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(Research Paper)

A Solution Approach for Optimizing a Closed-Loop Supply Chain Network Based on Circular Economy: an Application of NSGA-II Algorithm

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Abstract
In response to increasing attention to the circular economy, supply chain network design is an effective approach in which firms can integrate and allocate resources and improve their overall performance. This paper presents a multi-objective mathematical model for a multi-echelon multi-product multi-period closed-loop supply chain network, focusing on the circular economy concept. GAMS software is used to find an optimal solution for a small-size problem. However, this problem in large dimensions is included in the class of complex problems known as NP-hard, where obtaining the solution using the exact methods will be very time-consuming and sometimes impossible. Therefore, the specific development of this study is to present an application of the NSGA-II algorithm to solve the proposed model on a large scale. Some examples of small, medium and large problems are solved in 20 and 100 iterations. Then sensitivity analysis and Pareto diagram are presented. A comparison of the results obtained from the NSGA-II algorithm with the exact solution method for small-sized problems confirms the effectiveness of the

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proposed method for solving large-scale complex problems. Taking environmental and social impacts, as well as economic objectives into account, the results of this paper assist decision-makers in designing their circular supply chain network. Also, the general results of the research are practical for managers who intend to move towards a circular economy, reduce costs, and increase productivity and efficiency.

Keywords: Complex network, Supply Chain, Circular economy, Optimization, Meta-heuristic

1. Introduction

The design of an effective supply chain is one of the catalysts for economic growth and social welfare in a modern economy (Ncube et al., 2023). A supply chain includes all operations and activities required to prepare and manufacture final products from raw materials and to distribute to final customers, including materials and storage management (Zijm et al., 2019). Given that the demand for various products is constantly increasing worldwide, and because resources are limited on the planet, the consumption rate of raw materials, extracted from the earth and used to manufacture different products must be controlled and reduced. Thus, researchers have paid more attention to encompassing this matter while designing supply chains (Farooque et al., 2019).

Since a linear consumption model is no longer sustainable, circular modes of production which is known as the circular economy have overcome the shortcomings of traditional linear operating models and have attracted the attention of political and business management (Govindan et al. 2023; Saccani et al., 2023). The circular economy is a new concept for eliminating harmful environmental waste and increasing product life, and it can help in designing circular supply chains. Adopting the circular economy notion in the supply chain perspective is necessary for the sustainability viewpoint (Agarwal et al., 2023). The supply chain design process includes decisions on various aspects. A circular supply chain considers economic, environmental and social concerns through restorative and regenerative aspects (Batista et al., 2018). The closed-loop supply chain (CLSC) originates from the concept of the circular economy and its purpose is to increase efficiency and profitability by reducing waste and energy consumption (Farooque et al., 2019). A CLSC is highly recommended for dealing with environmental concerns and strict rules on reducing waste in the product lifecycle (Reimann et al., 2019).

The three methods of simulation, optimization, and meta-heuristics are used to solve supply chain problems (Ballou, 1988). Nevertheless, during the last decades, optimization has been preferred, rather than mathematical models for optimally solving complex supply chain problems (Ragsdale, 2012). Optimization finds a better answer by maximizing or minimizing an objective function. Meta-heuristic algorithms have received more attention from researchers and have been developed rapidly in the last two decades. Although the initial discussions of meta-heuristics started about 50 years ago, there has been vast development in meta-heuristic algorithms in the past 20 years (Griffis, 2012). Meta-heuristics are described as a tool to find the optimal solution. Meta-heuristics coordinate and interact with heuristics to exit from local optimums in a solution space. Meta-heuristic algorithms perform a more detailed search to find the answer. That's why, they rapidly became popular solution methods for solving complicated real-world problems (Glover and Kochenberger, 2003).

It is mathematically hard to solve large-scale problems. Also, exact algorithms behave very slowly, and they are not suitable (McMullen and Tarasewich, 2006). The traditional mathematical methods (e.g., integer, linear, mixed-integer programming, and so on), regularly are incapable of getting optimal solutions for non-convex or large-scale models (Castillo-Villar, 2014), while Meta-heuristics can reach near-optimal solution in a suitable period (Alorf, 2023). Meta-heuristic algorithms can find solutions by scanning percentages of optimal, and offer intuition into complex issues that linear programming or simulation cannot analyze. Not only do they solve large-scale problems, but also they can often discover optimal solutions to complicated problems that have non-continuous or differentiable objective functions or constraints. Meta-heuristics can create different solutions for multi-objective problems, allowing the results of such solutions to improve an efficient frontier diagram (McMullen and Tarasewich, 2006). Particularly, they can deal with complexities of real-world supply chains, including multi-objectives, multiple parameters, large size and sometimes non-linear aspects of the problems (Griffis, 2012).

While the issues of the supply chain have been widely discussed by numerous researchers, there is a serious paucity of studies about the optimization of a complicated real-world supply chain network based on circular economy aspects. Given the changing conditions of the market, it is now a must to create value in the supply chains by closing all the loops of material flows toward a zero-waste vision. Supply chain design should not merely be based on profit optimization. Instead, environmental issues should also be considered at the design level to meet the requirements of the circular economy.

With a focus on the circular economy concept, this study presented a multi-objective mathematical model for a multi-echelon multi-product multi-period closed-loop supply chain network toward a zero-waste vision. However, this problem in large dimensions is included in the class of complex problems known as NP-hard, where obtaining the solution using the exact methods will be very time-consuming and sometimes impossible. Therefore, the main contribution of this study is to present an application of the NSGA-II (non-dominated sorting genetic algorithm II) method to solve the proposed model on large scales.

The rest of this article is organized as it shows. The second section provides a literature review of previous research. In the third section, the methodology and mathematical model for supply chain structure based on circular economy is provided. In the fourth section, the solution approaches including exact and metaheuristics algorithms and also numerical results of analyzing the small/large-size problems are presented. In the fifth section, managerial insights are presented and finally, in the sixth section, a conclusion and suggestions for further research on the research topic are provided.

2. Literature review

Metaheuristic algorithms include simulated annealing, tabu search, genetic algorithms, and ant colonies. Many other algorithms have been developed based on them (Griffis et al., 2012). Faramarzi-Oghani et al. (2022) have presented a literature review about Metaheuristics algorithms and their ability to solve sustainable (forward) supply chain problems. The results showed that the number of articles using these algorithms is increasing. They also demonstrated more use of hybrid meta-heuristics than pure meta-heuristics algorithms. The most used multi-objective and single algorithms were the non-dominated sorting GA (NSGA-II) and genetic algorithm (GA).

Che and Chiang (2010) for multi-objective build-to-order supply chain (BOSC) planning, presented a modified Pareto genetic algorithm. They considered costs, quality, and delivery time as three assessment criteria and established a multi-objective optimization model for the BOSC planning. The quality of the solution was improved through modification of mutation and crossover operations. They showed that the performance of the proposed model was better than the basic models. Griffis et al. (2012) have provided information about the methods of solving supply chain problems. They outlined recent improvements in metaheuristic methods and considered the ability of these improved techniques to resolve various kinds of logistics and supply chain problems.

Olivares-Benitez Et al. (2013) to select transportation channels in a two-echelon single-product supply chain designed a bi-objective mixed-integer program. Time and cost were considered in the selection of transportation channels. An optimal solution was found by implementing a metaheuristic algorithm. The meta-heuristic algorithm provided good results for large samples. Castillo-Villar (2014) believed that bioenergy accounts for a significant part of renewable energy production in many countries. Bioenergy has many benefits, such as abundance and having no harmful emissions. That is why wide bioenergy production is expected. But there are some supply-related problems. To solve these problems, Castillo-Villar applied metaheuristic algorithms because the traditional mathematical methods could not reach optimal solutions for large-scale or non-convex models. Samanta et al. (2018) have applied a modified heuristic algorithm to optimize an allocation problem. They formulated a bi-objective dependent location quadratic allocation problem and solved it by using a modified artificial bee colony algorithm which was proposed by themselves. The obtained data demonstrated better performance compared with other optimization algorithms.

Due to the importance of medicine, failure in its supply chain will have irreparable consequences, Goodarzian et al. (2020) have investigated the supply chain in the pharmaceutical field. They proposed a new multi-objective multi-echelon multi-product multi-period pharmaceutical supply chain network. The design of the distribution and inventory system has been considered and the problem has been modeled as a fuzzy mixed-integer non-Linear programming. Different metaheuristic algorithms were applied to recognize optimal solutions and sensitivity analyses evaluated changes in input parameters.

Verma and Snasel (2021) investigated all kinds of multi-objective optimization algorithms NSGA-II, which is used for solving different problems. Three various forms of this algorithm have been mentioned and discussed considering some other techniques. The first is the original version of NSGA-II, the next is the modified NSGA-II and the last is the Hybrid NSGA-II variants. Slama et al. (2021) for a stochastic capacitated disassembly lot-sizing problem under random lead times have used the combination of genetic algorithm and Monte Carlo simulation. Optimization of whole costs was the objective function. To solve the studied problem three attitudes were extended. The results demonstrated the efficiency of their approaches. Che and Chiang al. (2021) proposed a multi-objective genetic algorithm to solve supplier selection and assembly planning problems considering capacity constraints. A multi-objective mathematical model was created to specify optimal resource allocation of product and supplier combinations. They applied the genetic algorithm to optimize this model and to enhance the quality of solutions derived from the NSGA-II.

Sadeghi et al. (2023) for inventory management of reusable products in a two-level supply chain presented a nonlinear mathematical model. Two novel metaheuristics solution approaches were used to solve the problem which are grey wolf optimizer (GWO) and whale optimization algorithm (WOA). Extensive analysis was established by solving several numerical results in different sizes and utilizing several comparison measures. Tabrizi et al. (2022) presented a paper for designing a supply chain for pharmaceutical distribution companies, resulting in the best coverage and performance at the lowest cost. The model has been solved using a two-tier genetic algorithm in combination with priority-based coding and the K-medoids clustering method. Optimal points for distribution centers were located and an optimal distribution plan for goods was recommended for a company distributing 239 types of pharmaceutical products.

Table 1. Papers reviewed in the field of supply chain network designed and solution approaches to show research cap

	authors	year	Circular supply chain	Other kinds of supply chains	NSGA-II	Other metaheuristic solution approach
1	Sadeghi et al.	2023		✓		✓
2	Tabrizi et al.	2022		✓		✓
	Faramarzi et al.	2022			✓	
3	Che et al.	2021		✓	✓	
4	Slama et al.	2021		✓		✓
5	Verma and Snasel	2021		✓	✓	
6	Goodarzian et al.	2020		✓		✓
7	Samanta et al.	2018		✓		✓
8	Castillo-Villar	2014		✓		✓
9	Olivares-Benitez Et al.	2013		✓		✓
10	Griffis et al.	2012		✓	✓	
11	Che and Chiang	2010		✓		✓
12	This article		✓		✓	

According to Table 1, previous studies have covered other kinds of supply chain problems, and none of them consider both circular supply chain problems and their solutions, simultaneously, which have been covered in this paper.

Fig. 1 illustrates the strategy of supply chain firms to integrate circular economy practices worldwide in 2019. It shows that the circular economy is a new and efficient concept.

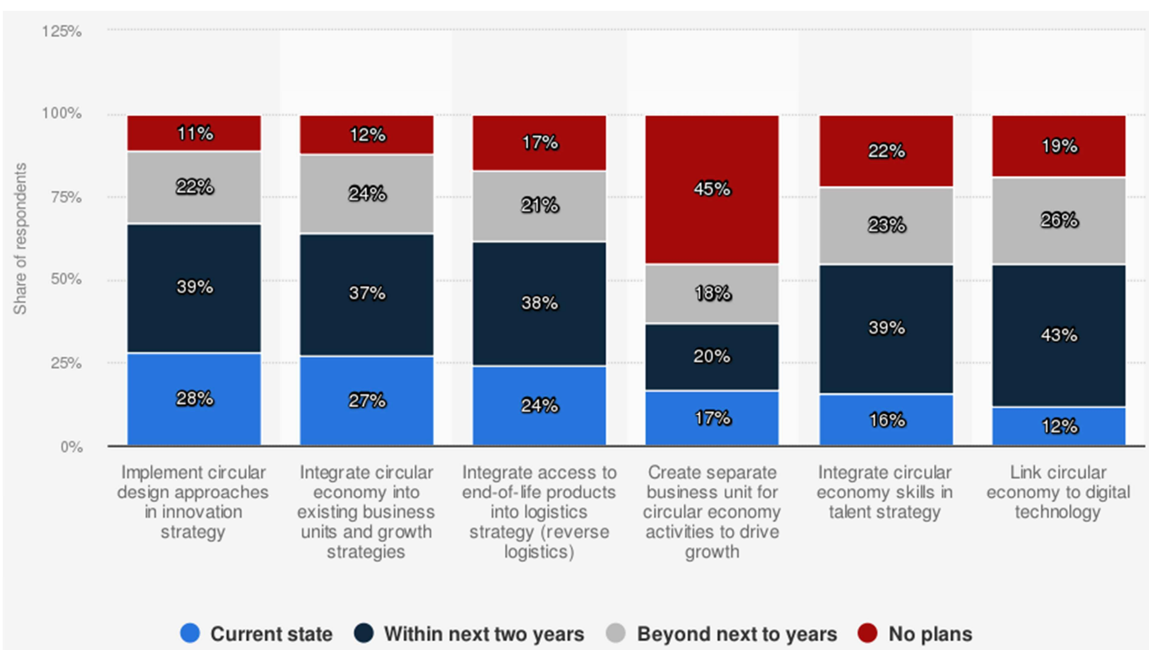

Fig. 1. Strategy of supply chain firms to integrate circular economy practices worldwide in 2019 (www.statista.com)

3. Methodology

3.1 Supply chain structure based on circular economy

An existing mathematical programming model for optimizing the closed-loop supply chain network, focusing on the circular economy concept has been investigated. The supply chain network is related to digital goods such as laptops, smart TVs, smartphones, etc. The structure of this supply chain is depicted in Fig. 2. The assumptions considered for the model and the circular economy concepts applied in the model are as follows:

- A product has been designed based on the principles of the circular economy, since its inception and therefore has parts and components related to the biological cycle.
- Technical components are used in the product and one of the various centres of the supply chain network enters the technical cycle. In a technological cycle technical components are recovered through repair, renovation, reconstruction or recycling processes.
- Customers can buy and sell second-hand products. Reusable products are exchanged among customers through second-hand product sales channels.
- 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. If the parts cannot be recovered, they are sent to the recycling centre in each of such centres.
- 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. However, the manufacturer is not required to replace the returned parts with new parts on the product being used by the customer.
- After being separated into parts, the products returned to the collection centres. Then they can be returned to any supplier, distributor, or recycling centre. The returned products can be also sold or separated into other supply chains.
- Products that go to the recycling centre 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 of the biological cycle that cannot be reused are buried and returned to the environment. The useable biological materials and parts return to the current supply chain network or are sold as inputs to other supply chains.

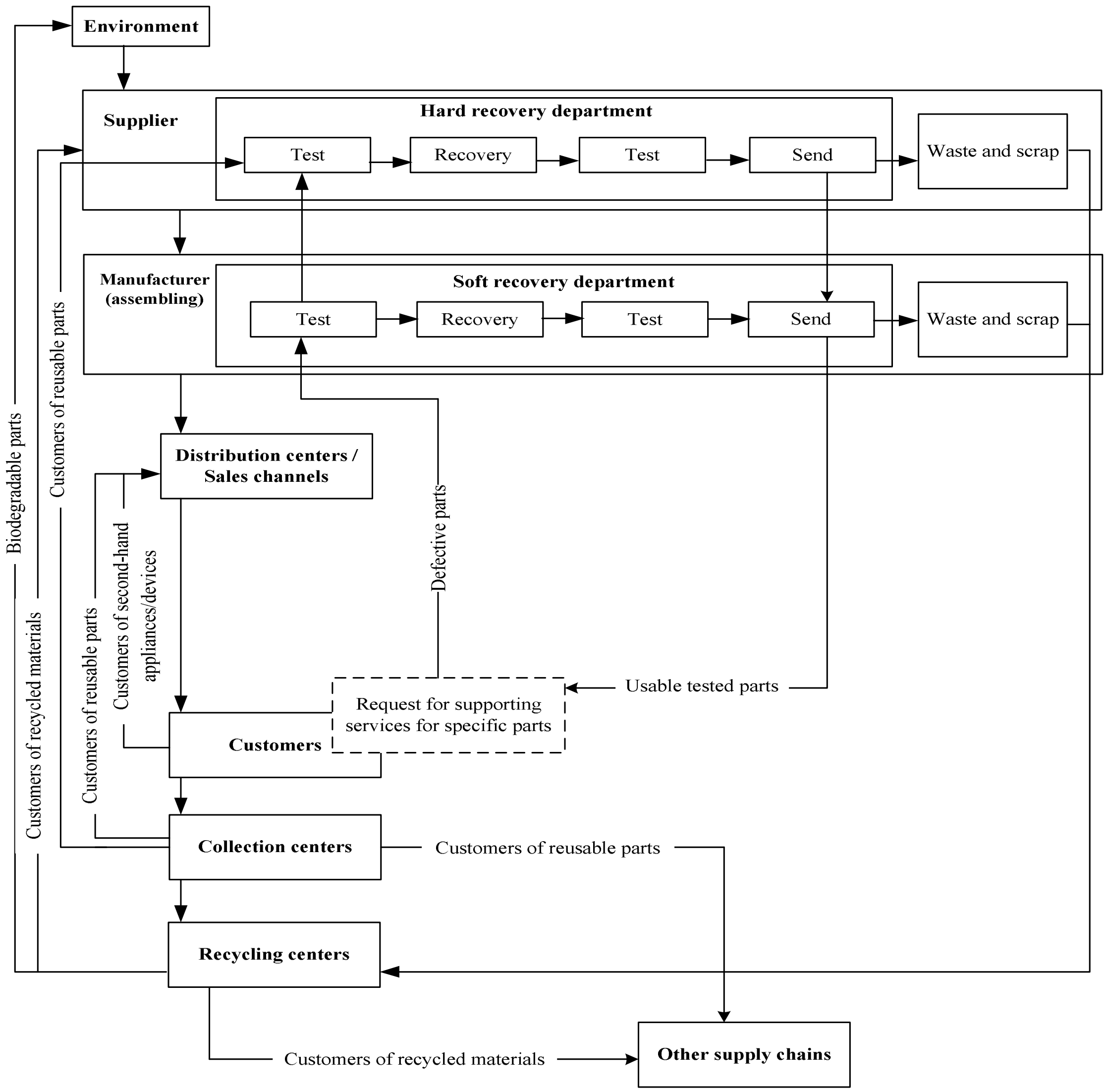

Fig. 2. Structure of the proposed supply chain network

3.2 The Mathematical Modeling

An existing multi-objective mathematical model has been investigated for multi-period, multi-product and multi-level closed-loop supply chain networks with a focus on the circular economy concept. This section introduces sets, parameters, variables, objective functions and constraints of this mathematical model.

All the sets considered in this research are I environmental centres set, J supply centres set, K manufacturing centres set, L distribution centres set, C a customer's set, N recycling centres set, M collection centres set, T set of periods, R primary parts set P , products set, C' external supply chain set, h_r set of products that have part r, h'_p set of parts that are used in product p, and K' : raw materials set.

3.2.1 Indices

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

3.2.2 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 centre 'm' sent to the distributor centre for functional products.	Uniform [0.1; 0.3]
α'_{rp}	Product (%) in collection centre 'm' sent to the supplier for reuse by removing its parts.	Uniform [0.1;0.3]
α''_{rp}	Products (%) in collection centre 'm' sent to the recycling centre and separating its parts.	Uniform [0.2; 0.4]
σ_{rp}	Products (%) in the collection centre 'm' sent to external customers and separated their 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 centre	Uniform [0.2; 0.3]
λ''_{r}	Percentage of degradable and usable parts for the supplier in the recycling centre	$\lambda''_{rk'} + \lambda'_{rk'} = 1$
η_{rp}	Percentage of *r* parts removed per each unit of product *p* in the collection centre.	Uniform [0.1; 0.3]
θ_{p}	Percentage of environmental damage for production of each product *p* in production centres	Uniform [0.2; 0.3]
$\theta'_{k'}$	Percentage of environmental damage for production of raw material k' in the recycling centre	Uniform [0.2; 0.3]
θ''_{r}	Percentage of environmental damage for production of each part r in the supplier centre	Uniform [0.2; 0.3]
γ_r	Percentage of environmental damage for disassembly of each part *r* in the collection centre	Uniform [0.2; 0.4]
$\psi_{k'r}$	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 centre m for product *r* at time *t*	Uniform [1100; 2200]
$capN_{nk't}$	Maximum capacity of the *n*-th collection centre 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]]

Symbol	Description	Value
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 mth collection centre to the *j*th supply centre in period *t*	Uniform [140; 240]
$CD''_{njk't}$	Cost of transferring the k'-th raw material from the *n*-th recycling centre to the *j*th supply centre in period *t*	Uniform [130; 230]
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 centre in period *t*	Uniform [150; 250]
Cx_{jkrt}	Cost of transferring the *r*-th part from the *j*th supply centre to the *k*th factory in period *t*	Uniform [160; 260]
CC_{kpt}	Cost of defective products 'p' to be sent to recycling centres 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 centre to the c'-th external customer in period *t*	Uniform [110; 240]
$CDM_{mc'rt}$	Cost of transferring the *r*-th part from the *M*-th collection centre to the c'-th external customer in period *t*	Uniform [156; 275]
cq_{lcpt}	Cost of transferring the quantity of product *p* that customer *c* receives from distribution centre *l* at time *t*	Uniform [185; 275]
cqq_{clpt}	Cost of transferring the quantity of returned product *p* that customer *c* sends to distribution centre *l* at time *t*	Uniform [285; 375]
cqq''_{ckrt}	Cost of the quantity of returned product *p* that customer *c* sends to manufacturing centre *k* at time *t*	Uniform [205; 305]
$CIN_{nk't}$	Cost of stock of raw material k' in the *n*-th recycling centre in the *t*-th period	Uniform [245; 325]
$CBN_{nk't}$	Cost of shortage of raw material k' in the *n*-th recycling centre in the *t*-th period	Uniform [265; 395]
CIM_{mrt}	Cost of stock of the *r*-th part in the *m*th collection centre in the *t*-th period	Uniform [275; 385]
CBM_{mrt}	Cost of shortage of the *r*-th part in the *m*th collection centre 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 centre to the *n*-th recycling centre in period *t*	Uniform [200; 450]
τ_{cpt}	Percentage of returned product *p* that is sent from customer *c* to collection centre sent in period *t*	Uniform [0.1; 0.2]

Symbol	Description	Value
$CDN_{nik't}$	Cost of raw material k' from the *n*-th recycling centre to the *j*th supplier in period *t*	Uniform [300; 450]
τ''_{cpt}	Percentage of returned product *p* sent from customer *c* to distribution centres 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 centres in period *t*	Uniform [0.15; 0.3]
$cbdm_{cmpt}$	Cost of returned product from customer *c* to collection centre m in period *t*	Uniform [100; 450]
β_{rt}	The customer satisfaction rate for part *r* from the factory to the customer centre in period *t*	Uniform [0.2;0.9]
β'_{rt}	The customer satisfaction rate for part *r* from collection centre to other supply chain in period *t*	Uniform [0.2;0.9]
$\beta''_{c't}$	The customer satisfaction rate for raw materials $'c'$ from recycling centres to another supply chain in period *t*	Uniform [0.2;0.9]
MM	It is a very large scalar.	

3.2.3 Variables

All variables considered for this problem are defined as follows. Continuous positive and binary variables are used in the mathematical model.

3.2.4 Continuous positive variables

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 centre to the *n*-th recycle centre 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*.

3.2.5 Binary variables

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

3.2.6 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. Maximizing the total rate of customer satisfaction is the first objective function that covers the social aspect. Minimizing the cost of the supply chain is the second objective function that covers the economic aspect. Finally, the third objective function minimizes the undesirable environmental effects of the supply chain. In the following sections, the equations for each of the objective functions are presented.

3.2.7 Social aspect

Equation (A1) calculates the total customer satisfaction rate for supporting services.

$$A1 = \sum_{k \epsilon K} \sum_{c \epsilon C} \sum_{r \epsilon R} \sum_{t \epsilon T} XX'_{kcrt} \cdot \beta_{rt}$$

Equation (A2) calculates the total customer satisfaction rate for the parts sent to external customers from collection centres.

$$A2 = \sum_{m\epsilon M} \sum_{c'\epsilon C'} \sum_{r\epsilon R} \sum_{t\epsilon T} DM_{mc'rt} \cdot \beta'_{rt}$$

Equation (A3) calculates the total customer satisfaction rate for sending parts to external customers from recycling centres.

$$A3 = \sum_{k\epsilon K} \sum_{c'\epsilon C'} \sum_{r\epsilon R} \sum_{t\epsilon T} DM_{kc'rt} \cdot \beta''_{c't}$$

3.2.8 Economic aspect

Equation (B1) calculates stock maintenance costs and shortages in the supplier, manufacturer, and distributor layers.

$$\begin{aligned} \mathrm{B1} = &\sum_{j\epsilon J} \sum_{r\epsilon R} \sum_{t\epsilon T} CBS_{jrt} \,.\, BS_{jrt} + \sum_{k\epsilon K} \sum_{p\epsilon P} \sum_{t\epsilon T} CBF_{kpt} \,.\, BF_{kpt} + \sum_{l\epsilon L} \sum_{p\epsilon P} \sum_{t\epsilon T} CBD_{lpt} \,.\, BD_{lpt} \\ &+ \sum_{j\epsilon J} \sum_{r\epsilon R} \sum_{t\epsilon T} CIS_{jrt} \,.\, IS_{jrt} + \sum_{k\epsilon K} \sum_{p\epsilon P} \sum_{t\epsilon T} CIF_{kpt} \,.\, IF_{kpt} \\ &+ \sum_{l\epsilon L} \sum_{p\epsilon P} \sum_{t\epsilon T} CID_{lpt} \,.\, ID_{lpt} \end{aligned}$$

Equation (B2) calculates the transfer costs from the supplier to other layers and from different layers.

$$\begin{aligned} B2 = &\sum_{i\epsilon I} \sum_{j\epsilon J} \sum_{r\epsilon R} \sum_{t\epsilon T} Cz_{ijk't} \,.\, z_{ijk't} + \sum_{n\epsilon N} \sum_{j\epsilon J} \sum_{k'\epsilon K'} \sum_{t\epsilon T} CD''_{njk't} \,.\, D''_{njk't} \\ &+ \sum_{m\epsilon M} \sum_{j\epsilon J} \sum_{r\epsilon R} \sum_{t\epsilon T} Cx'_{mjrt} \,.\, x'_{mjrt} + \sum_{j\epsilon J} \sum_{r\epsilon R} \sum_{t\epsilon T} zz_{jrt} \,.\, Czz_{jrt} \end{aligned}$$

Equation (B3) calculates the transfer cost from the manufacturer to the supplier, customer, distribution centre and recycling centre, and customer to the manufacturer.

$$\begin{aligned} B3 = &\sum_{k\epsilon K} \sum_{l\epsilon L} \sum_{t\epsilon T} \sum_{p\epsilon P} y_{klpt} \,.\, Cy_{klpt} + \sum_{k\epsilon K} \sum_{c\epsilon C} \sum_{t\epsilon T} \sum_{p\epsilon P} xx'_{kcrt} \,.\, Cxx'_{kcrt} \\ &+ \sum_{k\epsilon K} \sum_{j\epsilon J} \sum_{t\epsilon T} \sum_{r\epsilon R} x_{jkrt} \,.\, Cx_{jkrt} + \sum_{k\epsilon K} \sum_{j\epsilon J} \sum_{t\epsilon T} \sum_{r\epsilon R} xx_{kjrt} \,.\, Cxx_{kjrt} \\ &+ \sum_{k\epsilon K} \sum_{p\epsilon P} \sum_{t\epsilon T} \sum_{r\epsilon R} CC_{kpt}\,(1-\varepsilon_p).\,(\sum_{r\epsilon h'_p} \eta_{rp} \,.\, (\sum_{j\epsilon J} x_{jkrt} + \sum_{c\epsilon C} qq''_{ckrt}) \\ &+ \sum_{c\epsilon C} \sum_{p\epsilon P} \sum_{m\epsilon M} \sum_{t\epsilon T} bdm_{cmpt} \,.\, Cbdm_{cmpt} \end{aligned}$$

Equation (B4) calculates the cost of sending parts to external customers from collection and recycling centres.

$$B4 = \sum_{n\epsilon N} \sum_{k'\epsilon K'} \sum_{t\epsilon T} \sum_{c'\epsilon C'} \mathrm{DD}_{nc'k't} \,.\, CDD_{nc'k't} + \sum_{c'\epsilon C'} \sum_{m\epsilon M} \sum_{p\epsilon P} \sum_{t\epsilon T} \mathrm{DM}_{mc'rt} \,.\, \mathrm{CDM}_{mc'rt}$$

Equation (B5) calculates the shipping cost to customers.

$$B5 = \sum_{p\epsilon P} \sum_{t\epsilon T} \sum_{c\epsilon C} \sum_{l\epsilon L} [(\mathrm{q}_{lcpt} \,.\, Cq_{lcpt}) + (\mathrm{qq}_{clpt} \,.\, Cqq_{clpt})]$$

$$+ \sum_{c'\epsilon C'} \sum_{r\epsilon R} \sum_{t\epsilon T} \sum_{k\epsilon K} qq''_{ckrt} \,.\, Cqq''_{ckrt}$$

Equation (B6) calculates shortage and stock costs in collection and recycling centres.

$$B6 = \sum_{n\epsilon N} \sum_{k'\epsilon K'} \sum_{t\epsilon T} IN_{nk't} CIN_{nk't} + \sum_{n\epsilon N} \sum_{k'\epsilon K'} \sum_{t\epsilon T} BN_{nk't} CBN_{nk't}$$

$$+ \sum_{m\epsilon M} \sum_{r\epsilon R} \sum_{t\epsilon T} IM_{mrt} CIM_{mrt} + \sum_{m\epsilon M} \sum_{r\epsilon R} \sum_{t\epsilon T} BM_{mrt} CBM_{mrt}$$

3.2.9 Environmental aspect

Equation (C1) calculates the environmental damage in the collection centre.

$$C1 = \sum_{m\epsilon M} \sum_{r\epsilon R} \sum_{t\epsilon T} (\sum_{c'\epsilon C'} DM_{mc'rt} + \sum_{l\epsilon L} yy''_{mlrt} + \sum_{j\epsilon J} x'_{mjrt}).\gamma_r$$

Equation (C2) calculates the recycling centre's environmental-based damage.

$$C2 = \sum_{n\epsilon N} \sum_{k'\epsilon K'} \sum_{t\epsilon T} (\sum_{c'\epsilon C'} DD_{nc'k't} + \sum_{j\epsilon J} D''_{njk't}).\theta'_{k'} - \sum_{r\epsilon R} \sum_{k'\epsilon K'} \sum_{n\epsilon N} \sum_{m\epsilon M} \sum_{t\epsilon T} [(DX_{mnrt}).\lambda'_{rk'}]$$

Equation (C3) calculates the manufacturer's environmental-based damage.

$$C3 = \sum_{k\epsilon K} \sum_{p\epsilon P} \sum_{t\epsilon T} (\sum_{r\epsilon h'_p} \eta_{rp} \,.\, (\sum_{j\epsilon J} x_{jkrt} + \sum_{c\epsilon C} q''_{ckrt}).(\theta_p)$$

Equation (C4) calculates the suppliers' environmental-based damage.

$$C4 = \sum_{j\epsilon J} \sum_{r\epsilon R} \sum_{t\epsilon T} (\sum_{k\epsilon K} xx_{kjrt} + \sum_{m\epsilon M} x'_{mjrt} + [(\sum_{i\epsilon I} z_{ijk't} + \sum_{n\epsilon N} D''_{njk't})\psi_{k'r}])).(\theta''_r)$$

3.2.10 Constraints

Constraint (1) specifies the amount of stock in each supplier.

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

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

Constraint (2) specifies the maximum amount sent from the recycling centre to the supplier and external customers.

$$\sum_{j\in J} D''_{njk't} + \sum_{c'\in C'} DD_{nc'k't} + \sum_{i\in I} DN(n,i,k',t) \le \qquad \forall \; n\in N, k'\in K', t\in T \quad (2)$$

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

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

Constraint (3) ensures that the return amount sent from the customer centre to the distribution centre must be the same as the amount sent back to the same customer.

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

Constraint (4) determines the maximum amount of products sent from the collection centre to suppliers.

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

Equation (5) determines the maximum amount of products sent from the collection centre to distributors.

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

Constraint (6) determines the maximum amount of products sent from the collection centre to external customers.

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

Constraint (7) specifies the amount of stock in each manufacturer.

$$IF_{kpt} - BF_{kpt} = IF_{kpt-1} - BF_{kpt-1} + \varepsilon_p.(\sum_{r\in h'_p}\sum_{p\in P} \eta_{rp}.(\sum_{j\in J} x_{jkrt} + \sum_{c\in C} q''_{ckrt})) \quad \forall \; k\in K, p\in P, t\in T \quad (7)$$

$$-\sum_{l\in L} y_{klpt} - \sum_{c\in C}\sum_{r\in R} xx'_{kcrt} - \sum_{j\in J}\sum_{r\in R} xx_{kjrt}$$

Constraint (8) specifies the amount of stock in each distributor.

Constraint (9) This constraint assigns the amount of forwarding demand to the distributor.

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

Constraint (10) assigns the amount of reverse demand to the distributor.

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

Constraint (11) assigns the amount of reverse demand to the manufacturer.

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

Constraint (12) specifies the capacity of each distributor.

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

Constraint (13) specifies the capacity of each manufacturer.

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

Constraint (14) specifies the capacity of each supplier.

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

Constraint (15) specifies the maximum number of manufacturers at each time.

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

Constraint (16) specifies the maximum number of suppliers at each time.

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

Constraint (17) specifies the maximum number of distributors at each time.

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

Constraint (18), this constraint determines that variables must be based on the binary variable q'_{jt} . In this relation, MM is a large number.

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

Constraint (19), this constraint determines that variables must be based on the binary variable qq'_{kt}.

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

Constraint (20), this constraint determines the value of the variables that must be based on the binary variable q''_{lt}.

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

Constraint (21), this constraint shows the maximum amount sent from the environment to the supplier.

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

Constraint (22), this constraint calculates the amount of stock in recycling centres.

$$IN_{nk't} - BN_{nk't} = IN_{nk't-1} - BN_{nk't-1} \qquad \forall\ \ n\in N, k'\in K, t\in T \tag{22}$$
$$(1-\varphi_{jt}).[\sum_{k\in K} x_{jkrt} + zz_{jrt} +$$
$$\sum_{r\in R}(\sum_{m\in m}(DX_{mnrt}.\lambda'_{rk'}) + \sum_{j\in J}\sum_{r\in R}\psi_{k'r}(\sum_{i\in I} z_{ijk't} + \sum_{n\in N} D''_{njk't-1})]$$
$$+\sum_{k\in K}\sum_{r\in R}\sum_{p\in h_r}(1-\varepsilon_p).(\sum_{r\in h'_p}\eta_{rp}.(\sum_{j\in J} x_{jkrt} + \sum_{c\in C} qq''_{ckrt})) - \sum_{i\in I} DN_{nik't}$$
$$-\sum_{c'\in C'} DD_{nc'k't} - \sum_{j\in J} D''_{njk't}$$

Constraint (23), this constraint calculates the amount of stock in collection centres.

$$IM_{mrt} - BM_{mrt} = IM_{mrt-1} - BM_{mrt-1} + \sum_{c\in C} bdm_{cmpt} \qquad \forall\ \ n\in N, k'\in K, t\in T \tag{23}$$
$$-\sum_{n\in N} dx_{mnrt} + \sum_{c'} DM_{mc'rt} + \sum_{l\in L} yy''_{mlpt} + \sum_{j\in J} x'_{mjrt}$$

Constraint (24), this constraint calculates the capacity of the stock in collection centres.

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

Constraint (25), this constraint calculates the capacity of stock in recycling centres.

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

Constraint (26) determines the suppliers' capacity for manufacturing.

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

Constraint (27) determines the maximum amount sent from collection centres to recycling.

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

Constraint (28) determines the maximum amount sent from recycling centres to environmental centres.

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

Constraint (29) determines the maximum amount of returned *r*th parts of the customer from factory centres to supply centres.

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

Constraint (31), is the number of returns that enter the collection centre from each customer.

$$\sum_{m\in M} bdm_{cmpt} = \tau_{cpt}.D_{cpt} \qquad \forall\ \ c\in C, p\in P, t\in T \tag{30}$$

4. Solution method

4.1. Exact algorithm

The mathematical model investigated in this article is a mixed integer linear programming (MILP) type. It has been formulated and implemented by GAMS v24.1 software. This mathematical model is a multi-objective function. To simplify and reduce the dimensions of the problem, the sum of each of the aspects-related functions has been added to each other. Therefore, the customer satisfaction rate of the supply chain is $Max(F1) = A1 + A2 + A3$, the costs in the supply chain are $Min(F2) = B1 + B2 + B3 + B4 + B5 + B6$, the amount of damage to the environment is $Min(F3) = C1 + C2 + C3 + C4$ and. To convert a three-objective problem into a single-objective problem the weighted sum rule has been used. In this method, each objective function is multiplied by a weight, and then their sum is considered as an objective. According to the importance of each objective function, the value of each weight is determined by decision-makers. Thus, the modified form of the objective function in this research is $F = -w_1 f_1 + w_2 f_2 + w_3 f_3$. In the weighted sum method, all objective functions must be of minimum type. Hence, the first negative objective function is considered to be minimized.

It is necessary to consider some assumptions before implementing the mathematical model developed in the previous section in GAMS software. The assumptions are as follows: number of supply centres: 2, number of manufacturer centres: 2, number of distributor centres: 2, customers: 3, collection centres: 3, recycling centres 2, number of external customers: 2, types of raw materials: 2, number of products: 2. Therefore, the results of solving the model obtained from Games software is 609376.074 for the total objective function.

4.1.1. Sensitivity analysis by use of exact algorithm

In the following, a sensitivity analysis has been carried out by changing the parameters on which the answer depends.

- ❖ Objective functions weight sensitivity analysis

According to the obtained solutions, the optimal value of the objective function is 609376.07. As mentioned earlier, to have a single-objective function the weighted sum method has been used. Thus the obtained value of the integrated objective function depends on the weights multiplied by each objective function in this method. Therefore, we want to see the behaviour of the objective function by changing the value of these weights. The result shows that the value of the objective function is sensitive to changing the weights. For example, by decreasing the value of w_2 from 0.5 to 0.4 the value of the objective function decreases from 609376.07 to 491688.72 which has been shown in Table 3. Consequently, by increasing the value of w_2 from 0.5 to 0.6 we will see an increase in the amount of objective function from 609376.07 to 724995.68. These changes are illustrated in Fig. 3.

Table 3. Sensitivity analysis of objective function coefficients

State	Weights			Objective function value
	w_1	w_2	w_3	
One	0.3	0.4	0.3	491688.72
Two	0.2	0.6	0.2	724995.68

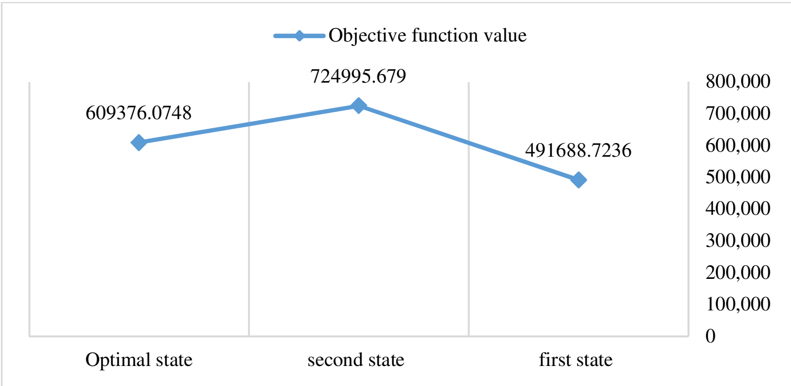

Fig. 3. Comparison of considered states with the optimal state

❖ Sensitivity analysis on products and parts inventory holding costs

By increasing the inventory holding costs of product *p* in the manufacturer *K*, the inventory value of product *p* decreases. Vice versa, if the inventory holding cost of product 'p' in the manufacturer 'K' is reduced, its inventory increases. This behaviour is also seen in the inventory of parts in suppliers by changing the inventory holding costs. Manufacturers and suppliers tend to reduce the inventory held when holding costs increase. Table 4 shows the changes of products holding costs in the manufacturer and Table 5 shows the changes of parts holding costs in the suppliers.

Table 4. Changes in inventory holding costs of products

State	**inventory holding cost distribution**
Increase	Uniform [220; 300]
Initial value	Uniform [110; 201]
decrease	Uniform [80; 100]

Table 5. Changes in inventory holding costs of parts

State	inventory holding cost distribution
Increase	Uniform [210; 250]
Initial value	Uniform [100; 200]
decrease	Uniform [150; 180]

Fig. 4 and Fig.5 show the changes in the inventory of products and parts in manufacturers and suppliers by increasing or decreasing the inventory holding costs in the specified time period, respectively.

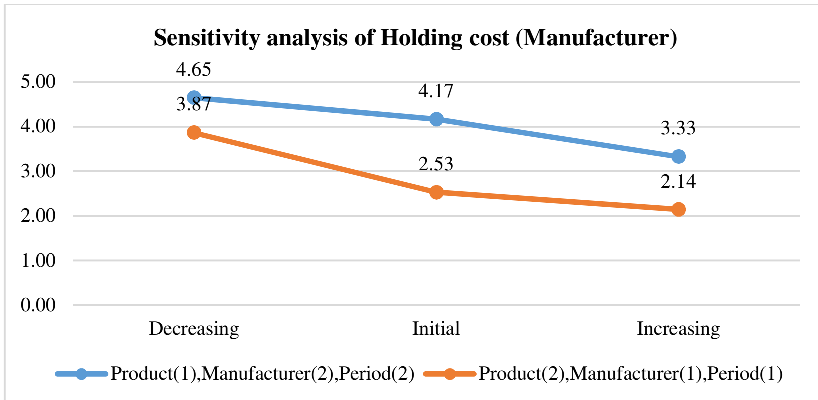

Fig. 4. Sensitivity analysis of manufacturer's inventory holding costs in the first and second period

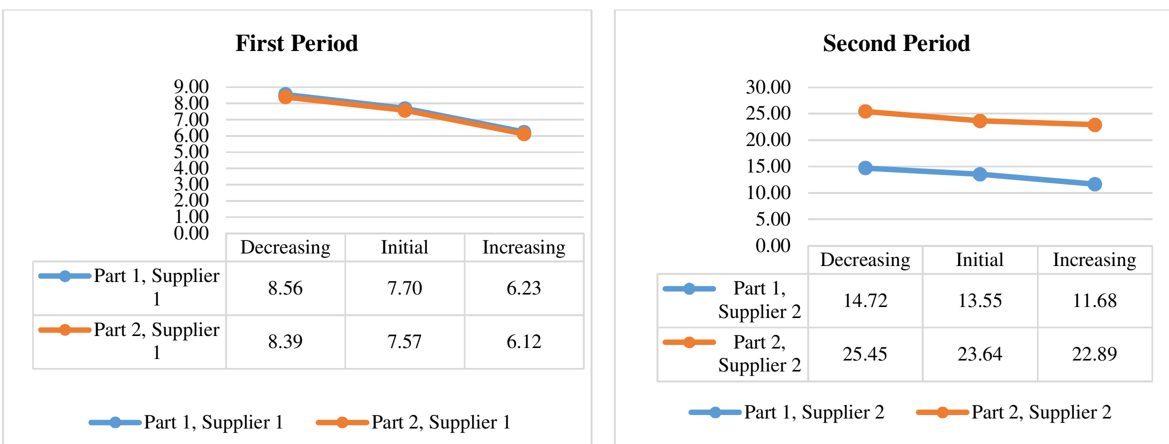

Fig. **5. Sensitivity analysis of supplier's inventory holding costs in the first and second period**

4.2. NSGA-II algorithm

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. These higher-level strategies aremetaheuristics (Liefooghe et al., 2014). For complex problems, metaheuristics find more effective optimization solutions. NSGA-II is a well-known metaheuristic algorithm that can obtain a near-optimal solution for large-scale complex problems (Devika et al., 2014). A literature review of optimization problems shows that NSGA-II algorithms can achieve good results in solving many complex optimization problems. Also, the genetic algorithm has been used in many studies that are common to the topic of this article, so it is implemented in this research.

4.2.1. Numerical 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. Because the problem is NP-hard and the solution time is long, the NSGA-II algorithm has been used to solve the model in small, medium and large dimensions. Optimal conditions were achieved and the answers had convergence. Since different results have been generated in each execution, to compare the performance of the objective functions, three types of problems have been considered as representatives of large, medium and small problems. For the problem in medium dimensions, the period is planned for six months. Also, the number of supplier and distributor centres has increased to 3 and the number of customers is considered 5. In large dimensions, the period is planned to be 10 months. Also, the number of supplier and distributor centres has increased to 4 and the number of customers is considered 6. Parameters related to the algorithm are: maxIt=100, npop=100, pc=0.7, nc=2*round (pc*npop/2), pm=0.4, nm=round (pm*npop). Since the optimal values of the parameters, which generally depend on the characteristics of the problem in question, have a significant effect on the performance of the mentioned algorithm and the better search of the solution space, therefore, considering the challenge of determining the best values of the parameters, from the two approaches of adjusting and controlling the parameters, with constant keeping or changing the random parameters has been analyzed and evaluated according to the possible range determined in the exact method and the answers obtained from this method.

In order to solve sample problems of different dimensions, 20 and 100 sample problems have been created randomly. Results of the three objective functions behaviour of 20 repetitions for small, medium and large size problems are shown in Fig. 6,7 and 8, respectively.

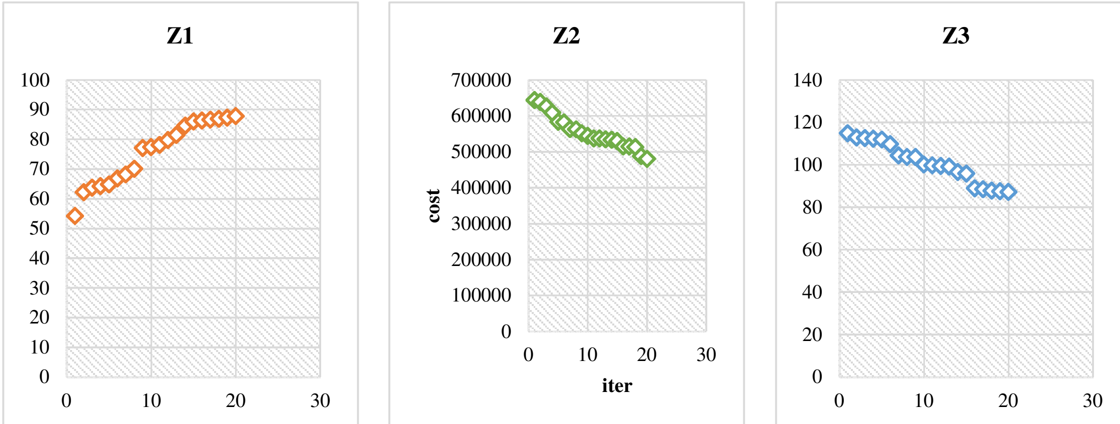

Fig. 6. Algorithm results for the 20 sample problems for small problems.

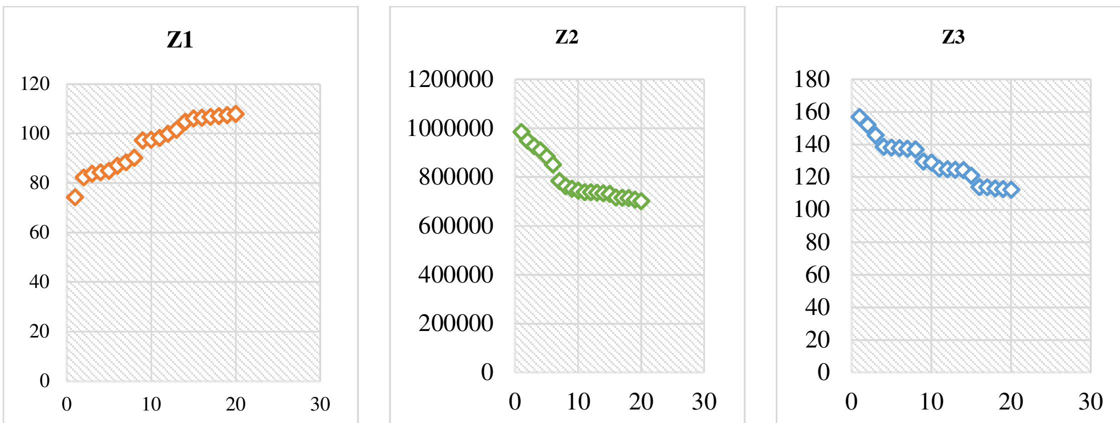

Fig. 7. Algorithm results for the 20 sample problems for medium problems.

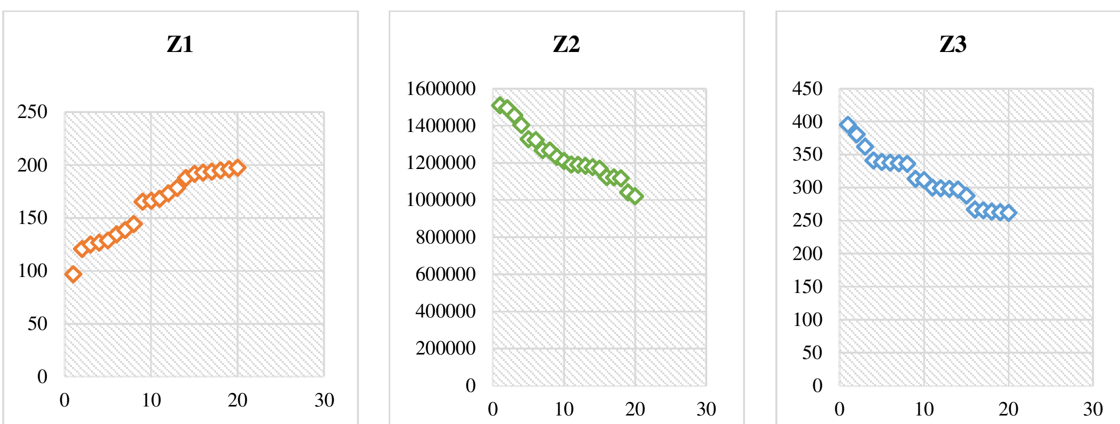

Fig. 8. Algorithm results for the 20 sample problems for large problems.

Due to the large number of pages of the article, the table related to the results of solving the model in 100 repetitions of medium problems is not presented, and only the tables of the small and large dimensions as complex problems are displayed. In Tables 6 and 7, the calculation results of the objective function are given in small and large scales, respectively.

Table 6. Results of objective functions of small dimension problems with NSGA-II algorithm

Problem No.	F-value	Problem No.	F-value	Problem No.	F-value	Problem No.	F-value
1	608,261	**26**	528,629	**51**	676,160	**76**	572,105
2	609,478	**27**	537,258	**52**	543,362	**77**	477,018
3	590,696	**28**	450,742	**53**	558,941	**78**	588,149
4	573,100	**29**	567,141	**54**	501,381	**79**	450,855
5	547,663	**30**	484,520	**55**	533,333	**80**	476,125
6	546,001	**31**	592,942	**56**	516,061	**81**	501,693
7	527,100	**32**	576,149	**57**	445,800	**82**	583,424
8	526,564	**33**	579,945	**58**	468,665	**83**	535,303
9	515,542	**34**	526,780	**59**	565,423	**84**	452,731
10	507,800	**35**	518,129	**60**	591,263	**85**	522,992
11	501,567	**36**	440,729	**61**	582,152	**86**	608,929
12	601,201	**37**	445,719	**62**	478,107	**87**	503,737
13	499,125	**38**	477,371	**63**	538,916	**88**	506,775
14	496,846	**39**	555,092	**64**	531,400	**89**	524,373
15	494,028	**40**	455,143	**65**	527,656	**90**	493,696
16	478,950	**41**	537,302	**66**	455,371	**91**	507,072
17	478,566	**42**	512,179	**67**	589,130	**92**	523,284
18	476,853	**43**	589,115	**68**	534,516	**93**	449,488
19	451,150	**44**	525,166	**69**	456,126	**94**	572,105
20	643,857	**45**	506,838	**70**	567,423	**95**	477,018
21	596,244	**46**	440,560	**71**	593,876	**96**	588,149
22	522,999	**47**	521,244	**72**	537,493	**97**	650,855
23	496,870	**48**	448,245	**73**	588,384	**98**	476,125
24	541,179	**49**	459,478	**74**	456,573	**99**	501,693
25	477,018	**50**	462,424	**75**	440,534	**100**	583,424

Table 7. Results of objective functions of large dimension problems with NSGA-II algorithm

Problem No.	F-value	Problem No.	F-value	Problem No.	F-value	Problem No.	F-value
1	1,428,056	**26**	1,263,608	**51**	1,322,361	**76**	1,572,715
2	1,469,421	**27**	1,179,198	**52**	1,259,478	**77**	1,548,302
3	1,175,498	**28**	1,364,492	**53**	1,086,225	**78**	1,132,962
4	1,490,323	**29**	1,127,089	**54**	1,353,622	**79**	1,401,644
5	1,167,872	**30**	1,219,639	**55**	1,365,020	**80**	1,148,158
6	1,481,735	**31**	1,210,692	**56**	1,196,073	**81**	1,591,086
7	1,534,588	**32**	1,326,066	**57**	1,400,263	**82**	1,212,307
8	1,603,933	**33**	1,373,565	**58**	1,296,890	**83**	1,189,391
9	1,355,052	**34**	1,422,950	**59**	1,517,008	**84**	1,452,563
10	1,359,350	**35**	1,110,116	**60**	1,428,362	**85**	1,494,765
11	1,082,399	**36**	1,198,577	**61**	1,245,359	**86**	1,531,527
12	1,146,858	**37**	1,427,962	**62**	1,323,462	**87**	1,566,358
13	1,183,916	**38**	1,386,667	**63**	1,499,245	**88**	1,585,661
14	1,453,675	**39**	1,409,255	**64**	1,192,655	**89**	1,230,381
15	1,235,742	**40**	1,393,392	**65**	1,659,043	**90**	1,269,879
16	1,249,290	**41**	1,491,222	**66**	1,604,982	**91**	1,519,055
17	1,196,501	**42**	1,117,509	**67**	1,445,539	**92**	1,360,426
18	1,072,923	**43**	1,182,518	**68**	1,459,689	**93**	1,515,165
19	1,281,260	**44**	1,291,815	**69**	1,215,874	**94**	1,120,921
20	1,155,839	**45**	1,397,309	**70**	1,448,784	**95**	1,619,722
21	1,227,489	**46**	1,431,771	**71**	1,573,005	**96**	1,361,654
22	1,086,663	**47**	1,439,183	**72**	1,509,229	**97**	1,354,128
23	1,622,757	**48**	1,439,287	**73**	1,277,686	**98**	1,562,765
24	1,225,074	**49**	1,191,670	**74**	1,388,904	**99**	1,147,058
25	1,530,299	**50**	1,237,309	**75**	1,368,901	**100**	1,226,631

In the following, the Pareto charts are illustrated. The more points are created in the Pareto front, the more efficient the algorithm is, and more points have been evaluated. Fig. 9 shows the comparison of Pareto optimal fronts for the 20 and 100 sample problems by the NSGA-II algorithm.

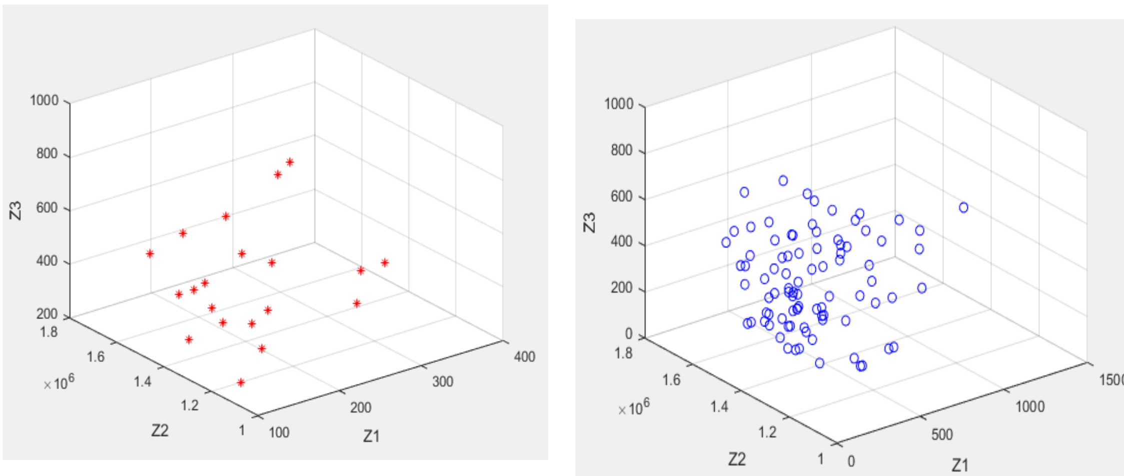

Fig. 9. The comparison of Pareto optimal fronts for the 20 and 100 sample problems by NSGA-II algorithm

5. Discussion

In this section, the results of the exact algorithm will be compared with the results of the NSGA-II algorithm. Based on the Fig. 10 as expected, the values of the objective function have increased with the increase in the dimensions of the problem.

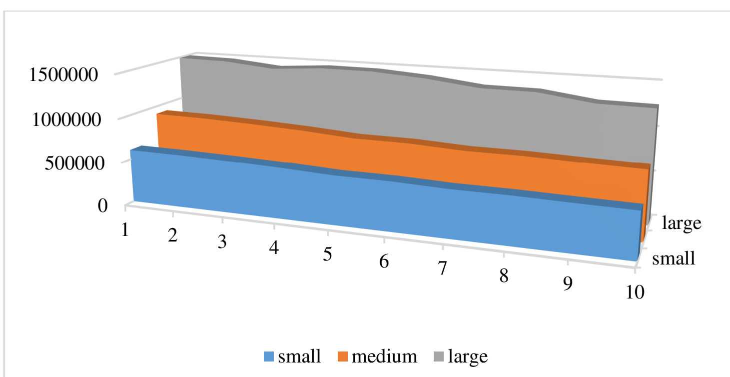

Fig. 10. Comparing the performance of the objective function with increasing problem dimensions

The objective functions are designed based on circular economy concepts as a contribution compared to previous studies. The social objective function is maximized and the environmental and economic objective functions are minimized. By comparing the answer obtained from the GAMS software which is 609376.074 (exact method) and the answer obtained from the NSGA-II algorithm in Table 6 (metaheuristic method) in small dimensions, it is seen that the obtained answers do not have a huge numerical difference, which confirms the optimal performance of the NSGA-II algorithm. Fig. 11 shows the comparison of the result of these two methods in three examples of the solved problems.

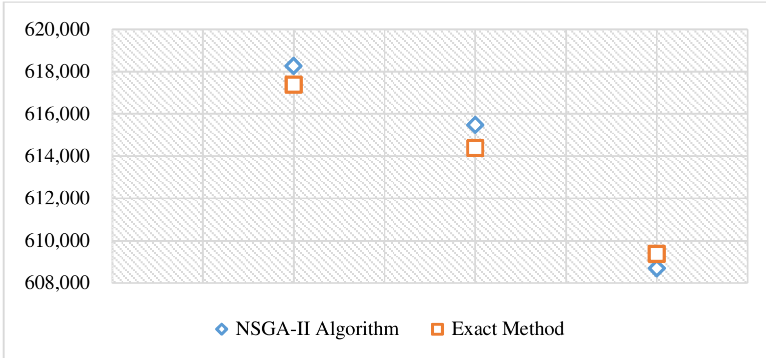

Fig. 11. Comparison of the result of the exact method and the meta-heuristic method

As the previous studies showed the effectiveness of the NSGA-II algorithm in supply chain problems, the results of this research also confirm the effectiveness of this algorithm for solving circular supply chain problems in large dimensions.

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. This network has been structured based on the digital devices industry. Real-world assumptions have been formulated in the proposed model to provide decision-makers with decision support. Given that a supply chain in the real world may have larger dimensions than what is considered in theory and such problems on a large scale are included in the class of complex problems known as NP-hard, where obtaining the solution using the exact methods will be very time-consuming and sometimes impossible. Therefore, an effective meta-heuristic method for finding the Pareto front in large dimensions is presented.

This study shows how integrated all upstream and downstream units of the supply chain network should be to meet circular economy requirements. It allows decision-makers to select the most appropriate solution from the collection of optimal solutions according to the available budget and their organization's policies. The proposed model and designed network can support managers in confronting the sudden changes in the market to increase their competitiveness and credibility. Using these managers can boost the supply chain flexibility to respond to the external environment. Furthermore, one of the main goals of the proposed model is to reuse and recycle products and parts, which is a major concern from a circular economy point of view. Meanwhile, making decisions on returning products may increase the profit and employment rate in many real-world situations in addition to meeting the legal and customer requirements.

7. Conclusion and further research

The design of an effective supply chain has been attracting the attention of decision-makers for many years. A supply chain that is agile and has the lowest cost and creates the most profit. The literature review showed the circular supply chain design that integrates the supply chain with a circular economy is an emerging issue and can be a perfect model to meet the needs of decision-makers. Therefore, a multi-echelon multi-product multi-period circular supply chain network was presented. According to the literature, it was the first closed-loop supply chain mathematical model that was designed with a focus on circular economy. Therefore, obtaining the answers to this problem in large size was very important. It helps decision-makers to implement this effective model in their business and take advantage of its benefits.

The exact solution to this circular supply chain network problem in small sizes can be found by exact algorithms, but they lose their efficiency for large-size problems. Therefore, the specific development of this study is to present an application of the NSGA-II algorithm to solve the circular supply chain model on a large scale. Due to the computational complexity of the proposed problem and being in the NP-Hard category problems, to solve the model in medium and large sizes, the NSGA-II meta-heuristic algorithm was used in R2016a MATLAB software. The result of the exact solution of the model using the GAMS software was presented. The value of the objective function in the small dimension problem was 609376.074. Sensitivity analysis was done on significant factors. Then, the results obtained from the application of the NSGA-II meta-heuristic algorithm were presented. The graphs related to the behaviour of the first, second and third functions in 20 repetitions were displayed for the problem with small, medium and large dimensions, respectively.

As more computational results of the NSGA-II algorithm, the value of the overall objective function for the problem in small and large sizes in 100 iterations was presented in the form of tables 5 and 6. The Pareto diagram related to the behaviour of the objective functions was depicted separately for 20 and 100 problem examples. Comparing the answers obtained from the GAMS software and the answers obtained from the NSGA-II algorithm in small dimensions shows that the obtained answers did not have a huge numerical difference, which confirms the optimal performance of the NSGA-II algorithm. Thus the answers obtained from the algorithm in medium and large problems can be considered acceptable.

The proposed model can be implemented in organizations and all businesses related to the production of digital goods (e.g., laptops, smart TVs, smartphones, and so on). For future research, it is suggested to redesign the proposed model to cope with demand uncertainty; to solve the proposed model using other meta-heuristic methods to compare their results; to take into account the resiliency; and finally to consider other objectives in the proposed model, such as minimizing service time and maximizing coverage level.

Furthermore, among the various choices, finding an optimal configuration for the supply chain network deals with many cost, performance, and other technical trade-off analyses at the network design level. For instance, in the broader perspective of practical evaluations, the benefits and savings associated with applying circular economy aspects (e.g., using biodegradable materials here) must be traded off against all production-related costs, which deserve further study.

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