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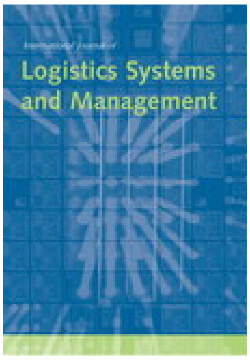

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Designing a closed-loop supply chain network with a focus on the circular economy concept

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Abstract: This paper aims to propose a multi-objective planning model to optimise the closed-loop supply chain network considering the circular economy concept. The intended mathematical model can view all aspects of sustainability, including economic, environmental, and social factors. Objective functions have become a one-objective planning problem using the additive weighing method. The designed mathematical model is solved by GAMS software. Designing a mathematical planning model to optimise the sustainable closed-loop supply chain network focusing on the circular economy concept and considering a framework for validation and solution of the developed model with an appropriate computational method are the main contributions in this paper. The results show that acceptable results are obtained by implementing the proposed model.

Keywords: circular economy; sustainable development; closed-loop supply chain; CLSC; supply chain.

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1 Introduction

Many discussions and debates have been evoked in the academic literature because of the sustainability, including the supply chain management (SCM) literature (Seuring and Müller, 2008; Morali and Searcy, 2013). Research studies' dominant focus is on sustainability aspects of business operations and the availability and commercial viability of recycling and reuse technologies. However, the unique global production, consumption, and trade patterns stay hazardously unsustainable (Preston, 2012). 'Take, make, dispose of' characterises the usual model in the industrial economy, where raw materials are extracted, turned into products, sold, and used by end-users, and then products are disposed of after their end-of-life. Some high-value items are also recycled, while in reality, much still ends up in landfills (Bernon et al., 2018). Soon, the world will be depleted of many natural resources, if there is no change in sourcing, producing, delivering, using, reclaiming, and regenerating products (Hazen et al., 2017). As the United Nations Sustainable Development Goals in 2016 have predicted, by 2030 and 2050, the demand for resources will need natural resources similar to two and three planets, respectively (Goyal et al., 2018; Kharola et al., 2022). One main concept that would make this change is the circular economy (CE), which is considerably known as a better alternative to the dominant linear (take, make, and dispose of) economic model (Ghisellini et al., 2016; Mogale et al., 2022). In both the literature and practice, the CE philosophy is changing into the main factor behind sustainability (Hobson, 2016; Stewart and Niero, 2018), and it is known as a great potential to contribute to organisations achieving an improvement in sustainability performance (Golpîra and Javanmardan, 2022). According to the existing literature on the circular vs. linear economy, the plan of the current economy is too unsustainable by using the comparative benchmarking method drained from literature (Sariatli, 2017). According to the wasteful take – make – dispose of flow, the inherent mechanics of the linear economy is harmful to the environment, cannot afford the increasing demand of the growing population of our planet with necessary services, and as a result, makes strained profitability. The main viewpoint of the CE is omitting waste by design, respect for the social, economic, and natural environment, and resource-conscious business conduct. Based on the stability of these principles, the CE has illustrated to transfer perceptible benefits and viability to handle the challenges of our days, such as the economic, environmental, and social issues (Sariatli, 2017). In 2014, the Ellen MacArthur Foundation (EMF) promoted CE as an industrial system that is restorative and regenerative by design (Farooque et al., 2019). By considering the 'take, make, disposش' triptych, the linear resource consumption model is against the CE, as a recent industrial model. Eliminating waste is its main goal it has a detrimental effect on the environment. Natural components called nutriments can boost the use of goods and the repurposing (repair and recycling, via reuse) of technical components that are not suitable for the biosphere. Indeed, the biosphere can reabsorb these components without any damage (Ouaddi et al., 2022). In a CE, the final consumption of goods must be built on a 'functional service economy', that is, the rental of goods and no longer on the sale of goods, which produces waste (Gallaud and Laperche, 2016). The CE aims to keep products, components, and materials at their best value and utility. CE can foster sustainability and environmental protection but emphasises the maximum circulation of the content of end-of-life products. It can be the major distinction between CE and sustainability, return to production and use point, and diminishing the impact on the environment. In end-of-life products, both biological and technical materials will be correctly treated so that is inevitable, these materials can be released into the biosphere without any danger. As a result, the final purpose of CE is twofold: minimising the contents that could end up in landfills or burning and maximising the recirculation (Bernon et al., 2018).

Having a capable supply, manufacturing, and distribution system is one of the most critical issues that have been considered a factor of development in recent decades and is understood in the form of a supply chain (Safaei et al., 2022). The capabilities and performance of the supply chain are of importance in this regard (Babaeinesami et al., 2022). Academic literature on the CE is nascent and it has little attention to SCM implications and the relevance of supply chain innovation toward a more resource-efficient and CE (De Angelis et al., 2018). From manufacturing and assembly to sending to customers is all included in this process. Storage steps, as well as material management, are all included (Zijm et al., 2019). There is a necessity to set rules that helps to pioneer in competitions based on the varying demands of customers. That results in the enhancement of individual supply chain partners (Green et al., 2006).

The planning, implementation, and control of supply chain processes and operations that are effective in maintaining the organisation's competitive advantage are called SCM (Mirghafoori et al., 2012; Vandchali et al., 2022). The job of SCM is to create coordination among activities that lead to the integration of exchanges between suppliers, manufacturers, distributors, retailers, and customers (Thakkar et al., 2008; Bouanane et al., 2022). The concept of SCM is linked to directing the material and financial flows and blending organisational units along a supply chain to meet (ultimate) customer needs and enhance the competitiveness of a supply chain (Kumar et al., 2016). From a sustainability standpoint, merging CE into SCM can bring about some advantages (Nasir et al., 2017). Increasing interest in SCM for CE is merely seen (Liu et al., 2018). Some terms are used in SCM review interchangeably, including sustainable supply chains, environmental supply chains, green supply chains, and closed-loop supply chains (CLSCs) (Gurtu et al., 2015). These expressions have been implied to demonstrate the integration of the sustainability concept in SCM (Ahi and Searcy, 2015). Despite expressing various degrees of integrating sustainability issues into supply chains. None of them integrated circular thinking, as an example into SCM. Few publications have recently dealt with integrating CE into SCM (Batista et al., 2018). Existing works on fundamental CE are implied at a strategic level while others deal with SCM functions like design, production, etc. In some studies, an effort has been made to link CE with SCM by using the phrase circular supply chain (De Angelis et al., 2018). Circular supply chain management (CSCM) is still in its infancy. Supply chain performance and end-of-life products management have been more at the centre of focus. Those topics cover a few specific research aspects in CSCM. More research must be done on all supply chain functions to shed light on its entire area. To make a CE real, various technical and process problems must be dealt with along with incentive issues. Since CE is developing to be a new frontier in sustainable thinking, it is pondered that progress in CSCM in the following areas will cause enhancement in SSCM and GSCM which helps organisations to boost their sustainability performance (Farooque et al., 2019).

Based on the knowledge gained from the research study, it can be seen that CSCM is still an emerging research field. Most published studies are conceptual works and case studies that are general to a research topic still in its infancy. Conversely, several specific research topics in CSCM, including supply chain performance and product management, have received relatively more attention. However, to achieve the full potential of CSCM, much more research needs to be conducted on all supply chain operations. There are many technical, process, and motivational issues to overcome the problems of CE realisation. Given that CE is a valuable new frontier in sustainable thinking, advancing the CSCM will significantly enhance other dimensions of SC, such as green supply chain management (GSCM), in helping organisations achieve a higher level of sustainable performance. Therefore, the most important contributions of this article are:

- Developing a mathematical planning model to optimise the CLSC network with a focus on the CE concept.
- Developing a multi-objective mathematical planning model that simultaneously considers minimising total supply chain costs, minimising unusable products that are buried, minimising environmental pollution, and maximising the number of jobs created to optimise a CLSC network with a focus on the concept of CE.

- Considering a framework for validation and solution of the developed model with an appropriate computational method.

The rest of this article is organised as it shows. Section 2 provides a literature review of previous research; in Section 3, the research method, which includes the introduction of symbols, parameters, and mathematical models, is provided. In Section 4, the results of model implementation in the real world are provided. Finally, in Section 5, a general conclusion is provided and suggestions for further research on the research topic.

2 Literature review

In this section, CSCM research on integrating CE philosophy at SCM levels or value chain (sustainability perspective) into employment in various industries is reviewed. For example, a tactical supply chain planning model that may be used to investigate the relation between cost and environmental degradation like energy consumption, carbon emission, and waste generation, has been presented by Fahimnia et al. (2015). This model also integrates other dimensions of the real-world supply chains like different transport lot sizing and flexible warehouse storage capacity. Ivanov et al. (2016) have developed an algorithm for short-term supply chain planning in the intelligent factories industry 4. The continuous maximum principle is mingled with mathematical optimisation to build up this algorithm. Ivanov et al. (2017) provided a control model of supply chain reconfiguration, formerly dealt with by mathematical programming. The dynamics of a continuous flow supply chain system along with a hybrid discrete-continuous state space can be indicated by this model. Margolis et al. (2018) found that for supply chain architects, a multi-objective network design model, as well as a decision support methodology based on optimisation, is required. The method we represent measures the balance between total network cost minimisation and maximising overall supply chain network junction. Saad et al. (2018) organised an integral framework for scheduling and optimising the oil supply chain. This framework consists of two steps: express strategic planning in mathematics and the optimising extracted oil which is within the oil supply chain. And then demonstrate operational scheduling of the refinery area by a mixture of both discrete and continuous simulation.

A mathematical definition of supply chain reliability theory is presented by Ha et al. (2018). This was followed by the models regarding the basic structural reliability models for various forms of supply chains. Another result stated is that presented functions and structural reliability models are suitable for different kinds of the supply chain. In a case study about a computer assembly company, Taleizadeh et al. (2019) have researched the effect of uncertainty using optimisation on leftover items and whether a proper accord method exists among the third-party logistics firms. These firms must gather leftover medicine from customers. The objective is to increase RSC members' profit as much as possible and bring about the opportunity to discuss replacement orders. Tosarkani and Amin (2019) schemed a multi-echelon lead-acid battery CLSC network under uncertain conditions. To gain maximum net profit, fully fuzzy programming (FFP) was mingled with stochastic programming (FFSP) to address different various scenarios. The distance technique is also used for solving stochastic multi-objective problems resulting from the need for environmental compliance of suppliers, plants, and battery recovery centres. The function of the mentioned model was shown in a network in Winnipeg, Canada. The work of Paksoy et al. (2019) focuses on a new model developed for managing the lean and green CLSC. Its idea came from an automotive supply chain. There are six objectives pursued by this model which are reducing the following factors:

1 transportation cost

2 fixed facility cost

3 purchasing and operational costs

4 environmental cost

5 handling cost

6 late deliveries.

By applying a fuzzy weighted additive method and investigating a numerical example, the model's validity has been verified. The weights are determined using the method of fuzzy analytic hierarchy process (fuzzy AHP). Hajipour et al. (2019) developed a nonlinear mixed-integer mathematical programming problem (CLSC) to model a stochastic multi-product CLSC. Two meta-heuristic algorithms are taken advantage of to solve the optimisation problem. Goli et al. (2019) presented the multi-objective, multi-period, and multi-products CLSC network under uncertainty. They aimed to combine the financial flow with fuzzy logic when the cash flow and debts constrain labour employment. This mathematical model has aimed to increase the cash flow as well as consumed raw materials reliability and create jobs in the supply chain. Del Giudice et al. (2020) have analysed the impact of CE rules while used in a firm, on its efficiency, for a circular supply chain. They prospected the mediocre effect a big-data-driven supply chain has on communication. Centobelli et al. (2021) for designing circular blockchain platforms proposed the integrated triple retry framework. A circular blockchain platform was provided in a supply chain. For instance, manufacturer, provider of reverse logistic service, decision panel, recycling panel, and landfill. The results approve the pioneering role of blockchain in control of waste movement and management of product comeback. Goodarzian et al. (2021) investigated the COVID-19 pandemic and addressed inventory holding, distribution, and flow problems associated with it. The most contributed to the sustainable-resilient health care network. Their model was run using hybrid meta-heuristic algorithms like teaching-learning-based optimisation (TLBO), particle swarm optimisation (PSO), and genetic algorithm (GA). Shirazi et al. (2021) presented a four-step supply chain to seek blood collection sites. Solving algorithms were sorting genetic algorithm II (NSGA-II), and multi-objective grey wolf optimiser (MOGWO). The paper is mostly focused on the crucial issue of blood substitutability. Tirkolaee et al. (2022) presented a closed-loop mask supply chain in the times of the COVID-19 pandemic. They proposed locational, production, distribution, recycling, and disposal decision in their problem. They designed MOGWO scheme as well as a non-dominated sorting genetic algorithm II (NSGA-II) to handle the problem.

Based on the papers mentioned above in the background of previous research, they apply the concept of CE in the supply chain, provide conceptual models, and identify stimuli and obstacles. They have only addressed the analytical approach and the importance of this issue in the supply chain. So far, the mathematical models proposed. They have only addressed the analytical approach and the importance of this issue in the supply chain. So far, the mathematical models proposed for the supply chain have not considered the CE, and they have been solved by mathematical, simulation, or metaheuristic methods. Therefore, in this research, a mathematical model will be presented to optimise the CLSC network design, focusing on the concept of CE.

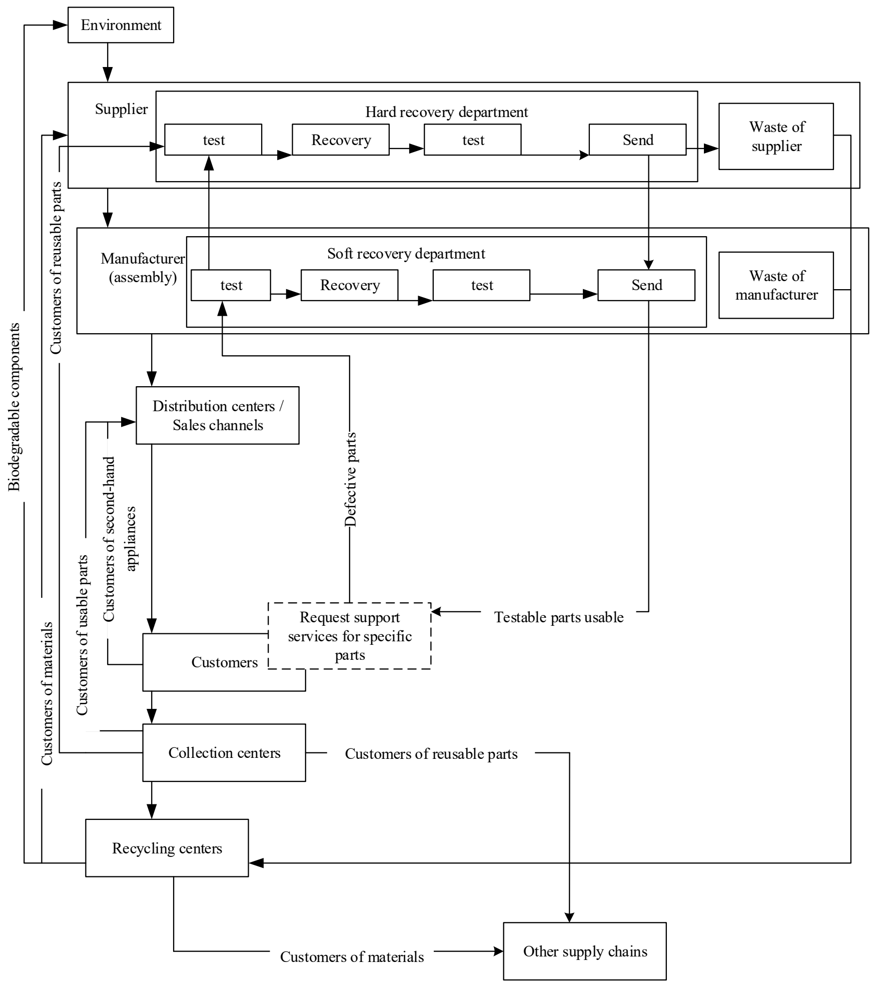
3 Methodology

3.1 Supply chain structure based on CE

To develop a mathematical planning model to optimise a CLSC network with a focus on the concept of CE and to consider its assumptions, we have imagined the supply chain network associated with digital products, such as laptops, smart TVs, etc. smartphones, etc. in this research. Figure 1 schematically shows the structure of this supply chain. The assumptions of the functional structure and the effect of the CE that have been considered in the design of this network are as follows:

- From the beginning, the product has been designed based on CE principles and, therefore, certainly has components and parts related to the biological cycle. For example, it is made of 'biodegradable plastics'. These plastics are substances broken down into the water, carbon dioxide, and biomass by living organisms (usually microbes). Biodegradable plastics are usually produced with renewable raw materials, microorganisms, petrochemicals, or a combination of these three categories. These components and parts (if not reusable) are buried and returned to the environment in the modelling process.
- The product has components and parts related to the technical cycle. These components and parts are recovered through repair, renewal, remanufacturing, or recycling in one of the various centres in the supply chain network.
- It is possible to buy and sell second-hand products among customers. Products still usable are exchanged between customers through second-hand product sales channels (such as the Sheipour or Divar websites).
- Depending on the severity of the defect, parts returned from the customer to the manufacturer (at the time of requesting after-sales services) may get weak recovery by the manufacturer or be returned to the supplier for hard recovery. If the parts are not recoverable in each of these centres, they are sent to the recycling centre.
- Parts returned from the customer to the manufacturer (when requesting after-sales services) are replaced with recovered and tested components. 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 can be returned to any of the suppliers and distributors. It is also possible to sell returned products or separated parts to other supply chains.
- The products sent to the recycling centres are first inspected. 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, unusable materials and components associated with the biological process are buried and returned to the environment.

Figure 1 Supply chain structure



3.2 Mathematical modelling

This section introduces sets, parameters, variables, and constraints related to the proposed mathematical model in this research.

All the sets considered in this research are: I a set of environmental centres, J a set of supply centres, K a set of manufacturing centres, L a set of distribution centres, C a set of customers, N a set of recycling centres, M a set of collection centres, T set of periods, R set of primary parts, P set of products, C' set of external customers to buy reusable components extracted from recycling centres and collection centres, h_r set of products that have part r, h_p' set of parts that are used in product p, and K' set of raw materials.

3.2.1 Indices

All the indices considered for the mathematical model proposed in this research are: $i \in I$ index related to environmental centres, $j \in J$ index related to supply centres, $k \in K$ Index related to manufacturing centres, $l \in L$ index related to distribution centres, $c \in C$ index related to customers, $n \in N$ index related to recycling centres, $m \in M$ index related to collection centres, $t \in T$ index related to periods, $r \in R$ index related to primary parts, $p \in P$ index related to products, $k' \in K'$ index related to raw materials, $c' \in C'$ index related to external customers to purchase reusable parts extracted from recycling centres and collection centres.

3.2.2 Parameters

The parameters considered in this research along with symbols, descriptions, and values are listed in Table 1.

Table 1 Predefined parameters

Value	*Symbol*	*Description*
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}	Percentage of products in collection centre 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 centre m which is sent to the recycling centre by separating its parts	Uniform [0.2; 0.4]
σ_{rp}	Percentage of products in the collection centre 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 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]
$\psi_{k'r}$	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 [1,500; 2,500]
$capS_{jrt}$	The capacity of supplier from product r at time t	Uniform [1,200; 2,500]
$capD_{lpt}$	The capacity of distributor l from product p at time t	Uniform [1,000; 2,000]
$CapM_{mrt}$	Maximum capacity of collection centre m for product r at time t	Uniform [1,100; 2,200]

Table 1 Predefined parameters (continued)

Value	*Symbol*	*Description*
$capN_{nk't}$	Maximum capacity of the n^{th} collection centre m for raw materials k' at time t	Uniform [1,100; 2,100]
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 [1,000; 2,000]
CBF_{kpt}	Costs of stock shortage of product p in manufacturer k at time t	Uniform [1,100; 2,100]
CBD_{lpt}	Costs of stock shortage of product in distributor l at time t	Uniform [1,200; 2,200]
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 centres i to supplier j at time t	Uniform [120; 220]
Cx'_{mjrt}	Cost of transferring the r^{th} part from the m^{th} 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; 28,000]
$CDD_{nc'k't}$	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]
$IDD_{nc'k't}$	Income of transferring the k'^{th} raw material from the n^{th} recycling centre 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 centre 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 centre to the c'^{th} external customer in period t	Uniform [140; 289]

Table 1 Predefined parameters (continued)

Value	*Symbol*	*Description*
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 [10,000; 450,000]
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]
$CDN_{nik't}$	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]
π_{it}	Unemployment rate reduction in region L if a distribution centre 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]
π''_{jt}	Unemployment reduction rate in region j if a supply centre is established in that region	Uniform [0.22; 0.29]
MM	It is a very large scalar	

3.2.3 Variables

The variables of this research are two types of continuous positive and binary variables. All variables of this problem are defined as follows.

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 centre in period t, x_{jkrt}: value of transferring the r^{th} part from the j^{th} supply centre 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 centre to the j^{th} supply centre 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 centre to the l^{th} distributor centre in period t, $D''_{njk't}$: value of transferring the k'^{th} raw material from the n^{th} recycling centre to the j^{th} supply centre in period t, $DD_{nc'k't}$: value of transferring the r^{th} part from the n^{th} recycling centre to the c'^{th} external customers in period t, $DM_{mc'rt}$: value of transferring the r^{th} part from the m^{th} collection centre to the c'^{th} external customers in period t, q_{lcpt}: value of product p that customer c receives distributor centre l at time t, qq_{clpt}: value of returned product p that is sent from customer c to distributor centre 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 centres to the j^{th} supply centre in period t, $IN_{nk't}$: stock of raw material k' in the n^{th} recycle centre in the t^{th} period, $BN_{nk't}$: shortage of raw material k' in the n^{th} recycling centre in the t^{th} period, IM_{mrt}: stock of the r^{th} part in the m^{th} collection centre in the t^{th} period, BM_{mrt}: shortage of the r^{th} part in the m^{th} collection centre 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 centre to supplier j in period t, Dx_{mnrt}: value of transferring the r^{th} part from the m^{th} collection centre to the n^{th} recycling centre in period t, bdm_{cmpt}: value of returned product from customer c to collection centre m in period t.

3.2.5 Binary variables

All variables in this category belong to the set $\{0, 1, \ldots\}$. 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, zero, q'_{jt} : if the supply centre j is open at time t, it is one otherwise zero.

3.2.6 Objective functions

The aspects considered in the CE are the same aspects of sustainability, including economic, environmental, and social. For this purpose, the first objective function minimises the cost of the supply chain. The second objective function minimises the environmental effects of the supply chain. Finally, the third calculates the total rate of unemployment reduction if a centre is established in the region.

3.2.7 Economic aspect

Constraint (1) calculates stock maintenance costs and shortages in the supplier, manufacturer, and distributor layers.

$$\begin{aligned} A1 = & \sum_{j\in J}\sum_{r\in R}\sum_{t\in T} CBS_{jrt}\cdot BS_{jrt} + \sum_{k\in K}\sum_{p\in P}\sum_{t\in T} CBF_{kpt}\cdot BF_{kpt} \\ & + \sum_{l\in L}\sum_{p\in P}\sum_{t\in T} CBD_{lpt}\cdot BD_{lpt} + \sum_{j\in J}\sum_{r\in R}\sum_{t\in T} CIS_{jrt}\cdot IS_{jrt} \\ & + \sum_{k\in K}\sum_{p\in P}\sum_{t\in T} CIF_{kpt}\cdot IF_{kpt} + \sum_{l\in L}\sum_{p\in P}\sum_{t\in T} CID_{lpt}\cdot ID_{lpt} \\ & + \sum_{c\in C}\sum_{p\in P}\sum_{m\in M}\sum_{t\in T} bdm_{cmpt}\cdot Cbdm_{cmpt} \end{aligned} \tag{1}$$

Constraint (2) calculates the transfer costs from the supplier to other layers and from different layers.

$$\begin{aligned} A2 = & \sum_{i\in I}\sum_{j\in J}\sum_{r\in R}\sum_{t\in T} Cz_{ijk't}\cdot z_{ijk't} + \sum_{n\in N}\sum_{j\in J}\sum_{k'\in K'}\sum_{t\in T} CD''_{njk't}\cdot D''_{njk't} \\ & + \sum_{m\in M}\sum_{j\in J}\sum_{r\in R}\sum_{t\in T} Cx'_{mjrt}\cdot x'_{mjrt} + \sum_{j\in J}\sum_{r\in R}\sum_{t\in T} zz_{jrt}\cdot czz_{jrt} \end{aligned} \tag{2}$$

Constraint (3) calculates the transfer cost from manufacturer to the supplier, customer, distribution centre and recycling centre, and customer to the manufacturer.

$$\begin{aligned} A3 = & \sum_{k\in K}\sum_{l\in L}\sum_{t\in T}\sum_{p\in P} y_{klpt}\cdot Cy_{klpt} + \sum_{k\in K}\sum_{c\in L}\sum_{t\in T}\sum_{p\in P} xx'_{kcrt}\cdot Cxx'_{kcrt} \\ & + \sum_{k\in K}\sum_{j\in J}\sum_{t\in T}\sum_{r\in R} x_{jkrt}\cdot Cx_{kjrt} + \sum_{k\in K}\sum_{j\in J}\sum_{t\in T}\sum_{r\in R} xx_{kjrt}\cdot Cxx_{kjrt} \\ & + \sum_{k\in K}\sum_{p\in P}\sum_{t\in T}\sum_{r\in R} CC_{kpt}\left(1-\varepsilon_p\right)\cdot\left(\sum_{r\in h'_p}\eta_{rp}\cdot\left(\sum_{j\in J} x_{jkrt} + \sum_{c\in C} qq''_{ckrt}\right)\right). \end{aligned} \tag{3}$$

Constraint (4) calculates the income and cost of sending parts to external customers from collection and recycling centres.

$$\begin{aligned} A4 = & \sum_{n\in N}\sum_{k\in K'}\sum_{t\in T}\sum_{c'\in C'} DD_{nc'k't}\cdot\left(CDD_{nc'k't} - IDD_{nc'k't}\right) \\ & + \sum_{c'\in C}\sum_{m\in M}\sum_{p\in P}\sum_{t\in T} DM_{mc'rt}\cdot\left(CDM_{mc'rt} - IDM_{mc'rt}\right) \end{aligned} \tag{4}$$

Constraint (5) calculates the shipping cost to customers.

$$A5 = \sum_{p\in P}\sum_{t\in T}\sum_{c\in C}\sum_{l\in L}\left[\left(q_{lcpt}\cdot Cq_{lcpt}\right)+\left(qq_{clpt}\cdot Cqq_{clpt}\right)\right] + \sum_{c'\in C}\sum_{r\in R}\sum_{t\in T}\sum_{k\in K} qq''_{ckrt}\cdot Cqq''_{ckrt} \tag{5}$$

Constraint (6) calculates shortage and stock costs in collection and recycling centres.

$$A6 = \sum_{n\in N}\sum_{k'\in K'}\sum_{t\in T} IN_{nk't}CIN_{nk't} + \sum_{n\in N}\sum_{k'\in K'}\sum_{t\in T} BN_{nk't}CBN_{nk't} + \sum_{m\in M}\sum_{r\in R}\sum_{t\in T} IM_{mrt}.CIM_{mrt} + \sum_{m\in M}\sum_{r\in R}\sum_{t\in T} BM_{mrt}.BIM_{mrt} \tag{6}$$

3.2.8 Environmental aspect

Constraint (7) calculates the amount of environmental damage in the recycling centre.

$$B1 = \sum_{n\in N}\sum_{k\in k'}\sum_{t\in T}\left(\sum_{c'\in C'} DD_{nc'k't} + \sum_{j\in J} D''_{njk't}\right)\cdot\theta'_{k'} - \sum_{r\in R}\sum_{k'\in K'}\sum_{n\in N}\sum_{m\in M}\sum_{t\in T}\left[\left(DX_{mnrt}\right)\cdot\lambda'_{rk'}\right] \tag{7}$$

Constraint (8) calculates the amount of environmental damage to the manufacturer.

$$B2 = \sum_{k\in K}\sum_{p\in P}\sum_{t\in T}\left(\sum_{r\in h'_p}\eta_{rp}\cdot\left(\sum_{j\in J} x_{jkrt} + \sum_{c\in C} q''_{ckrt}\right)\right)\cdot\left(\theta_p\right) \tag{8}$$

Constraint (9) calculates the amount of environmental damage to suppliers.

$$B3 = \sum_{j\in J}\sum_{r\in R}\sum_{t\in T}\left(\sum_{k\in K} xx_{kjrt} + \sum_{m\in M} x'_{mjrt} + \left[\left(\sum_{i\in I} z_{ijk't} + \sum_{n\in N} D''_{njk't}\right)\psi_{k'r}\right]\right)\cdot\left(\theta''_r\right) \tag{9}$$

3.2.9 Social aspect

If a distribution centre, a manufacturing centre (factory), and a supply centre 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 $C3$ by equations (10), (11), and (12), respectively.

Equation (10) calculates the total rate of unemployment reduction if a distribution centre is established in region L.

$$C1 = \sum_{l\in L}\sum_{t\in T}\pi_{lt}\cdot q''_{lt} \tag{10}$$

Constraint (11) calculates the total rate of unemployment reduction if a factory centre is established in region k.

$$C2 = \sum_{k\in K}\sum_{t\in T}\pi'_{kt}\cdot qq'_{kt} \tag{11}$$

Constraint (12) calculates the total rate of unemployment reduction if a supply centre is established in region j.

$$C3 = \sum_{j \in J} \sum_{t \in T} \pi''_{jt} \cdot q'_{jt} \tag{12}$$

Due to the unity of the functions related to each of the considered aspects, to simplify and reduce the dimensions of the problem, we add the sum of each of the functions related to the aspects together. For this purpose, the costs in the supply chain are the amount of damage to the environment and the unemployment reduction rate in different areas of the supply chain max(F3) = C1 + C2 + C3. We also use the weighted sum rule to turn the three-objective problem into a one-objective problem. To use this method, each function is multiplied by the weight that the decision-maker considers given the importance of each function, then the sum of them is regarded as an objective. The transformed form of the objective functions in this research is considered as $F = w_1 f_1 + w_2 f_2 - w_3 f_3$. Because according to the weighted sum method, all objectives must be of type min, the third objective function is considered with a negative sign to be minimised.

3.2.10 Constraints

Constraint (13) specifies the amount of stock in each supplier.

$$\begin{aligned} IS_{jrt} - BS_{jrt} &= IS_{jrt-1} - BS_{jrt-1} + (\varphi_{jt}) \cdot \left[\left(\sum_{i \in I} z_{ijk't} + \sum_{n \in N} D''_{njk't} \right) \psi_{k'r} \right] \\ &+ \sum_{m \in M} x'_{mjrt} + \sum_{k \in K} xx_{kjrt} - \sum_{k \in K} x_{jkrt} \qquad \forall\, j \in J, r \in R, t \in T \end{aligned} \tag{13}$$

Constraint (14) specifies the maximum amount sent from the recycling centre to the supplier and external customers.

$$\begin{aligned} &\sum_{j \in J} D''_{njk't} + \sum_{c' \in C'} DD_{nc'k't} + \sum_{i \in I} DN(n, i, k', t) \le \sum_{r \in R} \Bigg(\sum_{m \in m} \left(DX_{mnrt} \cdot \lambda'_{rk'} \right) \\ &+ \sum_{j \in J} \sum_{r \in R} (1 - \varphi_{jt}) \Bigg) \cdot \left[\sum_{k \in K} x_{jkrt} + zz_{jrt} + \psi_{k'r} \left(\sum_{i \in I} z_{ijk't} + \sum_{n \in N} D''_{njk't-1} \right) \right] \\ &+ \sum_{k \in K} \sum_{r \in R} \sum_{p \in h_r} (1 - \varepsilon_p) \cdot \left(\sum_{r \in h'_p} \eta_{rp} \cdot \left(\sum_{j \in J} x_{jkrt} + \sum_{c \in C} qq''_{ckrt} \right) \right) \qquad \forall\, n \in N, k' \in K', t \in T \end{aligned} \tag{14}$$

Constraint (15) ensures that the return amount sent from the customer centre to the distribution centre must be equal to the amount sent back to the same customer.

$$qq''_{ckrt} = xx'_{kcrt} \qquad \forall\, k \in K, r \in R, t \in T, c \in C \tag{15}$$

Constraint (16) determines the maximum amount of products sent from the collection centre to suppliers.

$$\sum_{j \in J} x'_{mjrt} \le \sum_{p \in h_r} \alpha'_{rp} \cdot \left(\tau_{rp} \cdot \sum_{c \in C} D_{cpt} \right) \qquad \forall\, m \in M, p \in P, t \in T \tag{16}$$

Equation (17) determines the maximum amount of products sent from the collection centre to distributors.

$$\sum_{l\in L} yy''_{mlpt} \le \alpha_{rp}\cdot\left(\tau_{rp}\cdot\sum_{c\in C} D_{cpt}\right) \qquad \forall\, m\in M,\, p\in P, t\in T \tag{17}$$

Constraint (18) determines the maximum amount of products sent from the collection centre to external customers.

$$\sum_{c'} DM_{mc'rt} \le \sigma_{rp}\cdot\left(\tau_{rp}\cdot\sum_{c\in C} D_{cpt}\right) \qquad \forall\, m\in M,\, p\in P, t\in T \tag{18}$$

Constraint (19) specifies the amount of stock in each manufacturer.

$$\begin{aligned} &IF_{kpt} - BF_{kpt} = IF_{kpt-1} - BF_{kpt-1} + \varepsilon_p \\ &\cdot\left(\sum_{r\in h'_p}\sum_{p\in P}\eta_{rp}\cdot\left(\sum_{j\in J} x_{jkrt} + \sum_{c\in C} q''_{ckrt}\right)\right) \\ &-\sum_{l\in L} y_{klpt} - \sum_{c\in C}\sum_{r\in R} xx'_{kcrt} - \sum_{j\in J}\sum_{r\in R} xx_{kjrt} \qquad \forall\, k\in K,\, p\in P, t\in T \end{aligned} \tag{19}$$

Constraint (20) specifies the amount of stock in each distributor.

$$\begin{aligned} &ID_{lpt} - BD_{lpt} = ID_{lpt-1} - BD_{lpt-1} \\ &+\left(\sum_{c\in C} qq_{clpt} + \sum_{r\in R}\sum_{m\in M} yy''_{mlpt}\right) - \sum_{c\in C} q_{lcpt} + \sum_{k\in K} y_{klpt} \qquad \forall\, l\in L,\, p\in P, t\in T \end{aligned} \tag{20}$$

Constraint (21), this constraint assigns the amount of forwarding demand to the distributor.

$$\sum_{l\in L} q_{lcpt} = D_{cpt} + \sum_{l\in L} qq_{clpt} \quad \forall\, c\in C,\, p\in P, t\in T \tag{21}$$

Constraint (22) assigns the amount of reverse demand to the distributor.

$$\sum_{l\in L} qq_{clpt} = D_{cpt}\cdot\tau''_{cpt} \qquad \forall\, c\in C,\, p\in P, t\in T \tag{22}$$

Constraint (23) assigns the amount of reverse demand to the manufacturer.

$$\sum_{k\in K} qq''_{ckrt} = \sum_{p\in P; h'_r} D_{cpt}\cdot\tau_{crpt} \;\; \forall\, c\in C,\, r\in R, t\in T \tag{23}$$

Constraint (24) specifies the capacity of each distributor.

$$ID_{lpt} \le capD_{lpt} \qquad \forall\, l\in L,\, p\in P, t\in T \tag{24}$$

Constraint (25) specifies the capacity of each manufacturer.

$$IF_{kpt} \le capF_{kpt} \qquad \forall\, k\in K,\, p\in P, t\in T \tag{25}$$

Constraint (26) specifies the capacity of each supplier.

$$IS_{jrt} \le capS_{jrt} \qquad \forall\, t\in T \tag{26}$$

Constraint (27) specifies the maximum number of manufacturers at each given time.

$$\sum_{k \in K} qq'_{kt} \leq UU_t \qquad \forall\, t \in T \tag{27}$$

Constraint (28) specifies the maximum number of suppliers at each given time.

$$\sum_{j \in J} q'_{jt} \leq UU'_t \qquad \forall\, t \in T \tag{28}$$

Constraint (29) specifies the maximum number of distributors at each given time.

$$\sum_{l \in L} q''_{lt} \leq UU''_t \qquad \forall\, t \in T \tag{29}$$

Constraint (30), this constraint determines that variables must be based on the binary variable q'_{jt}. In this relation, *MM* is a large number.

$$\begin{aligned} &\sum_{r \in R} BS_{jrt} + \sum_{r \in R} zz_{jrt} + \sum_{n \in N} \sum_{r \in R} D''_{njrt} + \sum_{m \in M} \sum_{r \in R} x'_{mjrt} + \sum_{k \in K} \sum_{r \in R} xx_{kjrt} \\ &+ \sum_{k \in K} \sum_{r \in R} x_{jkrt} \leq q'_{jt} \cdot MM \qquad \forall\, j \in J, t \in T \end{aligned} \tag{30}$$

Constraint (31), this constraint determines that variables must be based on the binary variable qq'_{kt}.

$$\begin{aligned} &\sum_{p \in P} BF_{kpt} + \sum_{l \in L} \sum_{p \in P} y_{klpt} + \sum_{r \in R} \sum_{c \in C} qq''_{ckrt} \\ &+ \sum_{r \in R} \sum_{c \in C} xx_{kcrt} \leq qq''_{kt} \cdot MM \qquad \forall\, k \in K, t \in T \end{aligned} \tag{31}$$

Constraint (32), this constraint determines the value of the variables that must be based on the binary variable q''_{lt}.

$$\begin{aligned} &\sum_{c \in C} \sum_{p \in P} q_{lcpt} + \sum_{c \in C} \sum_{p \in P} qq_{clpt} + \sum_{k \in K} \sum_{p \in P} y_{klpt} \\ &+ \sum_{m \in M} \sum_{v \in V} yy''_{mlvt} \leq q''_{lt} \cdot MM \qquad \forall\, l \in L, t \in T \end{aligned} \tag{32}$$

Constraint (33), this constraint shows the maximum amount sent from the environment to the supplier.

$$\sum_{i \in I} z_{ijk't} \leq \sum_{n \in N} DN(n, i, k', t-d) \qquad \forall\, k \in K, t \in T, t \geq d \tag{33}$$

Constraint (34), this constraint calculates the amount of stock in recycling centres.

$$\begin{aligned} & IN_{nk't} - BN_{nk't} = IN_{nk't-1} - BN_{nk't-1} \sum_{r \in R} \Bigg(\sum_{m \in m} \left(DX_{mnrt} \cdot \lambda'_{rk'} \right) \\ & + \sum_{j \in J} \sum_{r \in R} \left(1 - \varphi_{jt}\right) \Bigg) \cdot \left[\sum_{k \in K} x_{jkrt} + zz_{jrt} + \psi_{k'r} \left(\sum_{i \in I} z_{ijk't} + \sum_{n \in N} D''_{njk't-1} \right) \right] \\ & + \sum_{k \in K} \sum_{r \in R} \sum_{p \in h_r} \left(1 - \varepsilon_p\right) \cdot \left(\sum_{r \in h'_p} \eta_{rp} \cdot \left(\sum_{j \in J} x_{jkrt} + \sum_{c \in C} qq''_{ckrt} \right) \right) \\ & - \sum_{i \in I} DN_{nik't} - \sum_{c' \in C'} DD_{nc'k't} - \sum_{j \in J} D''_{njk't} \qquad \forall\, n \in N, k' \in K, t \in T \end{aligned} \tag{34}$$

Constraint (35), this constraint calculates the amount of stock in collection centres.

$$\begin{aligned} & IM_{mrt} - BM_{mrt} = IM_{mrt-1} - BM_{mrt-1} + \sum_{c \in C} bdm_{cmpt} \\ & - \sum_{n \in N} dx_{mnrt} + \sum_{c'} DM_{mc'rt} + \sum_{l \in L} yy''_{mlpt} + \sum_{j \in J} x'_{mjrt} \qquad \forall\, n \in N, k' \in K, t \in T \end{aligned} \tag{35}$$

Constraint (36), this constraint calculates the capacity of the stock in collection centres.

$$IM_{mrt} \le CapM_{mrt} \qquad \forall\, n \in N, k' \in K, t \in T \tag{36}$$

Constraint (37), this constraint calculates the capacity of stock in recycling centres.

$$IN_{nk't} \le capN_{nk't} \qquad \forall\, n \in N, k' \in K, t \in T \tag{37}$$

Constraint (38) determines the amount of manufacturing in the supplier in terms of capacity.

$$zz_{jrt} \le capzz_{jrt} \cdot q'_{jt} \qquad \forall\, j \in J, r \in R, t \in T \tag{38}$$

Constraint (39) determines the maximum amount sent from collection centres to recycling.

$$\sum_{n \in N} Dx_{mnrt} \le \sum_{c \in C} \sum_{p \in P} \tau_{cpt} \cdot D_{cpt} \cdot \alpha_{rp} \qquad \forall\, m \in M, r \in R, t \in T \tag{39}$$

Constraint (40) determines the maximum amount sent from recycling centres to environmental centres.

$$\sum_{i \in I} DN_{nik't} \le \sum_{r \in R} \lambda''_{rk'} \cdot \sum_{m \in M} Dx_{mnrt} \qquad \forall\, n \in N, k' \in K', t \in T \tag{40}$$

Constraint (41) determines the maximum amount of returned r^{th} parts of the customer from factory centres to supply centres.

$$\sum_{j \in J} xx_{kjrt} \le \sum_{c \in C} qq''_{ckrt} \qquad \forall\, k \in K, r \in R, t \in T \tag{41}$$

Constraint (42), the number of returns and demand to be supplied by each customer.

$$\sum_{l \in L} q_{lcpt} = D_{cpt} + \sum_{l \in L} qq_{clpt} \qquad \forall\, c \in C, p \in P, t \in T \tag{42}$$

Constraint (43), the number of returns that enter the collection centre from each customer.

$$\sum_{m \in M} bdm_{cmpt} = \tau_{cpt} \cdot D_{cpt} \qquad \forall\, c \in C,\, p \in P,\, t \in T \tag{43}$$

4 Results

The mathematical model developed in the previous section has been formulated and implemented in GAMS software. Before implementing the model, it is necessary to consider some assumptions. These assumptions are number of distributors: 2, number of factories (manufacturers): 2, supply centres: 2, customers: 3, collection centres: 3, recycling: centres 2, types of raw materials: 2, number of products: 2, and external customers: 2. Therefore, the results of model solving are reported as follows. The stock of parts in suppliers during the first and second periods is shown in Table 2. According to Table 2, supplier 2 has the highest stock to supply parts in the second period, and supplier 1 has the lowest stock for Part 1 in the first period.

Table 2 The stock of part *r* in supplier *j* at time *t*

IS_{jrt}	*First period*	*Second period*
	Supplier 1	*Supplier 2*
Part 1	6.368	20.035
Part 2	6.482	11.483

Table 3 Sock of product *p* in manufacturer *k* at time *t*

IF_{kpt}	*First period*		*Second period*	
	Manufacturer 1	*Manufacturer 2*	*Manufacturer 1*	*Manufacturer 2*
Product 1	0.000	0.000	0.000	3.719
Product 2	2.256	0.000	0.000	0.000

Table 3 shows the stock of products in manufacturers in the considered periods. According to the results, manufacturers have stock of products in only two cases. For example, in the first period, manufacturer 1 owns only the second product with a value of, and in the second period, manufacturer 2 owns the first product with a value of 3.719. In other cases, the manufacturers' stock of products is zero.

Table 4 shows the number of raw materials transferred from recycling centres to supply centres in the considered periods. Based on the results, the highest amount of transfer is related to raw materials of type 1, which is transferred from recycling centre 1 to supplier 1 in the second period.

Table 5 shows the amount of transfer of parts from collection centres to supply centres in the considered periods. According to the results, the most transferred part from collection centres is related to part 2 to supplier 2 in the second collection centre.

Table 6 shows the number of products transferred from the factory to distributors in each period. Most of the products transferred from the first factory to distributor 2 are

63,069. Also, the lowest amount of transfer of products is related to product 1 from the first factory to distributor 1 in the second period.

Table 4 The amount of transfer of raw materials k's from recycling centres n to manufacturer j at time t

Recycling centre	D''	*First period*		*Second period*	
		Manufacturer 1	*Manufacturer 2*	*Manufacturer 1*	*Manufacturer 2*
$n = 1$	Product 1	0	13.073	53.257	0
	Product 2	13.073	0	0	0
$n = 2$	Product 1	13.073	13.073	0	0
	Product 2	0	0	0	0

Table 5 The amount of transfer of part r from collection centres m to supplier j at time t

Collection centre	x'	*First period*		*Second period*	
		Supplier 1	*Supplier 2*	*Supplier 1*	*Supplier 2*
$m = 1$	Product 1	0	0	0	0
	Product 2	1.312	0	0	0
$m = 2$	Product 1	0	0	0	0
	Product 2	0	1.312	0	1.951

Table 6 The amount of transfer of product p from factory k to distributor j at time t

Factory	y	*First period*		*Second period*	
		Distributor 1	*Distributor 2*	*Distributor 1*	*Distributor 2*
$k = 1$	Product 1	0	0	4.185	63.069
	Product 2	0	0	56.237	11.92
$k = 2$	Product 1	24.000	23.917	3.155	0
	Product 2	41.266	22.905	0	1.757

Table 7 shows the number of parts transferred from the factory to customers in the considered periods. The highest number of parts transferred to customers is 14.916, which is transferred from factory 2, part 1 to customer 1 in the second period. The number of other transfers is shown in Table 7.

Table 7 The amount of transfer of part r from factory k to customer c at time t

Factory	xx'	*First period*			*Second period*		
		Customer 1	*Customer 2*	*Customer 3*	*Customer 1*	*Customer 2*	*Customer 3*
$k = 1$	Product 1	0	0	0	0	0	0
	Product 2	0	0	0	4.909	8.794	6.680
$k = 2$	Product 1	7.988	10.615	14.744	14.916	11.042	12.305
	Product 2	2.614	5.478	7.970	0	0	0

Table 8 shows the number of parts transferred from supply centres to the factory in the considered periods. According to the results, most transfers of parts are related to part 1 from supplier centre 1 to factory 1 in the second period, which is equal to 43,571. Also, the lowest transfer amount is related to part 2 from supplier centre 2 to factory 1 in the second period. Therefore, we conclude that factory 1 receives the most parts from the first supplier centre and the least parts from the second supplier centre.

Table 8 The amount of transfer of part *r* from distribution centres *j* to factory *k* at time *t*

Factory	*x*	*First period*		*Second period*	
		Distributor 1	*Distributor 2*	*Distributor 1*	*Distributor 2*
$k = 1$	Product 1	0	0	43.571	0
	Product 2	0	34.142	0	0
$k = 2$	Product 1	0	0	0	0
	Product 2	0	25.258	23.680	0

Table 9 shows the amount of returned products that customers send to the manufacturing centre. Based on the results, product 1 has the highest amount of return to manufacturer 2 in terms of customer 1. Also, the lowest return product is 2.614, which is related to product 2 to manufacturer 1.

Table 9 The amount of returned product *p* by the customer to manufacturing centre *k* at time *t*

Customer	qq''	*First period*		*Second period*	
		Distributor 1	*Distributor 2*	*Distributor 1*	*Distributor 2*
$c = 1$	Product 1	0	7.988	0	14.916
	Product 2	0	2.614	4.909	0
$c = 2$	Product 1	0	10.161	0	11.042
	Product 2	0	5.478	8.794	0
$c = 3$	Product 1	0	14.744	0	12.305
	Product 2	0	7.970	6.980	0

Table 10 shows the number of parts transferred from the recycling centre to external customers in the considered period. Based on the calculated results, the highest transfer is related to part 1 from recycling centre 2 to external customer 1.

Table 10 The amount of transfer of part *r* from recycling centre *n* to external customers c' at time *t*

Recycling	*DD*	*First period*		*Second period*	
		External customers 1	*External customers 2*	*External customers 1*	*External customers 2*
$n = 1$	Product 1	0	0	0	0
	Product 2	0	0	22.943	0
$n = 2$	Product 1	0	0	52.799	0
	Product 2	0	0	0	23.317

Table 11 shows the number of parts transferred from collection centres to external customers in the considered period. According to the results, the amount of transfer of parts related to customer 1 in collection centre 2 in the second period is 5.566. Also, the lowest amount of transfers related to collection centre 1 to external customer 2 in period 1 is 2.024.

Table 11 The amount of transfer of part r from collection centre *m* to external customers *c′* at time *t*

Collection centres	*DM*	*First period*		*Second period*	
		External customers 1	*External customers 2*	*External customers 1*	*External customers 2*
$m = 1$	Product 1	3.341	0	0	0
	Product 2	0	2.024	0	0
$m = 2$	Product 1	0	3.383	5.566	0
	Product 2	2.526	0	0	3.613

Table 12 shows the number of products that customers receive from distribution centres in the considered period. According to the results, customer 1 receives the most products in period 2 from distribution centre 2 with a value of 44.069. The lowest amount that customers receive is from distribution centre 1 in period 2 received by customer 2 with a value of 17.410.

Table 12 The amount of transfer of product *p* to customer *c* from distribution centre *I* at time *t*

Distribution centres	*q*	*First period*			*Second period*		
		Customer 1	*Customer 2*	*Customer 3*	*Customer 1*	*Customer 2*	*Customer 3*
$k = 1$	Product 1	0	25.575	0	0	17.410	0
	Product 2	12.262	0	29.581	28.612	0	29.639
$k = 2$	Product 1	23.527	0	22.440	44.069	0	19.439
	Product 2	29.585	0	0	0	31.763	0

Table 13 shows the number of parts transferred from collection centres to distribution centres in the considered periods. The highest transfer from collection centre 2 to distributor 2 in the second period is 5.238 and the lowest transfer with a value of 2.148 is from the first collection centre to distributor 1 in the second period.

Table 13 The amount of transfer of part *r* from collection centre *m* to the distribution centre *I* at time *t*

Collection centres	yy''	*First period*		*Second period*	
		Distributor 1	*Distributor 2*	*Distributor 1*	*Distributor 2*
$m = 1$	Product 1	0	2.771	2.148	0
	Product 2	0	0	0	4.220
$m = 2$	Product 1	0	2.771	2.148	0
	Product 2	0	2.194	0	5.238

Table 14 shows the amount of product returned from customers to collection centres in the considered period. The most product returned from customer 2 to collection centre 2 is in the second period. Also, the lowest amount of product returned is related to customer 3 to collection centre 2 in period 2.

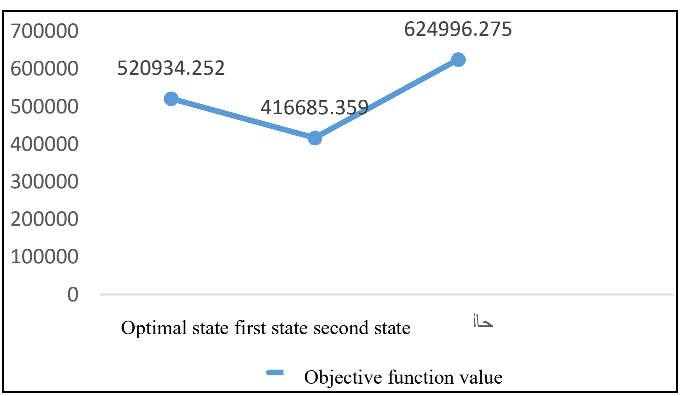
Table 14 The amount of product *p* returned from customer *c* to collection centre *m* at time *t*

Customer	*bdm*	*First period*		*Second period*	
		Collection centre 1	*Collection centre 2*	*Collection centre 1*	*Collection centre 2*
$c = 1$	Product 1	0	4.392	0	4.509
	Product 2	2.184	0	0	5.020
$c = 2$	Product 1	3.983	0	0	2.366
	Product 2	1.151	2.942	0	5.782
$c = 3$	Product 1	2.129	2.217	2.147	0.839
	Product 2	0	3.811	4.220	0

Table 15 Sensitivity analysis of objective function coefficients

State	*Weights*			*Objective function value*
	w_1	w_2	w_3	
One	0.4	0.3	0.3	416,685.359
Two	0.6	0.2	0.2	624,996.275

Figure 2 Comparison of considered states with the optimal state (see online version for colours)



Considering the obtained values, the optimal value of the objective function is 520,834.252. In the following, we want to carry out a sensitivity analysis for the problem by changing the parameters on which the answer depends. Considering that the value of the objective function depends on the weights that we assign to the objective functions according to the weighted sum method, we want to examine the optimal value of the objective function by changing the value of the weights of the objective functions. Table 15 shows the value of change of the objective function for change in values. According to the calculated results, it is found that the value of the objective function is sensitive to the weight of the first objective function. So that if the value decreases from

0.5 to 0.4, the value of the objective function decreases from 520,834.252 to 416,685.359. Consequently, if the value increases from 0.5 to 0.6, the value of the objective function increases from 520,834.252 to 624,996.275. Also, Figure 2 shows a comparison of the considered states for the weights of the objective functions for the value of the objective function.

5 Conclusions

In the literature, the circular design has been introduced as a tool to move away from the classic linear economy take-make-dispose model. The latter model is the fundamental challenge of the current economic arrangement, to get a more restorative, regenerative, and CE. To survive in a CE, products must cope with closed loops and adapt to make money (Moreno et al., 2016; Sariatli, 2017). The CE is suggested as a way to cultivate the economy while it remains a viable, sustainable, and inevitable alternative capable of dealing with problems of the current economic arrangement. This approach insists on recycling used products as well as their parts and materials. It also longs to remanufacture, fix and refurbish and cascade these products throughout the value chain and cradle to cradle life cycle (Sariatli, 2017; Korhonen et al., 2018). Quite a lot of applications exist on which the CE has a positive effect, such as supply chains, that require a model change when migrating from a linear to a sustainable supply chain (Govindan and Hasanagic, 2018). Using facts from this research, we found that circular-based supply chain design which integrates supply chain with a CE, has received less attention in studies and CSCM is an emerging area. Most of the published studies are case studies and conceptual works that are general to an infant topic. That is why the present work puts emphasis on these issues:

- Developing mathematical schemes to optimise the CLSC network that bears the concept of the CE.
- Developing a multi-objective mathematical planning model that considers minimising total supply chain costs, unstable products that are being disposed of, and environmental pollution all at once along with maximising the number of jobs created to optimise a CLSC network with great emphasis on CE.
- Considering a framework for validation and solution of the developed model with an appropriate computational model.

Hence the most critical and valuable aspect of our study lies in providing a multi-objective mathematical planning model that includes: minimising the total supply chain costs, minimising unusable products that are disposed of, minimising environmental pollution, and maximising the number of jobs created to optimise the CLSC network with emphasis on the concept of CE simultaneously.

The proposed model for the environmental organisation applies to all jobs related to the production of digital goods (laptops, smart TV, smartphones, etc.). It also benefits all members of society by reducing environmental pollution. For further research, it is suggested that consideration of uncertainty and robust planning can be added to the idea of a CE for other studies. The use of efficient metaheuristic algorithms in computing is also recommended.

Also, other further studies are suggested as follows:

1 Considering the proposed model as a scenario and solving the proposed CLSC model using robust optimisation.

2 Considering resiliency in the designed model.

3 Considering other objectives in the proposed model, such as minimising service providing time and maximising coverage level.

This research is not free of assumptions and limitations like every other research. Some of these limitations are mentioned in the coming parts of the text. Since no official data for some parts of cost elements were available, the driver's estimations were asked to help.

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