a non-dominated sorting genetic algorithm (NSGA-II) is used.

Perez Loaiza et al. [21] designed a model for supply chains considering location-inventory decisions and supplier selection. To solve the mixed-integer nonlinear programming model a metaheuristic based on a multi-objective evolutionary algorithm is presented. The objectives are conflict and include minimizing total costs and maximizing a combined value of overall equipment effectiveness from suppliers. Small- and medium-sized scenarios are solved and compared with Pareto fronts obtained with commercial optimization software applying the epsilon-constraint method. Olivares-Benitez et al. [22] considered a two-echelon single-product supply chain network and designed a bi-objective mixed-integer program model. In each echelon, several transportation channels with different transportation costs and times are available between nodes. Objective functions are transportation costs and time. An implementation of the classic epsilon-constraint method was used to generate Pareto fronts for small scenarios of the problem, and approximate efficient sets for larger examples. Govindan et al. [23] studied the tire and plastic goods manufacturers’ supply chain by applying genetic algorithm (GA) and particle swarm optimization (PSO) techniques. Multi-objective linear programming turned into a one-objective problem using the additive weighing method and was solved by GAMS software.

Table 1 presents a summary of the literature review on the recent supply chain network design. This review shows some research gaps in the literature for the CMSCs solution approach. The table shows the combination of epsilon-constraint and genetic algorithm methods in four cases that are not CMSC problems. In the case of CMSC problems, just one of the methods has been used separately. According to the literature review, no research has been found that uses the combination of epsilon-constraint and genetic algorithm (NSGA-II) solving methods, for small and large problems in the circular manufacturing supply chain. Considering such problems in large dimensions are in the category of NP-hard problems and accurate methods are not able to find the solution at the proper time and cost. Therefore, in this research appropriate solution method to solve CMSC problems in small and large dimensions is presented which is a combination of epsilon-constraint and genetic algorithm methods.

Table 1. Existing literature on supply chain network design and the proposed solution approach

Authors	CMSC	Other types of SC	Epsilon-constraint method	NSGA-II	Other solution approaches
Govindan et al. (2023)	✓		✓		
Erdoğan et al. (2023)		✓	✓		✓
Dastani et al. (2022)		✓	✓		
Lotfi et al. (2022)	✓				✓
Govindan et al. (2022)			✓		✓
Goudarzi et al. (2022)		✓	✓		✓
Ghasemi et al. (2022)			✓	✓	
Fasihi et al. (2021)		✓	✓		
Bala and Aberdeen (2021)	✓		✓		
Lahri et al. (2021)		✓	✓		
Moslehi et al. (2021)		✓	✓		
Pahlevan et al. (2021)		✓	✓		✓
Franco and Alfonso-Lizarazo (2020)		✓	✓		
Orjuela-Castro et al. (2019)		✓	✓		✓
Fakhrzad and Lotfi (2018)		✓	✓	✓	
Tavana (2018)		✓	✓	✓	
Loaiza et al. (2016)		✓	✓		
Olivares-Benitez et al. (2013)		✓	✓		
Govindan et al. (2009)		✓		✓	
Jaferi et al. (in press)	✓				✓
This study	✓		✓	✓	

3. Research Method

Consumerism and variety-seeking are increasingly growing in today's societies. Supply chain designers should try to control the disadvantages of this issue, for example, some electronic devices have a short lifetime, and electronic wastes contain precious substances such as gold, silver, copper, aluminum, and also other hazardous materials [14]. The proper disposal and processing of them in the supply chain design offer considerable advantages to the environment. The authors have presented a multi-echelon, multi-product, multi-period, multi-objective mixed-integer linear programming model. The objective of this model is to design a circular closed-loop supply chain network concerning digital goods, including laptops, smart TVs, smartphones, and more. In this regard, the proposed model optimizes conflict economic, social, and environmental objectives simultaneously. The biological and tactical components is considered in programming the model. The circular manufacturing supply chain has seven echelons with environment, suppliers, manufacturers, distribution centers, collections, recycling centers and other supply chains.

3.1 Circular manufacturing supply chain structure

The structure of this supply chain is depicted in Figure 1. The assumptions considered for the model and the circular economy concepts applied in the model are as follows:

- The product has been designed based on the principles of circular economy since its inception and therefore definitely has parts and components related to the biological cycle. For example, "biodegradable (degradable) plastics" have been used in its construction. These plastics are materials that are decomposed into water, carbon dioxide, and biomass by the action of living organisms (usually microbes). Degradable plastics are usually produced with renewable raw materials, microorganisms, petrochemicals, or a combination of these three categories. In the modeling process, these components and parts (if they cannot be reused) are buried and returned to the environment.
- Technical components are used in the product and one of the various centers of the supply chain network enters the technical cycle. In a technical cycle technical components are recovered through repair, renovation, reconstruction, or recycling processes.
- It is possible to buy and sell second-hand products between customers. The products that can still be used are exchanged between customers through the sales channels of second-hand products.
- The defective parts returned from the customer to the manufacturer (at the time of request support services for specific parts), depending on the severity of the defect, may be soft recovered by the manufacturer itself or returned by the manufacturer to its supplier for hard recovery. In each of these centers, if the parts cannot be recovered, they are sent to the recycling center.
- Defective Parts returned from the customer to the manufacturer (at the time of request for support services for specific parts) are replaced with recovered and tested parts. The manufacturer is not required to replace the returned parts with new parts on the product being used by the customer.
- The products returned to the collection centers, after being separated into parts, can be returned to any of the suppliers, distributors, and recycling centers. It is also possible to sell returned products or separate parts to other supply chains.
- Products that go to the recycling center are first checked and the materials and parts related to the technical cycle are returned to the current supply chain or sold to another supply chain after recovery. Also, the materials and parts related to the biological cycle that cannot be reused are

buried and returned to the environment. Biological materials and parts which are usable return to the current supply chain network or are sold as inputs to other supply chains.

3.2 The Mathematical Modeling

A multi-objective mathematical model has been proposed for multi-period, multi-product, and multi-level circular closed-loop supply chain networks. This section introduces sets, parameters, variables, objective functions, and constraints of this mathematical model. All the sets considered in this research are: I : environmental centers set, J : supply centers set, K : manufacturing centers set, L : distribution centers set, C : a customer's set, N *:* recycling centers set, M *:* collection centers set, T *: a* set of periods, R *:* primary parts set, P *:* products set, C' *:* external supply chain set, h_r *: a* set of products that have part *r*, h'_p *: set* of parts that are used in product *p*, and K' : raw materials set.

3.3 Indices

The indices used in this mathematical model are: $i \in I$: environmental centers index, $j \in J$: supply centers index, $k \in K$: manufacturing centers index, $l \in L$: distribution centers index, $c \in C$: Index related to customers, $n \in N$: recycling centers index, $m \in M$: collection centers index, $t \in T$: Index related to periods, $r \in R$: Index related to primary parts, $p \in P$: products index, $k' \in K'$: raw materials index, $c' \in C'$: external supply chain index.

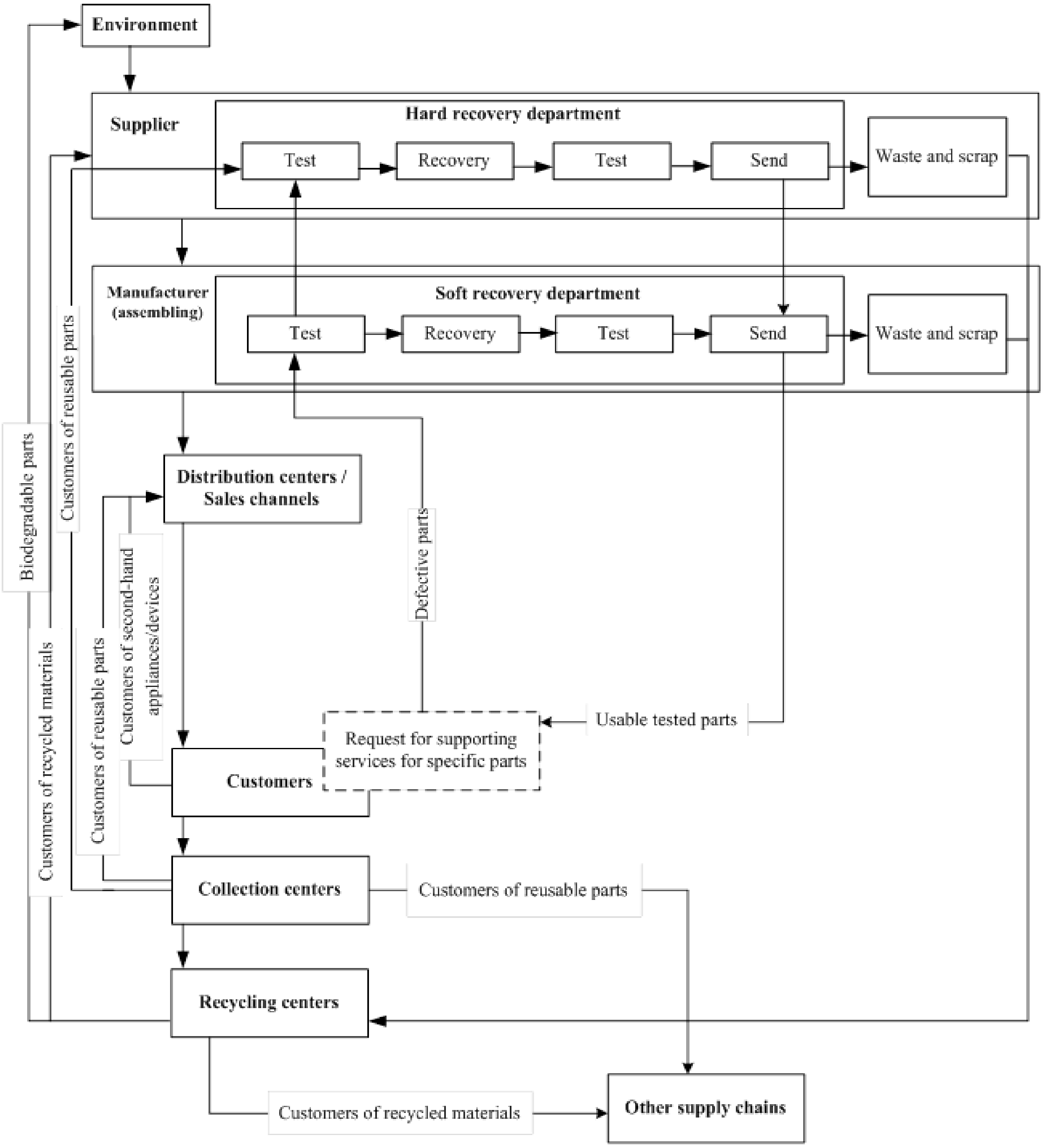

Figure 1. Structure of supply chain network

3.4 Parameters

The parameters along with symbols, descriptions, and values considered in this research are listed in Table 2.

Table 2. Predefined parameters

Symbol	Description	Value
φ_{jt}	Percentage of intact parts in supplier *j* that can be sent to other layers	Uniform [0.2;0.35]
α_{rp}	Percentage of usable products in the collection center m sent to the distributor center for functional products.	Uniform [0.1; 0.3]
α'_{rp}	Percentage of products in collection center m which is sent to the supplier for reuse by removing its parts.	Uniform [0.1;0.3]
α''_{rp}	Percentage of products in collection center m which is sent to the recycling center by separating its parts.	Uniform [0.2; 0.4]
σ_{rp}	Percentage of products in the collection center m which is sent to external customers by separating its parts.	$\alpha''_{rp}+\alpha'_{rp}+\alpha_{rp}+\sigma_{rp}=1$
$\lambda'_{rk'}$	Percentage of degradable parts that are reversible to the environment in the recycling center	Uniform [0.2; 0.3]
λ''_{r}	Percentage of degradable and usable parts for the supplier in the recycling center	$\lambda''_{rk'}+\lambda'_{rk'}=1$
η_{rp}	Percentage of *r* parts removed per each unit of product *p* in the collection center	Uniform [0.1; 0.3]
θ_{p}	Percentage of environmental damage for production of each product *p* in production centers	Uniform [0.2; 0.3]
$\theta'_{k'}$	Percentage of environmental damage for production of raw material k' in the recycling center	Uniform [0.2; 0.3]
θ''_{r}	Percentage of environmental damage for production of each part *r* in the supplier center	Uniform [0.2; 0.3]
$\psi_{k'r}$	Percentage of production of the *r*-the part for each unit of k' -th raw materials	Uniform [0.4; 0.5]
$capF_{kpt}$	The capacity of manufacturer *k* from product *p* at time *t*	Uniform [1500; 2500]
$capS_{jrt}$	The capacity of supplier from product *r* at time *t*	Uniform [1200; 2500]
$capD_{lpt}$	The capacity of distributor *l* from product *p* at time *t*	Uniform [1000; 2000]
$CapM_{mrt}$	Maximum capacity of collection center m for product *r* at time *t*	Uniform [1100; 2200]
$capN_{nk't}$	Maximum capacity of the *n*-th collection center m for raw materials k' at time *t*	Uniform [1100; 2100]
UU_{t}	Maximum number of manufacturers in the *t*-th period	Round [Uniform[2; 2]]
UU'_{t}	Maximum number of suppliers in the *t*-th period	Round [Uniform[2; 2]]
UU_{t}''	Maximum number of distributors in the *t*-th period	Round [Uniform[2; 2]]
ε_{p}	Percentage of products that remain intact during manufacturing.	Uniform [0.1; 0.4]
CBS_{jrt}	Cost of stock shortage of part *r* at *j*-th supplier at time *t*	Uniform [1000; 2000]
CBF_{kpt}	Costs of stock shortage of product *p* in manufacturer *k* at time *t*	Uniform [1100; 2100]
CBD_{lpt}	Costs of stock shortage of product in distributor *l* at time *t*	Uniform [1200; 2200]
CIF_{kpt}	Costs of stock maintenance of product *p* in producer *k* at time *t*	Uniform [110; 201]
CIS_{jrt}	Costs of stock maintenance of part *r* in supplier *j* at time *t*	Uniform [100; 200]
CID_{lpt}	Costs of stock maintenance of product *p* in distributor *l* at time *t*	Uniform [310; 341]
$Cz_{ijk't}$	Cost of transferring the k' -th raw material from environmental centers *i* to supplier j at time *t*	Uniform [120; 220]
Cx'_{mjrt}	Cost of transferring the *r*-th part from the m-th collection center to the *j*-th supply center in period *t*	Uniform [140; 240]
$CD''_{njk't}$	Cost of transferring the k' -th raw material from the *n*-th recycling center to the *j*-th supply center in period *t*	Uniform [130; 230]

Symbol	Description	Value
Cy_{klpt}	Cost of transferring the *p*-th product from the *k*-th factory to the *I*-th distributor in the period *t*	Uniform [140; 240]
cxx'_{kcrt}	Cost of transferring the *r*-th part from the *k*-th factory to the *c*-th customer in period *t*	Uniform [150; 250]
Cxx_{kjrt}	Cost of transferring the *r*-th part from the *k*-th factory to the *j*-th supply center in period *t*	Uniform [150; 250]
Cx_{jkrt}	Cost of transferring the *r*-th part from the *j*-th supply center to the *k*-th factory in period *t*	Uniform [160; 260]
CC_{kpt}	Cost of defective products *p* to be sent to recycling centers in manufacturer *k* are produced.	Uniform [180; 28000]
$CDD_{nc'k't}$	Cost of transferring the k' -th raw material from the *n*-th recycling center to the c' -th external customer in period *t*	Uniform [110; 240]
$IDD_{nc'k't}$	Income of transferring the k' -th raw material from the *n*-th recycling center to the c' -th external customer in period *t*	Uniform [123; 235]
$CDM_{mc'rt}$	Cost of transferring the *r*-th part from the *M*-th collection center to the c' -th external customer in period *t*	Uniform [156; 275]
$IDM_{mc'rt}$	Income from the quantity of transferring the *r*-th part from the *M*-th collection center to the c' -th external customer in period t	Uniform [140; 289]
cq_{lcpt}	Cost of transferring the quantity of product *p* that customer *c* receives from distribution center *l* at time *t*	Uniform [185; 275]
cqq_{clpt}	Cost of transferring the quantity of returned product *p* that customer *c* sends to distribution center *l* at time *t*	Uniform [285; 375]
cqq''_{ckrt}	Cost of the quantity of returned product *p* that customer *c* sends to manufacturing center *k* at time *t*	Uniform [205; 305]
$CIN_{nk't}$	Cost of stock of raw material k' in the *n*-th recycling center in the *t*-th period	Uniform [245; 325]
$CBN_{nk't}$	Cost of shortage of raw material k' in the *n*-th recycling center in the *t*-th period	Uniform [265; 395]
CIM_{mrt}	Cost of stock of the *r*-th part in the *m*-th collection center in the *t*-th period	Uniform [275; 385]
CBM_{mrt}	Cost of shortage of the *r*-th part in the *m*-th collection center in the *t*-th period	Uniform [175; 185]
D_{cpt}	Forward demand of customer c from the *p*-th product in the *t*-th period	Round [Uniform[10; 45]]
$D1'_{cpt}$	Reverse demand of customer *c* from the *p*-th product in the *t*-th period	Round [Uniform[10; 45]]
$capzz_{jrt}$	Maximum capacity of manufacturing raw material *r* at the supplier *j* location at time *t*	Uniform [100; 450]
czz_{jrt}	Cost of manufacturing raw material *r* at the supplier *j* location at time *t*	Uniform [10000; 450000]
CDx_{mnrt}	Cost of transferring the *r*-th part from the *m*-th collection center to the *n*-th recycling center in period *t*	Uniform [200; 450]
τ_{cpt}	Percentage of returned product *p* that is sent from customer *c* to collection center sent in period *t*	Uniform [0.1; 0.2]
$CDN_{nik't}$	Cost of raw material k' from the *n*-th recycling center to the *j*-th supplier in period *t*	Uniform [300; 450]
τ''_{cpt}	Percentage of returned product *p* sent from customer *c* to distribution centers in period *t*	Uniform [0.2; 0.25]
τ'_{crpt}	Percentage of the returned product of parts *r* from product *p* sent from customer *c* to factory centers in period *t*	Uniform [0.15; 0.3]
$cbdm_{cmpt}$	Cost of returned product from customer *c* to collection center m in period *t*	Uniform [100; 450]
π_{lt}	Unemployment rate reduction in region *L* if a distribution center is established in that region	Uniform [0.1; 0.15]
π'_{kt}	Unemployment rate reduction in region *K* if manufacturing is established in that region	Uniform [0.12; 0.18]

Symbol	Description	Value
π''_{jt}	Unemployment reduction rate in region *j* if a supply center is established in that region	Uniform [0.22; 0.29]
MM	It is a very large scalar	

3.5 Variables

All variables considered for this problem are defined as follows. Two types of continuous positive and binary variables have been used in this mathematical model. The following continuous positive variables are presented:

All variables in this category are continuous in the range of larger than or equal to zero ≥ 0. yy'_{jnrt} : quantity of transferring the *r*-th part from the *j*-th supply center to the *n*-th recycle center in period *t*. IS_{jrt} : stock of part *r* in supplier *j* at time *t*, IF_{kpt} : stock of product *p* in manufacturer *k* at time *t*, ID_{lpt} : stock of product *p* in manufacturer *k* at time *t*, BS_{jrt} : shortage of part *r* in supplier *j* at time *t*, BF_{kpt} : shortage of product *p* in manufacturer *k* at time *t*, BD_{lpt} : shortage of product *p* in distributor *l* at time *t*, xx_{kjrt} :value of transferring the *r*-th part from the *k*-th factory to the *j*-th supply center in period *t*, x_{jkrt} : value of transferring the *r*-th part from the *j*-th supply center to the *k*-th factory in period *t*, xx'_{kcrt} : value of transferring the *r*-th part from the *k*-th factory to the *c*-th customer in period *t*, x'_{mjrt} : value of transferring the *r*-th part from the *m*-th collection center to the *j*-th supply center in period *t*, y_{klpt} : value of transferring the *p*-th product from the *k*-th factory to the *l*-th distributor in period *t*, yy''_{mlrt} value of transferring the *r*-th part from the *m*-th collection center to the *l*-th distributor center in period *t*, $D''_{njk't}$: value of transferring the k' -th raw material from the *n*-th recycling center to the *j*-th supply center in period *t*, $DD_{nc'k't}$: value of transferring the *r*-th part from the *n*-th recycling center to the c' -th external customers in period *t*, $DM_{mc'rt}$: value of transferring the *r*-th part from the *m*-th collection center to the c' -th external customers in period *t*, q_{lcpt} : value of product *p* that customer c receives distributor center *l* at time *t*, qq_{clpt} :value of returned product *p* that is sent from customer *c* to distributor center *i* at time *t*, qq''_{ckrt} : value of returned product *p* sent from customer *c* to manufacturer *k* at time *t*, $z_{ijk't}$: value of transferring the k' -th raw material from the *i*-th environmental centers to the *j*-th supply center in period *t*, $IN_{nk't}$: stock of raw material k' in the *n*-th recycle center in the *t*-th period, $BN_{nk't}$: shortage of raw material k' in the *n*-th recycling center in the *t*-th period, IM_{mrt} : stock of the *r*-th part in the *m*-th collection center in the *t*-th period, BM_{mrt} : shortage of the *r*-th part in the *m*-th collection center in the *t*-th period, zz_{jrt} : value of manufacturing raw material *r* at location of supplier *j* at time t, $DN_{nik't}$: value of raw material k' from the *n*-th recycling center to supplier *j* in period *t*, Dx_{mnrt} : value of transferring the *r*-th part from the *m*-th collection center to the *n*-th recycling center in period *t*, bdm_{cmpt} : value of returned product from customer *c* to collection center m in period *t*.

3.6 Binary variables

All variables in this category belong to the set {0; 1..}. q''_{lt}: If the distribution center *l* is open at time *t*, it is one, otherwise zero, qq'_{kt}: If the manufacturing center k is open at time *t*, it is one, otherwise zero, q'_{jt} : If the supply center *j* is open at time *t*, it is one otherwise zero.

3.7 Objective functions

The economic, environmental, and social aspects are common in the circular economy and sustainability. These three aspects are considered to introduce objective functions. Minimizing the cost of the supply chain is the first objective function that covers the economic aspect. Minimizing the undesirable environmental effects of the supply chain is the second objective function that covers the environmental aspect. Finally, the third objective function maximizes the total rate of unemployment reduction if a center is established in the region. In the following sections, the equations for each of the objective functions are presented.

3.8 Economic aspect

Equation (A1) calculates stock maintenance costs and shortages in the supplier, manufacturer, and distributor layers.

$$A1=\sum_{j\in J}\sum_{r\in R}\sum_{t\in T}CBS_{jrt}.BS_{jrt}+\sum_{k\in K}\sum_{p\in P}\sum_{t\in T}CBF_{kpt}.BF_{kpt}+\sum_{l\in L}\sum_{p\in P}\sum_{t\in T}CBD_{lpt}.BD_{lpt}$$
$$+\sum_{j\in J}\sum_{r\in R}\sum_{t\in T}CIS_{jrt}.IS_{jrt}+\sum_{k\in K}\sum_{p\in P}\sum_{t\in T}CIF_{kpt}.IF_{kpt}+\sum_{l\in L}\sum_{p\in P}\sum_{t\in T}CID_{lpt}.ID_{lpt}+\sum_{c\in C}\sum_{p\in P}\sum_{m\in M}\sum_{t\in T}bdm_{cmpt}.Cbdm_{cmpt}$$

Equation (A2) calculates the transfer costs from the supplier to other layers and from different layers.

$$A2=\sum_{i\in I}\sum_{j\in J}\sum_{r\in R}\sum_{t\in T}Cz_{ijk't}.z_{ijk't}+\sum_{n\in N}\sum_{j\in J}\sum_{k'\in K'}\sum_{t\in T}CD''_{njk't}.D''_{njk't}$$
$$+\sum_{m\in M}\sum_{j\in J}\sum_{r\in R}\sum_{t\in T}Cx'_{mjrt}.x'_{mjrt}+\sum_{j\in J}\sum_{r\in R}\sum_{t\in T}zz_{jrt}.czz_{jrt}$$

Equation (A3) calculates the transfer cost from the manufacturer to the supplier, customer, distribution center and recycling center, and customer to the manufacturer.

$$A3=\sum_{k\in K}\sum_{l\in L}\sum_{t\in T}\sum_{p\in P}y_{klpt}.Cy_{klpt}+\sum_{k\in K}\sum_{c\in L}\sum_{t\in T}\sum_{p\in P}xx'_{kcrt}.Cxx'_{kcrt}+\sum_{k\in K}\sum_{j\in J}\sum_{t\in T}\sum_{r\in R}x_{jkrt}.Cx_{kjrt}$$
$$+\sum_{k\in K}\sum_{j\in J}\sum_{t\in T}\sum_{r\in R}xx_{kjrt}.Cxx_{kjrt}+\sum_{k\in K}\sum_{p\in P}\sum_{t\in T}\sum_{r\in R}CC_{kpt}(1-\varepsilon_p).(\sum_{r\in h'_p}\eta_{rp}.(\sum_{j\in J}x_{jkrt}+\sum_{c\in C}qq''_{ckrt}).$$

Equation (A4) calculates the income and cost of sending parts to external customers from collection and recycling centers.

$$A4=\sum_{n\in N}\sum_{k\in K'}\sum_{t\in T}\sum_{c'\in C'}DD_{nc'k't}.(CDD_{nc'k't}-IDD_{nc'k't})+\sum_{c'\in C}\sum_{m\in M}\sum_{p\in P}\sum_{t\in T}DM_{mc'rt}.(CDM_{mc'rt}-IDM_{mc'rt})$$

Equation (A5) calculates the shipping cost to customers.

$$A5=\sum_{p\in P}\sum_{t\in T}\sum_{c\in C}\sum_{l\in L}[(q_{lcpt}.Cq_{lcpt})+(qq_{clpt}.Cqq_{clpt})]+\sum_{c'\in C}\sum_{r\in R}\sum_{t\in T}\sum_{k\in K}qq''_{ckrt}.Cqq''_{ckrt}$$

Equation (A6) calculates shortage and stock costs in collection and recycling centers.

$$A6=\sum_{n\in N}\sum_{k'\in K'}\sum_{t\in T} IN_{nk't}CIN_{nk't}+\sum_{n\in N}\sum_{k'\in K'}\sum_{t\in T} BN_{nk't}CBN_{nk't}+\sum_{m\in M}\sum_{r\in R}\sum_{t\in T} IM_{mrt}.CIM_{mrt}+\sum_{m\in M}\sum_{r\in R}\sum_{t\in T} BM_{mrt}.BIM_{mrt}$$

3.9 Environmental aspect

$$B1=\sum_{n\in N}\sum_{k\in k'}\sum_{t\in T}(\sum_{c'\in C'} DD_{nc'k't}+\sum_{j\in J} D''_{njk't}).\theta'_{k'}-\sum_{r\in R}\sum_{k'\in K'}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}[(DX_{mnrt}).\lambda'_{rk'}]$$

$$B2=\sum_{k\in K}\sum_{p\in P}\sum_{t\in T}(\sum_{r\in h'_p}\eta_{rp}.(\sum_{j\in J} x_{jkrt}+\sum_{c\in C} q''_{ckrt}).(\theta_p)$$

$$B3=\sum_{j\in J}\sum_{r\in R}\sum_{t\in T}(\sum_{k\in K} xx_{kjrt}+\sum_{m\in M} x'_{mjrt}+[(\sum_{i\in I} z_{ijk't}+\sum_{n\in N} D''_{njk't})\psi_{k'r}])).(\theta''_r)$$

B_1, B_2, B_3 calculates the amount of environmental damage in the recycling, manufacturer and Supplier centers.

3.10 Social aspect

If a distribution center, a manufacturing center (factory), and a supply center are established, it will socially affect job creation. Therefore, it will affect the unemployment rate. Consequently, we calculate this concept by summing the C1, C2, and C3 Equations.

$$C1=\sum_{l\in L}\sum_{t\in T}\pi_{lt}.q''_{lt}$$

$$C2=\sum_{k\in K}\sum_{t\in T}\pi'_{kt}.qq'_{kt}$$

$$C3=\sum_{j\in J}\sum_{t\in T}\pi''_{jt}.q'_{jt}$$

C1, C2, and C3 calculate the total rate of unemployment reduction if a distribution center is established in region *L, and* factory center is established in region *k and a* supply center is established in region j, respectively.

3.11 Constraints

$$IS_{jrt}-BS_{jrt}=IS_{jrt-1}-BS_{jrt-1}+(\varphi_{jt}).[(\sum_{i\in I} z_{ijk't}+\sum_{n\in N} D''_{njk't})\psi_{k'r}] \qquad \forall\ \ j\in J, r\in R, t\in T \tag{1}$$

$$+\sum_{m\in M} x'_{mjrt}+\sum_{k\in K} xx_{kjrt}-\sum_{k\in K} x_{jkrt}$$

$$\sum_{j\in J} D''_{njk't}+\sum_{c'\in C'} DD_{nc'k't}+\sum_{i\in I} DN(n,i,k',t)\leq \tag{۲}$$

$$\sum_{r\in R}(\sum_{m\in m}(DX_{mnrt}.\lambda'_{rk'})+\sum_{j\in J}\sum_{r\in R}(1-\varphi_{jt}).[\sum_{k\in K} x_{jkrt}+zz_{jrt}+\psi_{k'r}(\sum_{i\in I} z_{ijk't}+\sum_{n\in N} D''_{njk't-1})]$$

$$+\sum_{k\in K}\sum_{r\in R}\sum_{p\in h_r}(1-\varepsilon_p).(\sum_{r\in h'_p}\eta_{rp}.(\sum_{j\in J} x_{jkrt}+\sum_{c\in C} qq''_{ckrt}))$$

$$\forall\ \ n\in N, k'\in K', t\in T$$

$$qq''_{ckrt}=xx'_{kcrt} \qquad \forall\ \ k\in K, r\in R, t\in T, c\in C \tag{3}$$

$$\forall \ \ m \in M\,, p \in P,\ t \in T\ \sum_{j \in J} x'_{mjrt} \le \sum_{p \in h_r} \alpha'_{rp}.(\tau_{rp}.\sum_{c \in C} D_{cpt}) \tag{4}$$

$$\forall \ \ m \in M\,, p \in P,\ t \in T\ \ \ \sum_{l \in L} yy''_{mlpt} \le \alpha_{rp}.(\tau_{rp}.\sum_{c \in C} D_{cpt}) \tag{5}$$

$$\sum_{c'} DM_{mc'rt} \le \sigma_{rp}.(\tau_{rp}.\sum_{c \in C} D_{cpt}) \quad \forall \ \ m \in M\,, p \in P,\ t \in T \tag{6}$$

$$\begin{aligned} IF_{kpt} - BF_{kpt} &= IF_{kpt-1} - BF_{kpt-1} + \varepsilon_p.(\sum_{r \in h'_p} \sum_{p \in P} \ \eta_{rp}.(\sum_{j \in J} x_{jkrt} + \sum_{c \in C} q''_{ckrt})) \\ &- \sum_{l \in L} y_{klpt} - \sum_{c \in C} \sum_{r \in R} xx'_{kcrt} - \sum_{j \in J} \sum_{r \in R} xx_{kjrt} \\ &\forall \ \ k \in K\,, p \in P,\ t \in T \end{aligned} \tag{7}$$

$$\begin{aligned} ID_{lpt} - BD_{lpt} = ID_{lpt-1} - BD_{lpt-1} + (\sum_{c \in C} qq_{clpt} + \sum_{r \in R} \sum_{m \in M} yy''_{mlpt}) - \sum_{c \in C} q_{lcpt} + \sum_{k \in K} y_{klpt} \\ \forall \ \ l \in L\,, p \in P,\ t \in T \end{aligned} \tag{8}$$

$$\sum_{l \in L} q_{lcpt} = D_{cpt} + \sum_{l \in L} qq_{clpt} \qquad \forall\ c \in C,\, p \in P, t \in T \tag{9}$$

$$\sum_{l \in L} qq_{clpt} = D_{cpt}.\tau''_{cpt} \qquad \forall\ c \in C,\, p \in P, t \in T \tag{10}$$

$$\sum_{k \in K} qq''_{ckrt} = \sum_{p \in P; h'_r} D_{cpt}.\tau_{crpt} \qquad \forall\ c \in C, r \in R, t \in T \tag{11}$$

$$ID_{lpt} \le capD_{lpt} \qquad \forall\ l \in L,\, p \in P, t \in T \tag{12}$$

$$IF_{kpt} \le capF_{kpt} \qquad \forall\ k \in K,\, p \in P, t \in T \tag{13}$$

$$IS_{jrt} \le capS_{jrt} \qquad \forall\ \ j \in J,\, p \in P, t \in T \tag{14}$$

$$\sum_{k \in K} qq'_{kt} \le UU_t \qquad \forall\ t \in T \tag{15}$$

$$\sum_{j \in J} q'_{jt} \le UU'_t \qquad \forall\ t \in T \tag{16}$$

$$\sum_{l \in L} q''_{lt} \le UU''_t \qquad \forall\ t \in T \tag{17}$$

$$\begin{aligned} &\sum_{r \in R} BS_{jrt} + \sum_{r \in R} zz_{jrt} + \sum_{n \in N} \sum_{r \in R} D''_{njrt} + \sum_{m \in M} \sum_{r \in R} x'_{mjrt} + \sum_{k \in K} \sum_{r \in R} xx_{kjrt} \\ &+ \sum_{k \in K} \sum_{r \in R} x_{jkrt} \le q'_{jt}.MM \\ &\forall\ \ j \in J, t \in T \end{aligned} \tag{18}$$

$$\sum_{p \in P} BF_{kpt} + \sum_{l \in L} \sum_{p \in P} y_{klpt} + \sum_{r \in R} \sum_{c \in C} qq''_{ckrt} + \sum_{r \in R} \sum_{c \in C} xx_{kcrt} \le qq'_{kt}.MM \qquad \forall\ k \in K, t \in T \tag{19}$$

$$\sum_{c \in C} \sum_{p \in P} q_{lcpt} + \sum_{c \in C} \sum_{p \in P} qq_{clpt} + \sum_{k \in K} \sum_{p \in P} y_{klpt} + \sum_{m \in M} \sum_{v \in V} yy''_{mlvt} \le q''_{lt}.MM \quad \forall\ l \in L, t \in T \tag{20}$$

$$\sum_{i\in I} z_{ijk't} \le \sum_{n\in N} DN(n,i,k',t-d) \qquad \forall\ k\in K, t\in T; t\ge d \tag{21}$$

$$IN_{nk't} - BN_{nk't} = IN_{nk't-1} - BN_{nk't-1} \tag{22}$$

$$\sum_{r\in R}(\sum_{m\in m}(DX_{mnrt}.\lambda'_{rk'}) + \sum_{j\in J}\sum_{r\in R}(1-\varphi_{jt}).[\sum_{k\in K} x_{jkrt} + zz_{jrt} + \psi_{k'r}(\sum_{i\in I} z_{ijk't} + \sum_{n\in N} D''_{njk't-1})]$$

$$+\sum_{k\in K}\sum_{r\in R}\sum_{p\in h_r}(1-\varepsilon_p).(\sum_{r\in h'_p}\eta_{rp}.(\sum_{j\in J} x_{jkrt} + \sum_{c\in C} qq''_{ckrt})) - \sum_{i\in I} DN_{nik't} - \sum_{c'\in C'} DD_{nc'k't} - \sum_{j\in J} D''_{njk't}$$

$$\forall\ \ n\in N, k'\in K,\ t\in T$$

$$IM_{mrt} - BM_{mrt} = IM_{mrt-1} - BM_{mrt-1} + \sum_{c\in C} bdm_{cmpt} \tag{23}$$

$$-\sum_{n\in N} dx_{mnrt} + \sum_{c'} DM_{mc'rt} + \sum_{l\in L} yy''_{mlpt} + \sum_{j\in J} x'_{mjrt}$$

$$\forall\ \ n\in N, k'\in K,\ t\in T$$

$$IM_{mrt} \le CapM_{mrt} \qquad \forall\ \ n\in N, k'\in K,\ t\in T \tag{24}$$

$$\forall\ \ n\in N, k'\in K,\ t\in T \qquad IN_{nk't} \le capN_{nk't} \tag{25}$$

$$zz_{jrt} \le capzz_{jrt}.q'_{jt} \qquad \forall\ \ j\in J, r\in R,\ t\in T \tag{26}$$

$$\sum_{n\in N} Dx_{mnrt} \le \sum_{c\in C}\sum_{p\in P}\tau_{cpt}.D_{cpt}.\alpha_{rp} \quad \forall\ \ m\in M, r\in R,\ t\in T \tag{27}$$

$$\sum_{i\in I} DN_{nik't} \le \sum_{r\in R}\lambda''_{rk'}.\sum_{m\in M} Dx_{mnrt} \ \forall\ \ n\in N, k'\in K',\ t\in T \tag{28}$$

$$\sum_{j\in J} xx_{kjrt} \le \sum_{c\in C} qq''_{ckrt} \qquad \forall\ \ k\in K, r\in R,\ t\in T \tag{29}$$

$$\sum_{l\in L} q_{lcpt} = D_{cpt} + \sum_{l\in L} qq_{clpt} \qquad \forall\ \ c\in C, p\in P,\ t\in T \tag{30}$$

$$\sum_{m\in M} bdm_{cmpt} = \tau_{cpt}.D_{cpt} \qquad \forall\ \ c\in C, p\in P,\ t\in T \tag{31}$$

Constraint 1, specifies the amount of stock in each supplier. Constraint 2, specifies the maximum amount sent from the recycling center to the supplier and external customers. Constraint 3, ensures that the return amount sent from the customer center to the distribution center must be equal to the amount sent back to the same customer. Constraints 4 and 5, determine the maximum amount of products sent from the collection center to suppliers and distributors, respectively. Constraint 6, determines the maximum amount of products sent from the collection center to external customers. Constraint 7 and 8, specifies the amount of stock in each manufacturer and distributor, respectively. Constraint 9, assigns the amount of forwarding demand to the distributor. Constraints 10 and 11, assign the amount of reverse demand to the distributor and the manufacturer, respectively. Constraint 12, 13, and 14, specifies the capacity of each distributor, manufacturer, and supplier. Constraint 15, 16, and 17, specifies the maximum number of manufacturers, suppliers, and distributors, respectively at each given time. Constraint 18, 19 and 20, determines that variables must be based on the binary variable q'_{jt} , qq'_{kt} , q''_{lt} , respectively. In this relation, MM is a large number. Constraint 21, shows the maximum amount sent from the environment to the supplier. Constraint 22 and 23, calculates the amount of stock in recycling and collection centers, respectively. Constraint 24 and 25, calculates the capacity of the stock in collection and recycling centers, respectively. Constraint 26, determines the amount of manufacturing in the supplier in terms of capacity. Constraint 27 and 28, determines the maximum amount sent from collection centers to recycling and recycling centers to environmental centers, respectively. Constraint 28, determines the maximum amount sent from recycling centers to environmental centers. Constraint 29, determines the maximum amount of returned *r*-th parts of the customer from factory centers to supply centers. Constraint 30, is the number of returns and demand to be supplied by each customer. Constraint 31, is the number of returns that enter the collection center from each customer.

4. Solution method

In the real world, optimization problems mostly are accompanied by conflicting objectives. Multi-objective optimization searches for optimal points while considering the balance between existing objectives. In general, a multi-objective optimization problem can be defined as follows:

Min $F(x)= [\ f_1(x), f_2(x), \dots, f_m(x)]$

Subject to: $X= (x_1, \dots, x_n) \in S$

Where $X= (x_1, ..., x_n)$ is the vector of decision variables and belongs to the feasible and non-zero space S. Also, the objective function vector $F: S \rightarrow R^m$, which includes m (≥ 2) objective functions. If $m = 2$, the problem is bi-objectives, and if $m \geq 3$, the problem is multi-objectives. In multi-objective problems, the set of non-dominant optimal solutions or Pareto fronts replaces the optimal solution in a single-objective problem [27]. To solve the multi-objective model many methods can be used, such as the goal programming technique, LP-metric method, epsilon-constraint method, extended weighted fuzzy approach, etc.

4.1 Epsilon constraint method

The multi-objective optimization problem is a sub-branch of multi-criteria decision-making methods. In such problems, unlike single-objective optimization problems, and due to the existence of several conflicting objectives, instead of only one solution, a set of solutions is obtained. The goal of multi-objective optimization is to find the set of Pareto (non-dominated) solutions to the given problem. As mentioned, various methods have been proposed to solve such problems. Among these various methods, the epsilon-constraint focuses on optimizing just one objective function and simultaneously other objectives are considered as constraints [5]. It was first proposed by [25]. The epsilon-constraint method is regarded as a highly effective one that can produce the exact Pareto optimal set [26]. One of the main features of this method is its application in various multi-objective optimization problems [27].

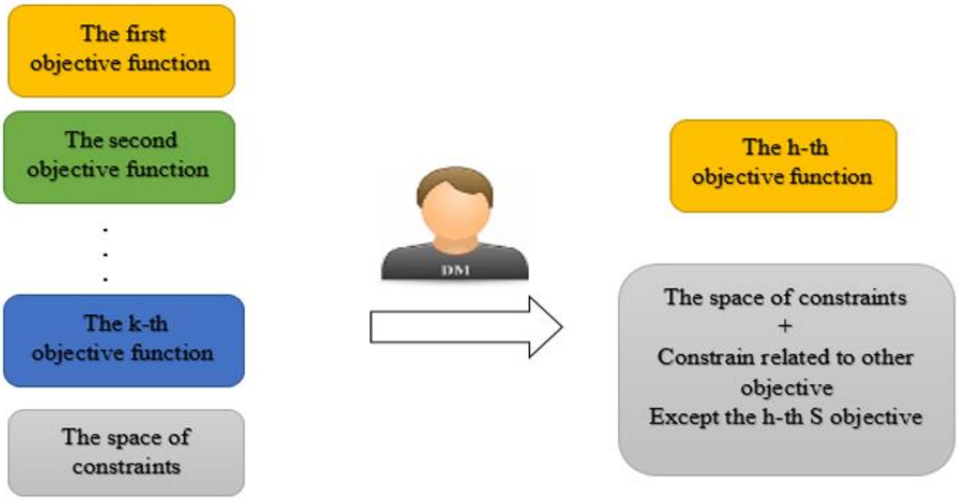

Figure 2. The general approach of the epsilon constraint method

In the following to show this method by formulas a maximization multi-objective integer programming problem is considered as follows: where k represents the number of objective functions, $z_i(x)$ the i-th objective function, $g_i(x)$ the constraint, and m the number of constraints. To convert a multi-objective to a single-objective problem, one objective is considered as the main objective (for example $Z_h(x)$) and other objective functions are considered as constraints ($Z_j(x) \leq e$).

$$\begin{array}{l} \max Z(x) = [z_1(x), z_2(x), \dots, z_k(x)] \\ g_i(x) \leq 0, \forall i = 1, 2, \dots, m \end{array} \Longrightarrow \begin{array}{l} \max z_h(x) \\ s.t. \\ g_i \leq 0, \forall i = 1, 2, \dots, m \\ z_j(x) \geq e_j, j = 1, 2, \dots, h-1, h+1, \dots, k \end{array}$$

This method is proven to provide Pareto-optimal solutions and so, fixing various values of constraint enables the Pareto front to be approximated. In SCM, this method is well adapted to the extension of a single-objective economic approach to bi-objective models integrating environmental or social criteria. Indeed, by considering the economic model as the primary objective, this approach enables decision-makers to measure the financial impact of environmental or social constraints [28].

4.2 NSGA-II

Large-scale problems with multiple objective functions and constraints are complex problems and cannot be easily solved by exact optimization algorithms. Therefore, a higher-level strategy is needed to produce solutions. This higher-level strategy is metaheuristics [29]. For complex problems, metaheuristics find near-optimal solutions more effective than classical optimization. NSGA-II is one of the well-known metaheuristic algorithms that can obtain a near-optimal solution for large-scale complex problems [30]. NSGA-II is a genetic algorithm to optimally solve multi-objective problems. This algorithm aims to produce a population of solutions. Each member of the population represents a solution for the proposed mathematical model [20]. To use the NSGA-II algorithm, first, a random population of size N is created. Other steps of this algorithm are defined according to the flowchart in Figure 3.

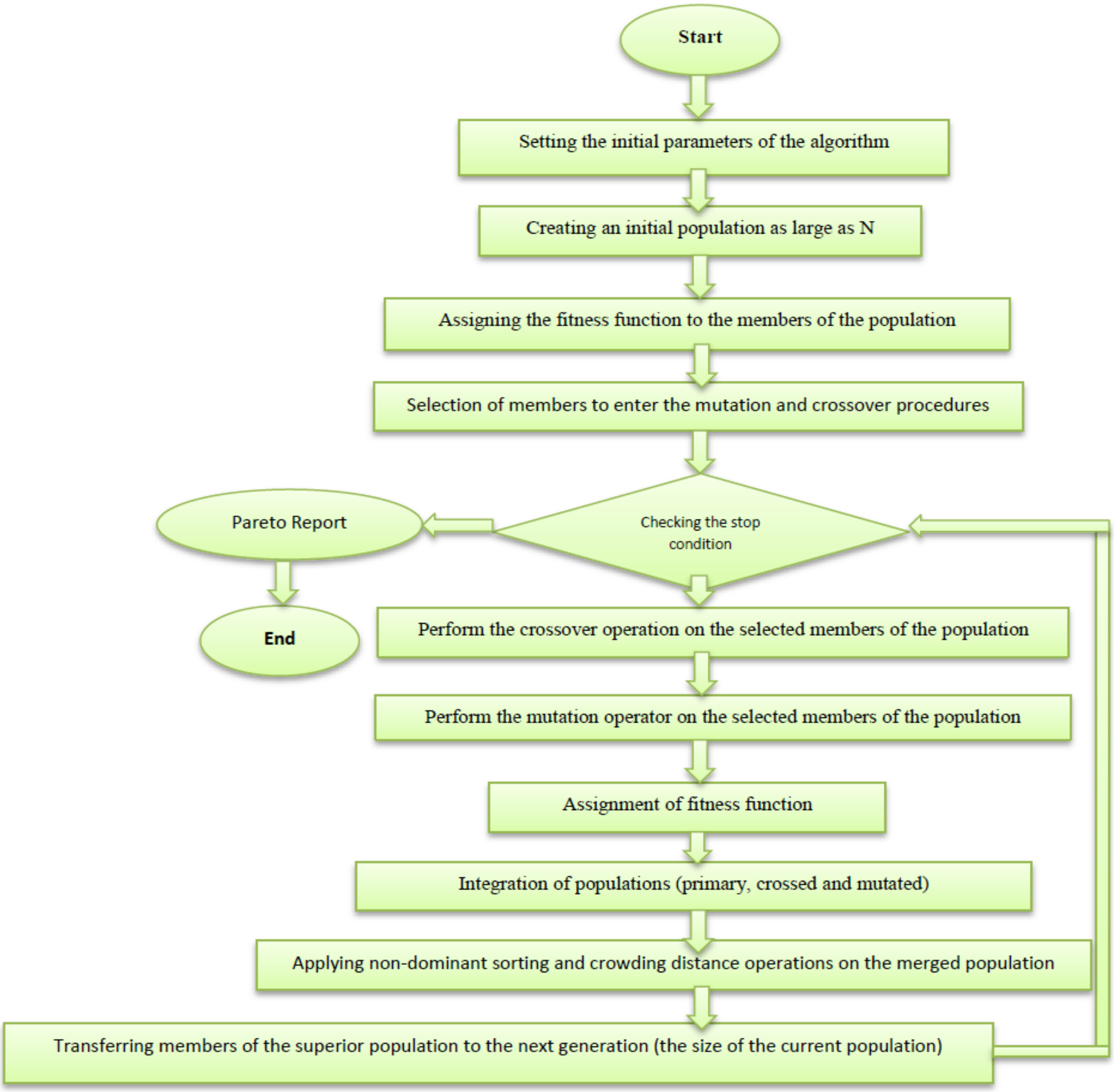

Figure 3. Genetic algorithm (NSGA-II) flowchart

The function of the NAGA-II algorithm is shown in Figure 3.

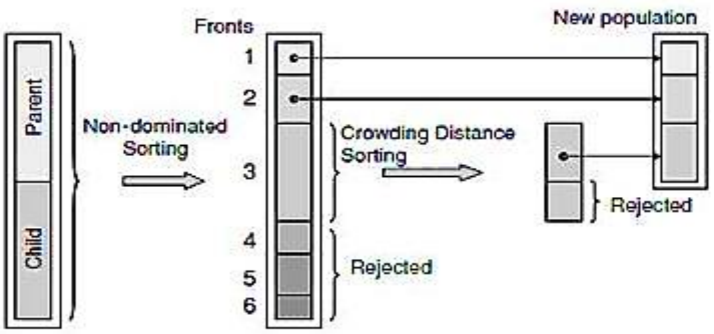

Figure 4. Schematic procedure of NAGA-II

5. Computational results

5.1 Analyzing the results of small-size problems

- Epsilon constraint results

This section highlights the results of the research. The mathematical model presented in the previous section has been formulated and implemented based on the epsilon-constrain method in GAMS v24.1 software. In this research, the first objective function is considered the main objective function, and other functions are set as constraints. Some assumptions have been considered before implementing the model. These assumptions are the number of supply centers:2, number of manufacturers: 2, distributor centers: 2, number of customers: 3, collection centers: 3, recycling centers: 2, types of raw materials: 2, number of products: 2, and number of external customers: 2. To solve, 20 sample problems have been created randomly. Therefore, Table 3 presents the payoff table results obtained, the value of the first objective function is equal to **1088214** for the best case of costs. The best environmental objective value is **99.773**. finally, the best solution offers the maximum social objective function is **1.099**.

Table 3. Payoff table

	Costs*	Environmental effects*	Social effects*
Economy objective	**1088214**	2.23E+07	2.21E+07
Environmental objective	314.349	**99.773**	134.629
Social objective	1.05	1.053	**1.099**

Pareto points are shown in Table 4. In total, 20 feasible Pareto optimal solutions are obtained. Each solution produces a different supply chain network design with relatively different objective values. Evaluation of Pareto optimal solutions is important for decision-makers. Each solution may produce different network configurations and thus, they should be well understood.

Table 4. Results of Pareto optimal solutions

Example number	**Economy objective**	**Environmental objective**	**Social objective**	**Example number**	**Economy objective**	**Environmental objective**	**Social objective**
1	1107902	271.433	1.077	**11**	1262600	228.518	1.091
2	1109523	271.433	1.08	**12**	1435641	228.518	1.099
3	1144316	271.433	1.05	**13**	1218257	185.603	1.061
4	1107135	271.433	1.066	**14**	1221180	185.603	1.077
5	1195540	271.433	1.091	**15**	1266486	185.603	1.08
6	1395510	271.433	1.099	**16**	1216635	185.603	1.05
7	1158985	228.518	1.066	**17**	1406644	185.603	1.091
8	1160607	228.518	1.077	**18**	1525360	185.603	1.099
9	1201750	228.518	1.08	**19**	1089836	314.349	1.061
10	1158985	228.518	1.066	**20**	1093386	314.349	1.077

Also, its three-dimensional Pareto front diagram is as follows:

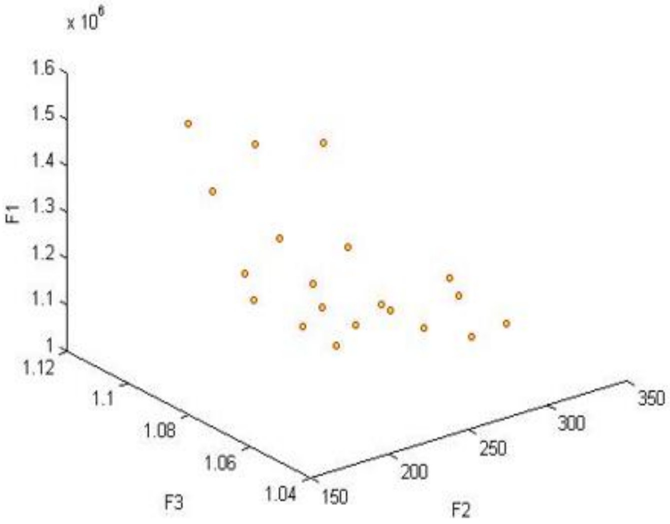

Figure 5. Pareto front diagram

- *NSGA-II algorithm results*

As stated before; by creating different numerical examples; the correct numerical mixed programming model has been formulated and implemented by GAMS v24.1 software. Likewise, MATLAB R2016a software was used to implement and run the NSGA-II algorithm. All models were run on a personal computer with an Intel Core™ i5-1.8GHz processor and memory. Internal 4GB is programmed and implemented. Adjusting the parameters of the algorithm has a significant effect on its performance and strongly affects the solution quality (best answer, solution time, etc.) of any meta-heuristic method. In this paper, the parameters of the algorithm are set by trial and error method. Parameters related to the algorithm are: maxIt=50; npop=50; pc=0.7; nc=2*round(pc*npop/2); pm=0.4; nm=round(pm*npop). To solve the problem, ۲0 sample problems have been created randomly. In Figure 6 the calculation results of the objective functions of problems are illustrated in small dimensions.

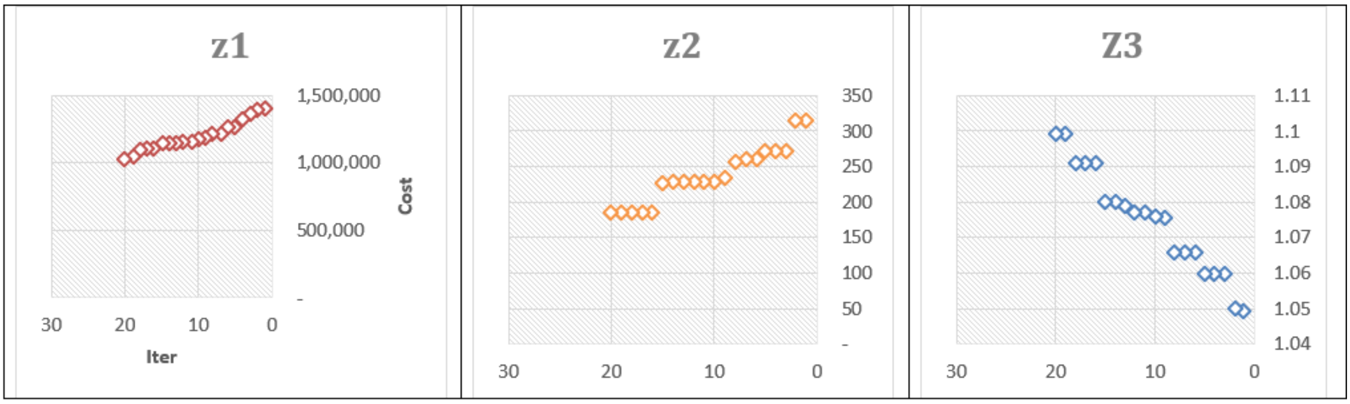

Figure 6. Algorithm results for the 20 sample problems for small problems

In addition to showing the results of the NSGA-II algorithm in Table 5, the comparison between the two methods (Epsilon-constrain method and NSGA-II algorithm) and relative cap is presented.

Table 5. Results of NSGA-II and comparison with epsilon-constraint

Problem No.	**NSGA-II**			**ε-constraint**			**Relative GAP**		
	Z1	**Z2**	**Z3**	**Z1**	**Z2**	**Z3**	**Z1**	**Z2**	**Z3**
1	1,106,600.250	260.400	1.060	1,107,901.74	271.43	1.077	0.12%	4%	1.58%
2	1,107,488.500	260.400	1.079	1,109,523.25	271.43	1.080	0.18%	4%	0%
3	1,142,351.500	271.433	1.049	1,144,315.94	271.43	1.050	0.17%	0%	0.10%
4	1,102,627.250	271.433	1.066	1,107,134.96	271.43	1.066	0.41%	0%	0%
5	1,192,111.000	271.433	1.091	1,195,540.35	271.43	1.091	0.29%	0%	0%
6	1,395,509.788	255.900	1.099	1,395,509.79	271.43	1.099	0%	6%	0%
7	1,148,911.750	228.518	1.066	1,158,985.05	228.52	1.066	0.87%	0%	0%
8	1,159,830.250	227.918	1.077	1,160,606.57	228.52	1.077	0%	0.26%	0%
9	1,174,246.250	228.518	1.080	1,201,750.23	228.52	1.080	2%	0%	0%
10	1,158,985.053	228.518	1.066	1,158,985.05	228.52	1.066	0%	0%	0%
11	1,262,600.260	228.518	1.091	1,262,600.26	228.52	1.091	0%	0%	0%
12	1,365,974.000	228.518	1.099	1,435,641.42	228.52	1.099	4%	0%	0%
13	1,217,688.000	185.603	1.060	1,218,256.71	185.60	1.061	0.05%	0%	0%
14	1,218,928.500	185.603	1.077	1,221,180.31	185.60	1.077	0.18%	0%	0%
15	1,266,486.351	185.601	1.080	1,266,486.35	185.60	1.080	0%	0%	0%
16	1,154,226.250	185.601	1.050	1,216,635.19	185.60	1.050	5%	0%	0%
17	1,406,643.948	185.602	1.091	1,406,643.95	185.60	1.091	0%	0%	0%
18	1,325,319.903	185.602	1.099	1,525,359.90	185.60	1.099	13%	0%	0%
19	1,026,270.750	314.347	1.060	1,089,835.97	314.35	1.061	6%	0%	0%
20	1,043,136.500	314.348	1.076	1,093,386.41	314.35	1.077	4%	0%	0%
Average	1,198,796.803	235.191	1.076	1,223,813.969	237.101	1.077	0.018	0.007	0.001

The average cap for the objective functions is equal to 0.018, 0.007, and 0.001 respectively. The results show a small gap between the two methods and this confirms that the NSGA-II method is reliable for solving large-scale problems.

5.2. Analyzing the results of large-size problems

In large dimensions, the period is planned to be 10 months. Also, the number of supplier and distributor centers has increased to 4 and the number of customers is considered 6. 20 large size problems were solved by implementing NSGA-II. Figure (7) shows the chart of the value obtained for each of the objective functions.

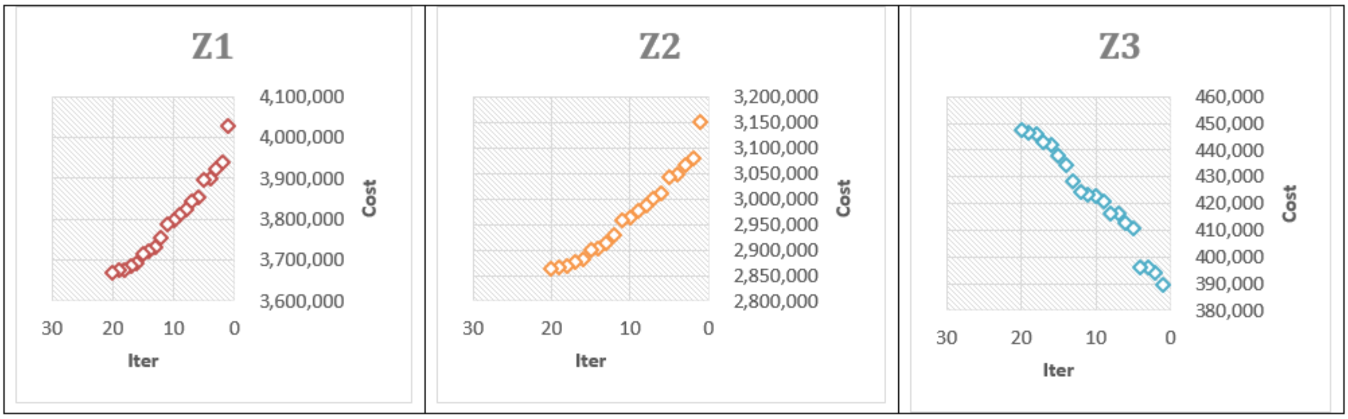

Figure 7. Algorithm results for the 20 sample problems for large problems

Table (6) provide a representation of the Pareto solutions to the large-size problem obtained through NSGA-II.

Table 6. Results of Pareto optimal solutions in lager size problem

Problem No.	**F-value**	**Problem No.**	**F-value**	**Problem No.**	**F-value**	**Problem No.**	**F-value**
1	5,987,956	**26**	6,981,268	**51**	7,261,574	**76**	7,548,225
2	5,138,460	**27**	5,862,990	**52**	6,097,117	**77**	7,233,240
3	5,746,569	**28**	7,782,442	**53**	6,273,971	**78**	6,962,722
4	6,836,133	**29**	5,332,924	**54**	7,496,986	**79**	7,257,517
5	5,716,296	**30**	6,239,928	**55**	5,380,924	**80**	5,364,067
6	5,222,794	**31**	6,197,092	**56**	7,354,701	**81**	7,312,266
7	5,802,267	**32**	5,945,051	**57**	6,691,778	**82**	5,861,507
8	5,548,625	**33**	7,266,963	**58**	7,423,046	**83**	5,756,959
9	5,648,968	**34**	5,244,429	**59**	6,889,927	**84**	5,838,573
10	5,206,393	**35**	6,732,823	**60**	6,075,928	**85**	5,579,585
11	7,271,660	**36**	5,410,224	**61**	6,720,801	**86**	6,767,933
12	6,252,354	**37**	6,549,507	**62**	6,950,792	**87**	5,688,800
13	6,536,263	**38**	6,569,831	**63**	6,022,526	**88**	7,710,777
14	7,232,172	**39**	7,534,706	**64**	6,051,688	**89**	5,837,273
15	7,009,554	**40**	7,396,124	**65**	5,611,671	**90**	7,610,655
16	5,332,048	**41**	5,864,889	**66**	6,967,346	**91**	6,766,247
17	7,694,576	**42**	7,380,440	**67**	7,736,418	**92**	6,844,123
18	6,584,878	**43**	7,512,304	**68**	7,684,928	**93**	6,950,865
19	6,197,250	**44**	7,606,029	**69**	6,710,759	**94**	5,617,856
20	6,930,770	**45**	5,926,394	**70**	7,046,852	**95**	5,480,288
21	7,201,074	**46**	6,064,531	**71**	5,159,511	**96**	7,800,478
22	6,375,411	**47**	5,772,992	**72**	6,015,909	**97**	7,269,210
23	5,345,119	**48**	7,822,455	**73**	5,592,169	**98**	7,821,987
24	5,412,612	**49**	5,444,120	**74**	5,722,522	**99**	6,884,470
25	5,931,226	**50**	6,674,138	**75**	5,257,844	**100**	7,708,872

The Pareto front chart for large-size problems is depicted in Figure 8.

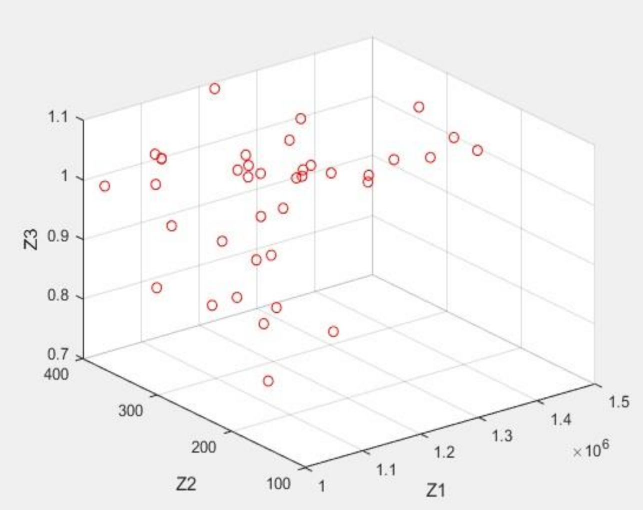

Figure 8. Pareto front diagram for large-size problem

6. Managerial insights

In this paper, a multi-period multi-echelon multi-product and multi-objective mixed integer linear mathematical programming model of circular CLSC network has been studied and solution approaches for small and large dimensions of the problem are presented. This network has been structured based on the digital devices industry. Real-world assumptions have been formulated in the proposed model to provide DMs with a decision support system. Because some technical raw materials used in the digital device industry are reusable, in the proposed model some loops to repair, remanufacture, recycle, and reuse have been designed. It leads to a reduction in resource consumption and costs. In addition to technical loops, some loops for biodegradable material have been considered and therefore, circular economy concepts have been included in the model. It causes environmental protection due to the proper management of natural resources consumption and reuse of returned or end-of-life products, so having proper solutions for this model in small and large sizes is important. The proposed solution approach allows DMs to identify the best options that include the best possible combination of economic, environmental, and social effects. On the other hand, using the epsilon-constraint method allows DMs to provide a set of efficient optimal solutions. According to the limitations and conditions of their company, DMs can choose the best solution. Given that a supply chain in the real world may have larger dimensions than what is considered in theory and such problems in large dimensions are in the category of NP-hard problems, and also accurate methods are not able to find the solution at the proper time. Therefore, an effective meta-heuristic method for finding the Pareto front in large dimensions is presented. One of the advantages of the proposed solution approach is that it does not offer just one optimal solution to DMs; it allows DMs to select the most appropriate solution from the collection of optimal solutions according to the available budget and their organization policies. This model is flexible which means that with a few changes in its structure, it can be easily employed in similar areas such as household appliance chains and industries/SCNs where recycling and waste management are important (the automotive parts manufacturing [31, 32], plastic and tire industries [33, 34].

7. Conclusion

Circular modes of production which is known as the circular economy has overcome the shortcomings of traditional linear operating models and has attracted the attention of political and business management circles. CEs have been increasingly recognized as better alternatives than the prevalent linear (take, make, dispose) economic model. Therefore, planning and implementing visions and actions are evolving toward CE principles. The field of CSCM is rapidly progressing. The term ‘circular supply chains’, is defined as the embodiment of circular economy concepts within supply chain management [35]. This study aims at presenting proper solving approaches to the proposed multi-objective mixed integer linear programming (MILP) model which is designed for a new circular closed-loop supply chain network. In this model, economic, social, and environmental objectives are considered. These objectives are contradictory. The environmental and economic function should be minimized while the social function should be maximized. The model was designed for digital devices, but can easily be applied to other types of products. It should be noted that by applying this model, in addition to considering reducing the amount of environmental damage in the recycles, manufacturers, and supplier’s centers by environmental objective in the model, the circular concept and circular loops that have been designed in the model will occur more protect to improving environmental quality. Therefore, having an optimal solution for this novel model is of particular importance.

To solve the multi-objective model and obtain an efficient optimal solution set, an the epsilon-constraint method was employed. The model was run using 20 examples to get the Pareto frontier. The Pareto optimal results extracted showed a tradeoff between economy, environment, and social objectives. Thus, for decision-makers, it is important to pay attention to these tradeoffs and make appropriate selections with their preferences. This model is in the category of NP-hard problems and it is not possible to solve it in large sizes by exact solution methods and commercial software. Therefore, a meta-heuristic NSGA-II algorithm was used to find the Pareto front for the large dimension of the problem. The comparison between the results of the epsilon-constraint method and the NSGA-II algorithm in small-size problems shows an acceptable average cap and this confirms that the NSGA-II method is reliable for solving large-scale problems and helps managers to make appropriate decisions.

There are many important aspects for future extension of this research. To develop this research, it is suggested the uncertainty be taken into account in demand and other parameters. Solving model by use of other meta-heuristic methods and comparing them. Considering other objectives in the proposed model, such as minimizing service providing time and maximizing coverage level.

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