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RESEARCH PAPER

# Capacitated Sustainable Resilient Closed-Loop Supply Chain Network Design: A Heuristics Algorithm

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## Abstract

Consideration of environmental and social issues in addition to economic ones is a critical strategy that companies pay special attention to designing their supply chain. A resilient system prevents organizations from being surprised by catastrophic disruptions and critical conditions and eliminates high unwanted costs. In this study, a mixed-integer mathematical programming model is proposed to design a sustainable and resilient closed-loop supply chain network. Since suppliers are the most important external players, the slightest probability of disruptions can have a significant impact on chain performance. Accordingly, applying efficient strategies can be very helpful for coping with them. Also, because of the uncertain nature of some input parameters, the *P*-robust optimization method has been used to tackle them. An efficient algorithm has been carried out beside a heuristic method based on the strategic variables relaxation to solve the model. A case study of a lighting projectors industry has been conducted to evaluate the efficiency of the proposed approach. Finally, sensitivity analysis is performed on critical parameters of the problem. By solving the example, it is seen that 3 primary suppliers and 3 backups are selected, and 3 production centers, 2 collection centers and 1 repair, recycling and disposal centers have been established. The value of the economic objective function is equal to 565.857552 monetary units (MU). The CL-SCN environmental score is 658.07, while it is 608.93 in the social dimension. Eventually, the value of the final multi-objective function is equal to 0.658.

**Keywords:**
Closed-Loop Supply Chain Network;
Sustainability;
Resilience;
Heuristic Algorithm;
Uncertainty;
Lighting Projectors Industry

## Introduction

The supply chain (SC) includes many players who are operating to satisfy their customers' demands. Supply chain management (SCM) is a noteworthy subject in all organizations recently, in addition to concepts such as cost, quality, etc. Other ideas, such as resilience, agility, and sustainability have also received special attention.

In the 21st century, sustainability is a main priority in supply chain network design (SCND). To achieve sustainability, systems try to make products that improve the long-term performance to solve social, economical, and environmental issues in the SC [1]. Sustainable SC has an effective role in achieving a better performance of the organization, including attracting government support and creating a competitive advantage, reducing costs, effectively reducing unemployment, ensuring equal treatment, protection and health of employees, safety and prevention of social exclusion, better product quality, environmental protection, increasing employee motivation and productivity, etc. Therefore, designing an SC network taking into

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account sustainable development considerations, causes the intended SC to improve efficiency in economical, environmental, and social dimensions in the long-term future [2]. On the other hand, today, the customers of SCs pay much attention to environmental and social issues that numerous governmental and non-governmental organizations consider them more important than economic issues. Therefore, it seems vital to adopt an approach such as closed-loop supply chain network design (CL-SCND), which allows the return and reuse of inappropriate products and raw materials.

Research in the field of SC resilience is one of the new topics in risk management that helps managers. Given the increasing importance and complexity of SCM for organizations in today's business environment full of disruption, it is necessary to anticipate and realize the resilience capabilities of the SC to deal with or prevent disruption in the activities of the organization.

Unusual conditions in the SCN are called disruptions that occur with low probability and high severity of the effect. The modern market is characterized by high levels of volatility and turbulence. Demand in every industry has fluctuated a lot compared to the past and also, the competitiveness of the markets has shortened the life of the products. During this time, SC vulnerabilities to disruptions have also increased. Therefore, the field of SCM disorders has attracted the attention of many researchers and many articles have been published in this regard.

Resilience before adaptation to the context of supply chain management is a multidimensional, multidisciplinary concept with roots in psychology and ecosystems [3].

SCND not only requires resilience to errors and disruptions, but also the need for resilience as the ability of a system to return to its original state or move after turbulence to a new and more desirable state in which consolidated demand It is about flexibility and adaptability [4]. When disruption occurs, there are few mobile resources in terms of infrastructure, the reason being that such strategic decisions cannot be changed quickly. Therefore, it is necessary to consider these events while designing the network. In fact, such systems are much more reliable and less expensive. Therefore, in the field of strategic planning under uncertainty, important concepts such as agility, adaptability, responsiveness, resilience and flexibility have been used. This leads to an increase in the organizational approach to risk and that is why SC costs are eliminated by reducing disruption costs [5,6].

The SCs face some risks that sometimes have a significant impact on their performance and cause disruption and affect the quality, cost, and sustainability of their system. The SC must be designed in such a way that it can withstand these risks and return to its optimal state in a reasonable time, or so-called must be resilient. In other words, resilience helps SCs not be affected by disruptions and continue to operate [7]. Consideration of SC resilience, besides sustainable development investigations, can have a significant effect on the competitiveness of SCs as the primary goal in competitive markets.

In this paper, scholars have tried to control several disruptions in suppliers and the transportation roads among SC echelons by considering the production and sale cycle as well as returning products. The supplier is one of the vital players in the SC and occurrence of disruption which can have irreparable damages because of some reasons such as price fluctuations, impossibility to supply the required raw materials, change in supply policies, etc. Therefore, an efficient strategy utilizing backup suppliers has been applied to resolve potential disruptions.

According to today's trading and technical conditions, the data required to design an SCN are not accurately available. This uncertainty arises from various reasons and factors that can cause trouble in the optimal outcomes, including product features, SC structure, information system complexity, customer’s final demand, escalation of demand, suppliers, infrastructure and facilities, environment, natural disruptions. For example, uncertain demand can have a significant impact on production, shipment time.

Accordingly, the proposed approach designs a six-echelons (consisting of the supplier, manufacturer, collection, repair, disposal, and customers) resilient CL-SCN concerning sustainable development considerations in an uncertain environment. Generally, it studies six categories of decisions, including selecting suppliers, facility location at different echelons, capacity planning, determining production volume, amount of products transferred between different echelons, and the shortage level in the SC.

The rest of the paper is structured as follows: Section 2 reviews the existing literature and research gaps related to resilient and sustainable CL-SCND (RSCL-SCND). The proposed model for the intended problem is presented in Section 3. Since the considered RSCL-SCND operates in an uncertain environment, it is necessary to adopt an efficient uncertain optimization method. Therefore, a robust RSCL-SCND scenario-based optimization method is presented to tackle it in Section 4. Model performance is evaluated by a practical example and sensitivity analysis on some crucial parameters of the model in Section 5. Finally, conclusions and future research directions are carried out in Section 6.

## Literature review

The existing literature on RSCL-SCND in an uncertain environment can be divided into four categories: I) CL-SCND under mixed uncertainties, II) sustainable CL-SCND, III) resilient CL-SCND and IV) resilient and sustainable CL-SCND.

### CL-SCND under mixed uncertainties

Fleischmann et al. [8] designed an integrated logistics network considering demand uncertainty. Vahdani et al. [9] proposed a multiple-period model for the CL-SCND, considering uncertain demand, costs, distance, and capacity. Pishvaee et al. [10] presented a bi-objective stochastic mixed-integer programming model that is adaptable to consider different uncertainties. Amin and Zhang [11] studied a CL-SCN, including factories, collection centers, demand zones, and products under uncertainty of demand and return rate. Baqalian et al. [12] proposed a stochastic mathematical programming model to design a food product supply network under disruption and uncertainty. Jabbarzadeh et al. [13] presented a hybrid stochastic optimization model for designing an SCN in which two categories of uncertainty in parameters and disruption in facilities are considered. The Lagrangian relaxation approach has been used to solve the larger sizes model.

Fazli-Khalaf et al. [14] proposed a mathematical programming model for designing a bi-objective stable CL-SCND. Due to the uncertainty in input data, they used scenario-based stochastic programming to tackle this combined uncertainty. Gholami et al. [15] presented a four-echelon multi-objective linear integer SCN under uncertainty. To tackle natural disruptions, they presented their model in stable conditions so that it can return to its initial state at the appropriate time after the occurrence of disruption. Islam et al. [16] presented an inventory programming model for an uncertain SCN in probable disruption conditions.

Tolooie et al. [17] addressed issues bordering on capacitated supply chain problems, specifically on how reliable supply chain networks can be designed in the face of random facility disruptions and uncertain demand with a combination of hardening selected facilities and product reassignment. The proposed multi-period capacitated facility location and allocation problem are modeled as a two-stage stochastic mixed-integer formulation that minimizes the total establishing and transportation cost. The L-shaped method of stochastic linear programming is applied by integrating with two types of optimality and feasibility cuts for solving the stochastic model.

Yan and Ji [18], analyzed an uncertain programming model to design the three-echelon supply chain network with the disruption risk, in which disruptions are considered as uncertain events. Under the constraint of satisfying customer demands, the model optimises the selection of retailers with uncertain disruptions and the assignment of customers and retailers, in order to minimise the expected total cost of network design. Zhu and Cao [19] introduced a novel recovery strategy, which used the investment to adjust the recovery speed and duration of production capacity, and modeled two recovery behaviors responding to different types of disruptions. They applied the risk-averse two-stage stochastic programming model for coping with the uncertain disruption scenarios and their ripple effects over the supply chain.

**Sustainable CL-SCND**

There are several studies in the CL-SCND that have considered sustainability considerations, while in some cases, only two of the three dimensions are considered. Pishvaei et al. [20] designed a sustainable SC by considering the criteria of created jobs, the use of hazardous materials and working conditions, Greenhouse gas emissions, and the total network costs. Yu et al. [21] presented a multi-objective model for designing an ethanol SC, taking into account three sustainability dimensions, including network costs, the life cycle of greenhouse gas emissions, and the number of created jobs per unit. Zhang et al. [22] optimally designed the SC by considering costs, greenhouse gas emissions, and response time (Chain Response Scale) as three sustainability criteria. Motta et al. [23] adopted the LCA method as a reliable method to evaluate environmental impacts, the negative effect of unemployment on society, and the total network design costs. Shen [24] introduced a sustainable multi-objective uncertain SC model and tackled the uncertainty by chance constraint. A hybrid genetic algorithm based on chromosome coding with variable length has been applied to solve the model. Zarei et al. [25] designed a mixed-integer linear programming model for optimizing the strategic and tactical decisions of the sustainable SC. Finally, they used data related to the gas industry to validate the model. Durmaza and Bilgen [26] optimally designed the biomass SCN taking into account sustainability considerations. They used geographic information systems (GIS) and the analytical hierarchy process (AHP) to determine the candidate point locations for biomass facilities. Mastrocinque et al. [27] presented a multiple criteria decision making (MCDM) framework due to the AHP and sustainable development in the renewable energy industry. They found that 86.8% of the total photovoltaic energy capacity of installed equipment in Europe is in operation. Recently, Jia et al. [28] have reviewed the literature on sustainable SC financing and identified potential future research issues.

Kalantari and Hosseininezhad [29], proposed a sustainable global food supply chain model with risk considerations. Perishable foods begin to deteriorate after being produced. Therefore, without proper maintenance and transportation, the inventories may deteriorate quickly before being used which leads to unavoidable costs. The proposed model has four levels; suppliers, producers, warehouses and demand centers.

Tseng et al. [30], contributed to developing the existing knowledge regarding data-driven sustainable supply chain management indicators under industrial disruption and ambidexterity. They proposed that the hybrid method generates indicators from a database and is based on the existing literature. This study proposed using the fuzzy Delphi method to validate these indicators in the textile industry and apply the best and worst methods to examine the most effective and ineffective indicators. Yazdanparast et al. [31] proposed a practical optimization model for the development of drop-in biofuels using the existing petroleum infrastructure. Their model took potential supply and production disruptions into account, and investigates four proactive strategies: flexible supply contracts, infrastructure fortification, alternative production routes, and prepositioning of emergency inventory to improve overall SC resilience.

Furthermore, a risk-averse two-stage stochastic program is developed to cope with uncertainty where a conditional value-at-risk (CVaR) is used as the risk measure.

**Resilient CL-SCND**

Kamalahmadi and Mellatparast [32] presented an integrated two-phase mixed-integer programming model to select suppliers and allocate orders with transportation channel selection. They also presented the appropriate programs to reduce the adverse effects of disruptions and minimize total network costs in a resilient SC. Poudel et al. [33] proposed a mathematical programming model for a resilient biomass fuel SC. They stated that since the facilities used in this SC may fail and cause problems for the system, multiple facilities have been used to deal with this disruption. Azad and Hosseini [34] proposed a mixed-integer programming model for a stable SCN resilient to unforeseen disruptions. Eventually, they concluded that their proposed model improved redundancy and total costs by 50% and 8%, respectively. Haghjoo et al. [35] designed a location-allocation network in the SC under the probability of facility disruption.

**Resilient and sustainable CL-SCND**

Soleimani et al. [36] designed a CL-SCND to minimize total profits and lost workdays due to occupational accidents as well as maximize satisfying demands. SahebJamnia et al. [37] developed a mixed multi-objective linear programming model for designing a sustainable CL-SCND. Zahiri et al. [38] proposed a sustainable-resilient integrated linear programming model for a drug SCN under uncertainty. Carvalho et al. [39] studied an SC simulation for a real case of a car SC. This study aims to evaluate alternative SC Scenarios to improve system resiliency in disruption time and to comprehend how reduction strategies affect SC performance. Jabbarzadeh et al. [40] stated that resilience in both sustainable development and the prevention of disruption occurring are two critical issues in the SC. Ahranjani et al. [41] proposed a mixed-integer mathematical optimization model for designing a bioethanol SCN taking into account sustainable development considerations. They adopted a hybrid robust possibilistic optimization approach to deal with unforeseen disruptions imposed on the system.

Mousavi Ahranjani et al. [42] proposed a mixed-integer linear sustainable programming model to address the design and planning of a multi-feedstock lignocellulosic bioethanol supply chain network. They employed a hybrid robust stochastic-possibilistic programming approach to cope with the resiliency against existing epistemic uncertainties and disruption risks in the supply chain. Sarkar et al. [43] introduced an optimization model for planning a versatile and dependable biomass-to-bioenergy sustainable supply chain network in which crop residuals from several agricultural sectors, multi-transportation disruption modes, multi-biorefineries, multi-biogas plants, and multi-market centers are investigated for two bioenergy sources, namely biofuel and biogas. For this reason, they analyzed three objective functions including economical, environmental and social pillars of sustainability.

Taleizadeh et al. [44] addressed bi-level programming to optimize a sustainable supply chain by considering resilience factors and pricing decisions. Moreover, it is defined how the governments can optimize and affect environmental and social responsibility by setting an emissions tax rate. They applied the Stackelberg game model while the government is considered as the leader and the manufacturer as the follower.

**Main contributions**

According to the relevant studies and Table 1, the main contributions of this paper are as follows:

- Designing six-echelon CL-SCN with respect to sustainable development considerations and system resiliency simultaneously. Given that in real-world businesses, the data is needed to be studied and planning different supply chains are not definitive and deterministic, it is very important to pay attention to the uncertainty in the input data. Also, paying attention to the reliability of the supply chain system ensures the absence of disruption, which causes the system to continue to operate normally in the event of this disruption. On the other hand, simultaneous attention to the dimensions of sustainable development, including the economy, society and the environment, makes the planned supply chain as friendly to humanity and the environment. Therefore, simultaneous attention to the characteristics of uncertainty, reliability and sustainability, makes complete and comprehensive planning for the supply chain.
- Dealing with disruptions in the supplier echelon and the transportation roads between supplier and manufacturer due to the backup system strategies,
- Considering uncertainty in parameters which exact determination or estimation of them is a difficult and unrealistic process, such as customer's demands and product return rate,
- Considering lost demand caused by the shortage,
- Proposing a heuristic algorithm to solve large-scale instances,
- Presenting a practical example in the lighting projectors industry.

## Problem description

This paper focuses on a CL-SCND of electrical devices (projectors) that can be repaired, reused, or destroyed. It also considers economic, environmental, and social aspects under uncertainty and disruption risks in suppliers and their transportation roads.

Fig. 1 shows the structure of the intended CL-SCN. The raw materials move forward from the supplier to the manufacturer. After the production process, the products are sent directly to the customers without intermediaries. Meanwhile, due to limited resources, it is possible to face a shortage and report it as a lost demand. Customers may return the received products to collection centers for reasons like expiration, breakdown, obsolescence, or environmental and social considerations. Then, they are entitled to a discount given by the manufacturer for subsequent purchases. This matter not only allows the manufacturer to retain its loyal customers but also satisfies customers by receiving services as compensation for returning products.

**Table 1.** The literature review

| Scholars | Sustainability: Economical | Sustainability: Environmental | Sustainability: Social | Resiliency | Uncertainty | Multi-Objective Method | Solution Algorithm/ Software | Problem Data |
|---|---|---|---|---|---|---|---|---|
| Min, & Ko (2008) | * | | | | | | Genetic Algorithm | Numerical Example |
| Pishvaee et al. (2011) | * | | | | * | | Branch and Bound | Numerical Example |
| Vahdani et al. (2012) | * | | | | | | Hybrid metaheuristic | Numerical Example |
| Amin & Zhang (2012) | * | | | | * | Fuzzy sets theory + compromise programming | Branch and Bound | Numerical Example |
| Pishvaee et al. (2012) | * | | * | | * | ε-constraint | Branch and Bound | Numerical Example |
| You et al. (2012) | * | * | * | | | ε-constraint | Branch and Bound | Dow Chemical business |
| Baghalian et al. (2013) | * | | | * | * | | Branch and Bound | Agri-Food/ IRAN |
| Zhang et al. (2014) | * | * | * | | | ε-constraint | Branch and Bound | Agri-Food/ State of Illinois |
| Mota et al. (2015) | * | * | * | | | ε-constraint | Branch and Bound | Batteries Industry/ Portugal |
| Jabbarzadeh et al. (2016) | * | | | * | * | | Lagrangian Relaxation | Sepahan Oil Company/ IRAN |
| Zhalechan et al. (2016) | * | | * | * | * | | self-adaptive hybrid genetic algorithm | LCD and LED TVs supply chain/ IRAN |
| Fazli-Khalaf et al. (2017) | * | * | | * | * | ε-constraint | Branch and Bound | Numerical Example |
| Soleimani et al. (2017) | * | * | * | | * | Fuzzy Programming | Branch and Bound +Genetic algorithm | Numerical Example |
| Zahiri et al. (2017) | * | * | * | * | * | multi-objective evolutionary algorithm | | Pharmaceutical supply chain network/ France |
| Poudel et al. (2018) | * | | | * | | | Constraint Generation Algorithm | Biomass Supply chain/ Mississippi and Alabama states |
| Sahebjamnia et al. (2018) | * | * | * | * | * | ε-constraint | Hybrid meta-heuristics | Numerical Example |
| Jabbarzadeh et al. (2018) | * | | * | * | | | Branch and Bound | Plastic pipes/ IRAN |
| Gholami et al. (2019) | * | | * | * | * | Goal programming, compromise programming | Branch and Bound | Numerical Example |
| Azad & Hassini (2019) | * | | | * | | | Benders decomposition | Numerical Example |
| Islam et al. (2020) | * | | | * | * | | Genetic Algorithm+Simulated Annealing | Numerical Example |
| Shen (2020) | * | * | * | | * | Chance-constrained | Hybrid Genetic Algorithm | Numerical Example |
| Zarei et al. (2020) | * | * | * | | | Fuzzy Programming | Branch and Bound | Gas Company/ IRAN |

**Table 1.** The literature review

| Scholars | Sustainability: Economical | Sustainability: Environmental | Sustainability: Social | Resiliency | Uncertainty | Multi-Objective Method | Solution Algorithm/ Software | Problem Data |
|---|---|---|---|---|---|---|---|---|
| Durmaz & Bilgen (2020) | * | * | | | | | GIS + AHP Branch and Bound | poultry supply chain/ Turkey |
| Mastrocinque et al. (2020) | * | * | * | | | | AHP Technique | Renewable Photovoltaic energy/ Europe |
| Haghjoo et al. (2020) | * | | | * | * | | Branch and Bound +Imperialist Competitive Algorithm | Numerical Example |
| Tirkolaee et al. (2020) | * | * | * | | | Weighted goal programming | Fuzzy ANP+ Fuzzy DEMATEL+Fuzzy TOPSIS | electronics lamp supply chain/ IRAN |
| Ahranjani et al. (2020) | * | | | * | * | | Branch and Bound | cereals supply chain/ IRAN |
| **Current Study** | ● | ● | ● | ● | ● | **Torabi-Hassini** | **Heuristics Algorithm** | **Power Projection Supply Chain/ IRAN** |

As a remarkable point, the production of a sustainable product has become such an essential issue whether as a consumer or as a manufacturer that consumers have reformed their shopping behavior because of the importance of environmental, social, and economic issues which today are of concern in life and society. Moreover, in order to support the sustainable development dimensions, manufacturers produce products that have the least environmental negative impacts at the same time, the most positive social and economic impacts. Accordingly, the collected returned products are checked in terms of quality such that those that are of good quality for repair or reuse, are sent to recycling centers and are put back in the sale cycle after required repairs. The remaining low-quality products are destroyed in disposal centers.

Since the supplier echelon is one of the most important players in the CL-SCN in which there is a possibility of disruption occurring in critical situations, the backup facilities strategy has been adopted for suppliers and their transportation roads to the manufacturer echelon. In addition, because estimating the values of parameters such as demand, cost, and the product return rate is impractical in the current situation, an efficient approach is adopted to deal with this uncertainty.

Consequently, in this paper, a multi-objective mixed integer mathematical programming model, including minimizing the total network costs, maximizing the performance of positive environmental issues as well as maximizing the performance of positive social issues, has presented for designing a resilient CL-SCN taking into account sustainable development considerations and the allowable shortages.

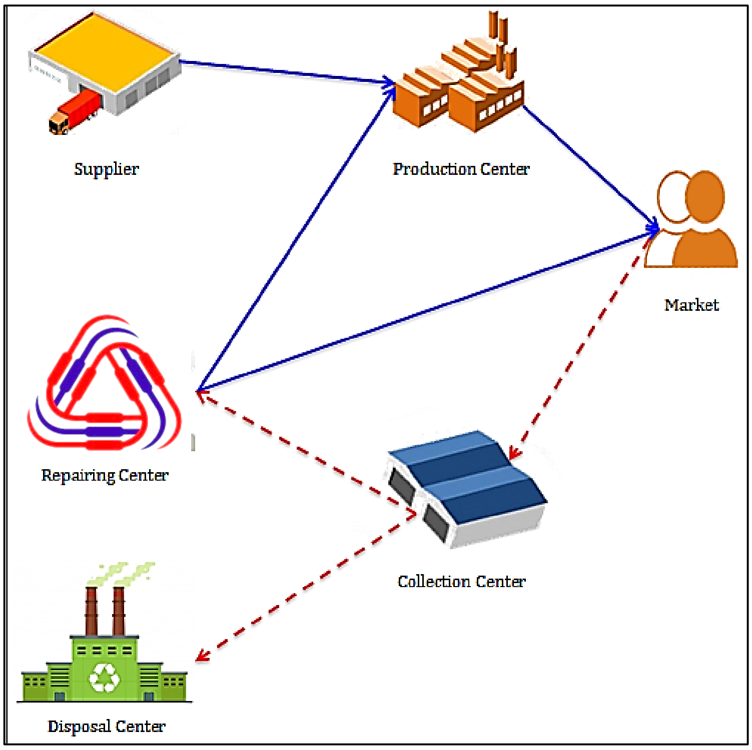



**Fig. 1.** The structure of the proposed CL-SCN.

Accordingly, the following important assumptions are taken into account to formulate the proposed model:

- The shortage is allowed and considered as the lost sale costs.
- The potential facility locations, including suppliers, manufacturers, collection centers, repair centers, and disposal centers are predetermined.
- Due to the nature of the problem, parameters demand, cost, and product return rate have uncertainty.
- There is a probability of disruption in suppliers and transportation roads between supply and production echelons.
- The backup supplier and transportation roads are always available and usable for an additional fee.
- All facilities are capacitated.
- It is possible to plan the capacity of facilities by selecting modular capacity.
- The exchange rate is not considered in exports and imports.

## Notations

The following indices, parameters, and decision variables are used in the formulation:

*Sets*:

| | |
|---|---|
| $Ro$ | : Set of raw materials ($ro \in Ro$) |
| $p$ | : Set of first-rate products ($p \in P$) |
| $P'$ | : Set of second-rate products (repaired products) ($p' \in P'$) |
| $Dp$ | : Set of discarded parts ($dp \in Dp$) |
| $S_1$ | : Set of main suppliers ($s_1 \in S_1$) |
| $Cu$ | : Set of customers ($cu \in Cu$) |

| | |
|---|---|
| $Co$ | : Set of potential collection centers ($co \in Co$) |
| $F$ | : Set of potential production centers ($f \in F$) |
| $Re$ | : Set of potential repair centers ($re \in Re$) |
| $Di$ | : Set of potential disposal centers ($di \in Di$) |
| $Ca_f$ | : Set of multiple capacity levels of production centers |
| $Ca_{co}$ | : Set of multiple capacity levels of collection centers |
| $Ca_{re}$ | : Set of multiple capacity levels of repair centers |
| $Ca_{di}$ | : Set of multiple capacity levels of disposal centers |
| $L$ | : Set of transportation roads between suppliers and production centers ($l \in L$) |

*Parameters:*

| | |
|---|---|
| $RM_{ro}^{p}$ | : The amount of required raw material *ro* to produce each unit of product *p* (Mass unit) |
| $Cap_{ro}^{s_1}$ | : The capacity of supplying raw material *ro* by supplier $s_1$ (Mass unit) |
| $Dem_{p}^{Cu}$ | : Predicted demand of product *p* for customer *cu* (Mass unit) |
| $Dem_{p'}^{Cu}$ | : Predicted demand of product *p'* for customer *cu* (Mass unit) |
| $Ssf_{s_1}$ | : Fixed cost of evaluating and selecting supplier $s_1$ (monetary unit*)* |
| $Mef_{Ca_f}^{f}$ | : Fixed cost of establishing a production center with capacity level $Ca_f$ at location *f* (monetary unit) |
| $Cef_{Ca_{Co}}^{co}$ | : Fixed cost of establishing a collection center with capacity level $Ca_{co}$ at location *co* (monetary unit) |
| $Ref_{Ca_{Re}}^{re}$ | : Fixed cost of establishing a repair center with capacity level $Ca_{re}$ at location re (monetary unit) |
| $Def_{Ca_{Di}}^{di}$ | : Fixed cost of establishing a disposal center with capacity level $Ca_{di}$ at location di (monetary unit) |
| $Sv_{ro}^{s_1,f}$ | : Variable cost of purchase of each unit of raw material *ro* from supplier $S_1$ for factory *f* (monetary unit) |
| $Mv_{p}^{f,cu}$ | : Variable cost of production each unit of product *p* in production center f for customer cu (monetary unit) |
| $Rv_{p'}^{re}$ | : Variable cost of recovery each unit of product *p'* in the repair center re (monetary unit) |
| $Cv_{p}^{cu,co}$ | : Variable cost of storage and examination each unit of product *p* sent from the customer *cu* to the collection center *co* (monetary unit) |
| $Dv_{p}^{co,di}$ | : Variable cost of disposal each unit of product *p* sent from the collection center *co* to the disposal center *di* (monetary unit) |
| $Sor_{p}^{cu}$ | : Unit cost of lost sales for each unit of product *p* for the customer *cu* (monetary unit) |
| $Sor_{p'}^{cu}$ | : Unit cost of lost sales for each unit of product *p'* for the customer *cu* (monetary unit) |
| $RM_{p}^{ro}$ | : The volume of using raw material *ro* in product *p* |
| $Pt_{p}^{f}$ | : Processing time to produce each unit of product *p* at the production center *f* (Unit of time) |
| $Cap_{Ca_f}^{f}$ | : Maximum hourly capacity of production center *f* with capacity level *Caf* |
| $Cap_{Ca_{co}}^{co}$ | : Maximum storage and examination capacity of collection center *co* with capacity level $Ca_{co}$ (Mass unit) |
| $Cap_{Ca_{re}}^{re}$ | : Maximum capacity of repair center *re* with capacity level $Ca_{re}$ (Mass unit) |
| $Cap_{Ca_{di}}^{di}$ | : Maximum capacity of disposal center *di* with capacity level $Ca_{di}$ (Mass unit) |
| $Cap_{s_1}$ | : Maximum supply capacity of supplier $S_1$ (Mass unit) |
| $RP$ | : Percentage of returned products from the customer |

$GP$ : Percentage of garbage production

$REP$ : Percentage of repairable products

$Trc_{ro}^{s_1,f,l}$ : Transportation cost for each unit of raw material *ro* from supplier $S_1$ to production center *f* by communication link *l* (monetary unit)

$Trc_{p}^{f,cu}$ : Transportation cost for each unit of product *p* from production center *f* to customer *cu* (monetary unit)

$Trc_{p}^{cu,co}$ : Transportation cost for each unit of product *p* from customer *cu* to collection center *co* (monetary unit)

$Trc_{p}^{co,re}$ : Transportation cost for each unit of product *p* from collection center *co* to repair center *re* (monetary unit)

$Trc_{p}^{co,di}$ : Transportation cost for each unit of product *p* from collection center *co* to disposal center *di* (monetary unit)

$Trc_{p'}^{re,cu}$ : Transportation cost for each unit of product *p'* from repair center *re* to customer *cu* (monetary unit)

$Trc_{dp}^{re,\mathrm{di}}$ : Transportation cost for each unit of discarded part *dp* from repair center *re* to disposal center *di* (monetary unit)

$EI_{s_1}^{re,f}$ : Environmental score of supplier $S_1$ to supply each unit of raw material *ro* for production center *f*

$SI_{s_1}^{ro,f}$ : Social score of supplier $S_1$ to supply each unit of raw material *ro* for production center *f*

Decision variables:

$SS_{s_1}\ SI_{s_1}^{ro,f}$ : 1 if supplier $S_1$ is selected; otherwise, 0

$M\,e_{Ca_f}^{f}$ : 1 if the production center with capacity level $Ca_f$ is established at location *f*; otherwise, 0

$CoE_{Ca_{co}}^{co}$ : 1 if the collection center with capacity level $Ca_{co}$ is established at location *co*; otherwise, 0

$Re\,E_{Ca_{re}}^{re}$ : 1 if the repair center with capacity level $Ca_{re}$ is established at location *re*; otherwise, 0

$DiE_{Ca_{di}}^{di}$ : 1 if the disposal center with capacity level $Ca_{di}$ is established at location di; otherwise, 0

$Q_{p}^{f}$ : The amount of product *p* produced in production center *f*

$Q_{ro}^{s_1,f,l}$ : The amount of raw material *ro* sent from supplier $S_1$ to production center *f* by communication link *l* (Mass unit)

$Q_{p}^{f,cu}$ : The amount of product *p* sent from production center *f* to customer *cu* (Mass unit)

$Q_{p}^{cu,co}$ : The amount of product *p* returned from customer *cu* to collection center *co* (Mass unit)

$Q_{p}^{co,re}$ : The amount of product *p* sent from collection center *co* to repair center *re* (Mass unit)

$Q_{p}^{co,di}$ : The amount of product *p* sent from collection center *co* to disposal center *di* (Mass unit)

$Q_{p'}^{re,cu}$ : The amount of product *p'* sent back from repair center *re* to customer *cu* (Mass unit)

$Q_{dp}^{re,di}$ : The amount of discarded part *dp* sent from repair center *re* to disposal center *di* (Mass unit)

$QL_{p}^{cu}$ : The amount of lost sales of product *p* for customer *cu* (Mass unit)

$QL_{p'}^{cu}$ : The amount of lost sales of product *p'* for customer *cu* (Mass unit)

$QG_{di}$ : The amount of garbage produced in the disposal center *di* (Mass unit)

**mathematical model**

According to the above notations, the multi-objective mathematical programming model of electronic product RSCL-SCN is presented as follows:

- **Objective Functions**

$$
\begin{aligned}
Min\, Z^{Eco} = {} & \\
& \sum_{S_1} Ssf_{s_1} SS_{s_1} \\
& + \sum_{Ca_f}\sum_{F} Mef^{f}_{ca_f}\; ME^{f}_{ca_f} + \sum_{ca_{co}}\sum_{co} Cef^{co}_{ca_{co}} CoE^{co}_{ca_{co}} \\
& + \sum_{Ca_{Re}}\sum_{Re} Ref^{re}_{ca_{re}}\; Re\,E^{re}_{ca_{re}} + \sum_{Ca_{di}}\sum_{Di} Def^{di}_{ca_{di}}\; DiE^{di}_{ca_{di}} \\
& + \sum_{Ro}\sum_{S_1}\sum_{Re}\sum_{L} Sv^{s_1 f}_{ro} Q^{s_1 f\, l}_{ro} + \sum_{P}\sum_{F}\sum_{Cu} Mv^{f\,cu}_{p} Q^{f\,cu}_{p} \\
& + \sum_{P}\sum_{Co}\sum_{Re} REP.Rv^{re}_{p} Q^{co\,re}_{p} + \sum_{P}\sum_{Cu}\sum_{Co} Cv^{cu\,co}_{p} Q^{cu\,co}_{p} \\
& + \sum_{P}\sum_{Co}\sum_{Di} Dv^{co\,di}_{p} Q^{co\,di}_{p} \\
& + \sum_{Ro}\sum_{S_1}\sum_{F}\sum_{L} Trc^{s_1 f\, l}_{ro} Q^{s_1 f\, l}_{ro} + \sum_{P}\sum_{F}\sum_{Cu} Trc^{f\,cu}_{p} Q^{f\,cu}_{p} \\
& + \sum_{P}\sum_{Co}\sum_{Re} Trc^{cu\,co}_{p} Q^{cu\,co}_{p} + \sum_{P}\sum_{Cu}\sum_{Co} Trc^{co\,re}_{p} Q^{co\,re}_{p} \\
& + \sum_{P}\sum_{Co}\sum_{Di} Trc^{co\,di}_{p} Q^{co\,di}_{p} \\
& + \sum_{P}\sum_{Cu} Sor^{cu}_{p} Ql^{cu}_{p} + \sum_{P'}\sum_{Cu} Sor^{cu}_{p'} Ql^{cu}_{p'}
\end{aligned}
\tag{1}
$$

The objective function (1) minimizes total network costs, including the supplier evaluation and selection costs, fixed establishment costs, raw material purchase costs, production, repair, collection, and disposal facility variable costs, transportation costs among different echelons, and finally, lost sale costs related to first-rate and second-rate products.

$$
Max\, Z^{Env} = \sum_{Ro}\sum_{F}\sum_{S_1}\sum_{L} EI^{re\,f}_{s_1} Q^{s_1 f\, l}_{ro} \tag{2}
$$

The objective function (2) maximizes the positive environmental performance of the CL-SCN.

$$
Max\, Z^{Soc} = \sum_{Ro}\sum_{F}\sum_{S_1}\sum_{L} SI^{ro\,f}_{s_1} Q^{s_1 f\, l}_{ro} \tag{3}
$$

The objective function (3) aims to maximize the positive social performance of the CL-SCN. Notably, the supplier performance scores in various sustainable development dimensions are different from each other. Therefore, their value determination requires a set of criteria by which the suppliers are evaluated. In this paper, the Delphi method, a survey of industrial and academic professional experts, have been applied to determine the performance values of suppliers.

The introduced model has three objective functions including economical, environmental and social concepts of sustainable development. By analyzing these objectives in detail, it is seen that, by increasing the cost, the model can use the more efficient facilities and carriers, then, negative impacts of environmental reduce. Also, by using good equipment, human injuries reduce significantly, therefore positive impacts of social responsibility increases, and vice versa.

- **The balance constraints**

$$\sum_{L}\sum_{S_1} Q_{ro}^{s_1 f l} = \sum_{P} RM_p^{ro} Q_p^{f} \qquad \forall F, Ro \tag{4}$$

Constraint (4) ensures that the sum of total raw materials entered into the production center by the main suppliers is equal to the amount of products produced at the production center.

$$\sum_{Ro} RM_p^{ro} Q_p^{f} = \sum_{Cu} Q_p^{f\,cu} \qquad \forall P, F \tag{5}$$

Constraint (5) guarantees the balance of products transferring in the production center; i.e., there is no depot in the production center.

$$\left(\sum_{P}\sum_{F} Q_p^{f\,cu} + \sum_{P'}\sum_{Re} Q_{p'}^{re\,cu}\right) RP = \sum_{P}\sum_{Co} Q_p^{cu\,co} \qquad \forall Cu \tag{6}$$

Constraint (6) indicates that $\%PR$ of the products entered the customer market are sent to collection centers.

$$\sum_{P}\sum_{Cu} Q_p^{cu\,co} REP = \sum_{Re} Q_p^{cu\,re} \qquad \forall Co \tag{7}$$

$$\sum_{P}\sum_{Cu} Q_p^{cu\,co}.(1 - REP) = \sum_{l \in L} Q_p^{co\,di} \qquad \forall Co \tag{8}$$

Constraints (7) and (8) state that $\%REP$ of the returned products from the customer are sent to repair centers and the rest to disposal centers, determined by quality inspectors.

$$\sum_{P}\sum_{Co} Q_p^{co\,re} = \sum_{P'}\sum_{Cu} Q_{p'}^{re\,cu} + \sum_{Dp}\sum_{Di} Q_{dp}^{re\,di} \qquad \forall Re \tag{9}$$

Constraint (9) specifies the inflow and outflow balance for the repair center.

$$\left(\sum_{P}\sum_{Co} Q_p^{co\,di} + \sum_{Dp}\sum_{Re} Q_{dp}^{re\,di}\right) \times GP = QG_{di} \qquad \forall Di \qquad (10)$$

Constraint (10) indicates that *GP* percent of the amount of products entered the repair centers are turned into garbage and are not recyclable.

- **Facility capacity constraints**

$$\sum_{P} Q_p^f Pt_p^f \le \sum_{Ca_f} Cap_f^{ca_f} ME_f^{ca_f} \qquad \forall\, F \qquad (11)$$

Constraint (11) denotes the operating capacity of the production center.

$$\sum_{P}\sum_{Cu} Q_p^{cu\,co} \le \sum_{Ca_{co}} Cap_{co}^{ca_{co}} CoE_{co}^{ca_{co}} \qquad \forall Co \qquad (12)$$

Constraint (12) denotes the operating capacity of the collection center.

$$\sum_{P}\sum_{Co} Q_p^{co\,re} \le \sum_{ca_{re}} Cap_{re}^{ca_{re}}\, Re\, E_{re}^{ca_{re}} \qquad \forall\, Re \qquad (13)$$

Constraint (13) represents the operating capacity of the repair center.

$$\sum_{P}\sum_{Co} Q_p^{co\,di} + \sum_{Dp}\sum_{Re} Q_{dp}^{re\,di} \le \sum_{Ca_{di}} Cap_{di}^{Ca_{di}} DiE_{di}^{Ca_{di}} \qquad \forall Di \qquad (14)$$

Constraint (14) denotes the operating capacity of the disposal center.

$$\sum_{F}\sum_{L} Q_{ro}^{s_1\,f\,l} \le Cap_{s_1} SS_{s_1} \qquad \forall S_1, Ro \qquad (15)$$

Constraint (15) denotes the supply operating capacity of suppliers.

- **Facility location constraints**

$$\sum_{Ca_f} ME_f^{ca_f} \le 1 \qquad \forall F \qquad (16)$$

$$\sum_{ca_{co}} CoE_{co}^{ca_{co}} \le 1 \qquad \forall Co \qquad (17)$$

$$\sum_{ca_{re}} Re\, E_{re}^{ca_{re}} \le 1 \qquad \forall Re \qquad (18)$$

$$\sum_{ca_{di}} DiE_{di}^{ca_{di}} \leq 1 \qquad \forall Di \qquad (19)$$

Constraints (16)-(19) ensure that the maximum number of facilities established in each location are equal to 1.

- **Customer's demand satisfaction constraints**

$$\sum_{F} Q_p^{f\,cu} + Ql_p^{cu} = Dem_p^{cu} \qquad \forall P, Cu \qquad (20)$$

$$\sum_{Re} Q_{p'}^{re\,cu} + Ql_{p'}^{cu} = Dem_{p'}^{cu} \qquad \forall P', Cu \qquad (21)$$

Constraints (20) and (21) guarantee that the sum of the total amount of products sent from the factory to the customer market and the amount of lost demand resulting from shortage is equal to the amount of customer demand for the product.

- **Decision variables type**

$$SS_{s_1}, Me_f^{Ca_f}, CoE_{co}^{Ca_{co}}, \mathrm{Re}E_{re}^{Ca_{re}}, DiE_{di}^{Ca_{di}} \in \{0,1\} \qquad \textit{For all Indices} \qquad (22)$$

$$\begin{bmatrix} Q_p^f, Q_{ro}^{s_1,f,l}, Q_p^{f,cu}, Q_p^{cu,co}, Q_p^{co,re}, \\ Q_p^{co,di}, Q_{p'}^{re,cu}, Q_{dp}^{re,di}, QL_p^{cu}, QL_{p'}^{cu}, QG \end{bmatrix} \in \{0,+\infty\} \qquad \textit{For all Indices} \qquad (23)$$

The type of decision variables is specified by constraints (22) and (23).

## Solution methodology

Due to environmental changes, many parameters are not deterministic in the real world. Since the chain deals with different customers with diverse and changing demands, the parameters related to customers, including demand, lost sale costs, and product return rates, are tainted with environmental uncertainty that simply can not be predicted. Besides, since disruption occurring at the supplier echelon and the transportation roads among production centers are not conveniently predictable, this disruption itself is tainted with uncertainty, too, which has been tackled using backup facilities here.

In order to deal with the uncertainty in mathematical programming models, several methods have been proposed by researchers, including fuzzy, stochastic, Gray theory, Dempster–Shafer evidence theory, robust, etc. However, an essential point in adopting the appropriate method is considering the problem conditions and the characteristics of the intended model. Since the practical example of this paper is conducted in Iran as a four-season country where the amount of demand for products and services varies from month to month, the amount of demand entered the network will also vary. Therefore, an efficient method based upon robust optimization is applied for coping with the model uncertainties.

The p-robust approach was proposed by Snyder and Daskin [45] in 2006 to deal with uncertainty in the location problems. Their proposed approach is known as the p-robust optimization approach and states that the maximum value of regret should be less than an appropriately determined value; i.e.,:

$$\frac{Z(X)-Z^{*}}{Z^{*}} \le p \Rightarrow Z(X) \le (1+P)Z^{*} \tag{24}$$

The left term of Eq. 24 indicates the value of relative regret for each scenario.

## Uncertain mathematical modeling

By defining the set $\Omega = \{1,\ldots,\theta\}$ as the set of possible scenarios of uncertainty and disruption, the set of uncertain parameters are redefined as $Dem^{Cu}_{p,\theta}$, $Dem^{Cu}_{p',\theta}$, $Mv^{f,cu}_{p,\theta}$, $Rv^{re}_{p',\theta}$, $Cv^{cu,co}_{p,\theta}$, $Sor^{cu}_{p,\theta}$, $Sor^{cu}_{p',\theta}$, $EI^{re,f}_{s_1,\theta}$, $SI^{ro,f}_{s_1,\theta}$, $GP_{\theta}$, $Pt^{f}_{p,\theta}$, $RM^{ro}_{p,\theta}$, $REP_{\theta}$, $RP_{\theta}$. Since uncertainty and disruption in the RSCL-SCND affect decision variables of operational and tactical level too, these decision variables also are redefined as $Q^{f}_{p,\theta}$, $Q^{s_1,f,l}_{ro,\theta}$, $Q^{f,cu}_{p,\theta}$, $Q^{cu,co}_{p,\theta}$, $Q^{co,re}_{p,\theta}$, $Q^{co,di}_{p,\theta}$, $Q^{re,cu}_{p',\theta}$, $Q^{re,di}_{dp,\theta}$, $QL^{cu}_{p,\theta}$, $QG_{di,\theta}$, $QL^{cu}_{p',\theta}$. Except for the mentioned elements, other notations are defined as follows:

Sets:

$S_2$ : Set of backup suppliers

Parameters:

$\lambda^{s_1}_{\theta}$ : 1, If supplier $S_1$ is disrupted under scenario $\theta$; otherwise 0.

$\lambda^{l}_{\theta}$ : 1, If the transportation road $l$ between supplier and production center under scenario $\theta$ is disrupted; otherwise 0.

$Sv^{s_2,f}_{ro,\theta}$ : The variable cost of purchase of raw material $ro$ from supplier $S_2$ for production center $f$ under scenario $\theta$ (monetary unit).

$Scc^{s_2,f}_{ro,\theta}$ : The cost of concluding the contract with supplier $S_2$ to supply raw material $ro$ to be sent to the production center $f$ under scenario $\theta$ (monetary unit).

$\pi_{\theta}$ : Probability of scenario $\theta$.

$\mu$ : Maximum permissible value of occurrence of objective functions.

Decision variables:

$SS_{s_2}$ : 1 if supplier $S_2$ is selected; otherwise 0.

$Sc^{s_2,f}_{ro,\theta}$ : 1 if supplier $S_2$ concludes a contract with production center $f$ to supply raw material $ro$.

$Q^{s_2,f,l}_{ro,\theta}$ : The amount of raw material $ro$ sent from supplier $S_2$ to production center $f$ by communication link $l$ under scenario $\theta$ (Mass unit).

$$
\begin{aligned}
& Min\, Z^{Eco} = \\
& \qquad \sum_{S_1} Ssf_{s_1}\, SS_{s_1} + \sum_{Ca_f}\sum_{F} Mef^{f}_{ca_f}\ \ ME^{f}_{ca_f} + \sum_{ca_{co}}\sum_{co} Cef^{co}_{ca_{co}}\, CoE^{co}_{ca_{co}} \\
& \qquad + \sum_{Ca_{Re}}\sum_{Re} Ref^{re}_{ca_{re}}\ \ Re\,E^{re}_{ca_{re}} + \sum_{Ca_{di}}\sum_{Di} Def^{di}_{ca_{di}}\ DiE^{di}_{ca_{di}} \\
& \qquad + \sum_{\Omega} \pi_\theta \left( \begin{aligned}
& \sum_{Ro}\sum_{S_1}\sum_{Re}\sum_{L} Sv^{s_1 f}_{ro\theta} Q^{s_1 f l}_{ro\theta} + \sum_{P}\sum_{F}\sum_{Cu} Mv^{f\,cu}_{p\theta} Q^{f\,cu}_{p\theta} \\
& + \sum_{P}\sum_{Co}\sum_{Re} REP_\theta . Rv^{re}_{p\theta} Q^{co\,re}_{p\theta} + \sum_{P}\sum_{Cu}\sum_{Co} Cv^{cu\,co}_{p\theta} Q^{cu\,co}_{p\theta} \\
& + \sum_{P}\sum_{Co}\sum_{Di} Dv^{co\,di}_{p\theta} Q^{co\,di}_{p\theta} + \sum_{Ro}\sum_{S_1}\sum_{F}\sum_{L} Trc^{s_1 f l}_{ro\theta} Q^{s_1 f l}_{ro\theta} \\
& + \sum_{P}\sum_{F}\sum_{Cu} Trc^{f\,cu}_{p\theta} Q^{f\,cu}_{p\theta} + \sum_{P}\sum_{Co}\sum_{Re} Trc^{cu\,co}_{p\theta} Q^{cu\,co}_{p\theta} \\
& + \sum_{P}\sum_{Cu}\sum_{Co} Trc^{co\,re}_{p\theta} Q^{co\,re}_{p\theta} + \sum_{P}\sum_{Co}\sum_{Di} Trc^{co\,di}_{p\theta} Q^{co\,di}_{p\theta} \\
& + \sum_{P}\sum_{Cu} Sor^{cu}_{p\theta} Ql^{cu}_{p\theta} + \sum_{P'}\sum_{Cu} Sor^{cu}_{p'\theta} Ql^{cu}_{p'\theta} \\
& + \sum_{Ro}\sum_{S_2}\sum_{F} Scc^{s_2 f}_{ro\theta} Sc^{s_2 f}_{ro\theta} + \sum_{Ro}\sum_{S_2}\sum_{F}\sum_{L} Sv^{s_2 f}_{ro\theta} Q^{s_2 f l}_{ro\theta}
\end{aligned} \right)
\end{aligned} \tag{25}
$$

$$Max\, Z^{Env} = \sum_{\Omega}\sum_{Ro}\sum_{F}\sum_{S_1}\sum_{L} \pi_\theta EI^{re\,f}_{s_1\theta} Q^{s_1 f l}_{ro\theta} \tag{26}$$

$$Max\, Z^{Soc} = \sum_{\Omega}\sum_{Ro}\sum_{F}\sum_{S_1}\sum_{L} \pi_\theta SI^{ro\,f}_{s_1\theta} Q^{s_1 f l}_{ro\theta} \tag{27}$$

$$Z^{Eco}_\theta \le (1+P).Z^{Eco*}_\theta \tag{28}$$

$$Z^{Env}_\theta \le (1+P).Z^{Env*}_\theta \tag{29}$$

$$Z^{Soc}_\theta \le (1+P).Z^{Soc*}_\theta \tag{30}$$

$$\sum_{L}\sum_{S_1} Q^{s_1 f l}_{ro\theta} = \sum_{I} h_{ri}\, Q^{f}_{p\,\theta} \qquad \forall F, Ro, \Omega \tag{31}$$

$$\sum_{Ro} RM^{\,ro}_{p\theta}\, Q^{f}_{p\theta} = \sum_{Cu} Q^{f\,cu}_{p\theta} \qquad \forall P, F, \Omega \tag{32}$$

$$\left( \sum_{P}\sum_{F} Q^{f\,cu}_{p\theta} + \sum_{P'}\sum_{Re} Q^{re\,cu}_{p'\theta} \right) RP_\theta = \sum_{P}\sum_{Co} Q^{cu\,co}_{p\theta} \qquad \forall Cu, \Omega \tag{33}$$

$$\sum_{P}\sum_{Cu} Q^{cu\,co}_{p\theta}\ REP_\theta = \sum_{Re} Q^{cu\,re}_{p\theta} \qquad \forall\ Co, \Omega \tag{34}$$

$$\sum_{P}\sum_{Cu} Q^{cu\,co}_{p\theta} .(1 - REP_\theta) = \sum_{l\in L}\ Q^{co\,di}_{p\theta} \qquad \forall Co, \Omega \tag{35}$$

$$\sum_{P}\sum_{Co} Q^{co\,re}_{p\theta} = \sum_{P'}\sum_{Cu} Q^{re\,cu}_{p'\theta} + \sum_{Dp}\sum_{Di} Q^{re\,di}_{dp\theta} \qquad \forall Re, \Omega \tag{36}$$

$$\left( \sum_{P}\sum_{Co} Q^{co\,di}_{p\theta} + \sum_{Dp}\sum_{Re} Q^{re\,di}_{dp\theta} \right) \times GP_\theta = QG_{di\,\theta} \qquad \forall Di, \Omega \tag{37}$$

$$\sum_{P} Q^{f}_{p\theta} Pt^{f}_{p\theta} \leq \sum_{Ca_f} Cap^{ca_f}_{f} ME^{ca_f}_{f} \qquad \forall F,\Omega \tag{38}$$

$$\sum_{P}\sum_{Cu} Q^{cu\,co}_{p\theta} \leq \sum_{Ca_{co}} Cap^{ca_{co}}_{co} CoE^{ca_{co}}_{co} \qquad \forall Co,\Omega \tag{39}$$

$$\sum_{P}\sum_{Co} Q^{co\,re}_{p\theta} \leq \sum_{ca_{re}} Cap^{ca_{re}}_{re} Re\,E^{ca_{re}}_{re} \qquad \forall Re,\Omega \tag{40}$$

$$\sum_{P}\sum_{Co} Q^{co\,di}_{p\theta} + \sum_{Dp}\sum_{Re} Q^{re\,di}_{dp\,\theta} \leq \sum_{Ca_{di}} Cap^{Ca_{di}}_{di} DiE^{Ca_{di}}_{di} \qquad \forall Di,\Omega \tag{41}$$

$$\sum_{F}\sum_{L} Q^{s_1\,f\,l}_{ro\,\theta} \leq Cap_{s_1} SS_{s_1} \qquad \forall S_1, Ro, \Omega \tag{42}$$

$$\sum_{Ca_f} ME^{ca_f}_{f} \leq 1 \qquad \forall F \tag{16}$$

$$\sum_{ca_{co}} CoE^{ca_{co}}_{co} \leq 1 \qquad \forall Co \tag{17}$$

$$\sum_{ca_{re}} Re\,E^{ca_{re}}_{re} \leq 1 \qquad \forall Re \tag{18}$$

$$\sum_{ca_{di}} DiE^{ca_{di}}_{di} \leq 1 \qquad \forall Di \tag{19}$$

$$\sum_{F} Q^{f\,cu}_{p\theta} + Ql^{cu}_{p\theta} = Dem^{cu}_{p\theta} \qquad \forall P, Cu, \Omega \tag{43}$$

$$\sum_{Re} Q^{re\,cu}_{p'\theta} + Ql^{cu}_{p'\theta} = Dem^{cu}_{p'\theta} \qquad \forall P', Cu, \Omega \tag{44}$$

$$SS_{s_1}, SS_{s_2}, Sc^{s_2,f}_{ro,\theta}, Me^{Ca_f}_{f}, CoE^{Ca_{co}}_{co}, \mathrm{Re}\,E^{Ca_{re}}_{re}, DiE^{Ca_{di}}_{di} \in \{0,1\} \qquad \text{For all Indices} \tag{45}$$

$$\begin{bmatrix} Q^{f}_{p,\theta}, Q^{s_1,f,l}_{ro,\theta}, Q^{f,cu}_{p,\theta}, Q^{cu,co}_{p,\theta}, Q^{co,re}_{p,\theta}, Q^{s_2,f,l}_{ro,\theta}, \\ Q^{co,di}_{p,\theta}, Q^{re,cu}_{p',\theta}, Q^{re,di}_{dp,\theta}, QL^{cu}_{p,\theta}, QL^{cu}_{p',\theta}, QG \end{bmatrix} \in \{0,+\infty\} \qquad \text{For all Indices} \tag{46}$$

Notably, values $Z^{*Eco}_{\theta}$, $Z^{*Env}_{\theta}$, $Z^{*Soc}_{\theta}$ obtained from solving different scenarios are placed in Eqs. 28-30.

**Multi-objective formulation**

Various sustainable development dimensions, including economic, environmental, and social issues, caused proposing a model in the form of a multi-objective mathematical programming model. Therefore, it is essential to adopt an appropriate method to solve the proposed multi-objective model. Due to the simplicity and applicability of the Torabi and Hosseini multi-objective programming model solution method, it is used to solve this multi-objective model as follows:

**Step 1:** Determining the positive and negative ideal solutions for each objective function.
To reduce computational complexity, negative ideal solutions are estimated using positive ideal solutions rather than solving a linear integer programming model separately. Assume that $X_{\zeta}^{*}$, $Z_{\zeta}(X_{\zeta}^{*})$ denotes the decision vector related to the positive ideal solution of solving ζ-objective function and its value, respectively. Then, the negative ideal solutions are estimated as follows:

$$Z_{NIS}^{Eco} = MAX\left\{Z^{Eco}\left(X^{Eco*}\right), Z^{Eco}\left(X^{Env*}\right), Z^{Eco}\left(X^{Soc*}\right)\right\} \tag{50}$$

$$Z_{NIS}^{Env} = MAX\left\{Z^{Env}\left(X^{Eco*}\right), Z^{Env}\left(X^{Env*}\right), Z^{Env}\left(X^{Soc*}\right)\right\} \tag{51}$$

$$Z_{NIS}^{Soc} = MAX\left\{Z^{Soc}\left(X^{Eco*}\right), Z^{Soc}\left(X^{Env*}\right), Z^{Soc}\left(X^{Soc*}\right)\right\} \tag{52}$$

**Step 2:** Determining a linear membership function for each objective function.
The following equations indicate the linear membership functions defined for each objective function based on their type.

$$\mu^{Eco}\left(X\right) = \begin{cases} 1 & ;\ Z^{Eco} \le Z_{PIS}^{Eco} \\ \dfrac{Z_{NIS}^{Eco} - Z^{Eco}}{Z_{NIS}^{Eco} - Z_{PIS}^{Eco}} & ;\ Z_{PIS}^{Eco} \le Z^{Eco} \le Z_{NIS}^{Eco} \\ 0 & ;\ Z^{Eco} \ge Z_{NIS}^{Eco} \end{cases} \tag{53}$$

$$\mu^{Env}\left(X\right) = \begin{cases} 1 & ;\ Z^{Env} \le Z_{PIS}^{Env} \\ \dfrac{Z_{NIS}^{Env} - Z^{Env}}{Z_{NIS}^{Env} - Z_{PIS}^{Env}} & ;\ Z_{PIS}^{Env} \le Z^{Env} \le Z_{NIS}^{Env} \\ 0 & ;\ Z^{Env} \ge Z_{NIS}^{Env} \end{cases} \tag{54}$$

$$\mu^{Soc}\left(X\right) = \begin{cases} 1 & ;\ Z^{Soc} \le Z_{PIS}^{Soc} \\ \dfrac{Z^{Soc} - Z_{NIS}^{Soc}}{Z_{NIS}^{Soc} - Z_{PIS}^{Soc}} & ;\ Z_{PIS}^{Soc} \le Z^{Soc} \le Z_{NIS}^{Soc} \\ 0 & ;\ Z^{Soc} \ge Z_{NIS}^{Soc} \end{cases} \tag{55}$$

**Step 3:** Converting the existing model to an equivalent single-objective model using TH [46] aggregation function as follows:

$$Max\sigma(v) = \eta\sigma_0 + \left(1-\eta\right).\sum_{\zeta=Eco,Env,Soc} \varphi^{\zeta}\mu^{\zeta} \tag{56}$$

$$\sigma_0 \le \mu^{\zeta}\left(X\right) \qquad \zeta = Eco, Env, Soc \tag{57}$$

$$x \in F(X), \eta, \sigma_0 \in \left[0,1\right] \tag{58}$$

In which $\mu^{\zeta}\left(X\right)$ states the satisfaction level of objective function $\zeta$ and $\sigma_0 = \underset{\zeta}{Min}\left\{\varphi^{\zeta}\mu^{\zeta}\right\}$ denotes the minimum satisfaction level for each objective function. Furthermore, $\varphi^{\zeta}$ refers to the relative importance of objective function $\zeta$ . Eventually, $\eta$ states the importance of satisfaction level lower bound of objective functions and the importance of their balance.

**Step 4:** solving the single-objective model
The above model is solved by computational software. Notably, if the decision-maker is satisfied with the efficiently obtained solution, solving is stopped. Otherwise, another efficient solution examines other solutions by changing the value of some control parameters $\eta=[0,1]$, $\varphi^{\zeta}$ .

## A two-phase heuristic method

By simplifying the above problem, a simple location-allocation model can be achieved. According to the NP-hard nature of the location-allocation problem in which the solution time increases exponentially, it is necessary to use an appropriate algorithm to solve the proposed model in medium and large sizes. In this paper, a two-stage heuristic algorithm is used to solve the model for large-sized instances.

The proposed heuristic method is based on the principle that reducing the number of integer variables can significantly affect the complexity of the mathematical model, followed by the solution time. Various approaches and techniques have been provided to reduce integer variables [47,48]. In this paper, according to the nature and structure of the intended problem, in the first phase, the production center selection variables ($SS_{s_1}$) and the production center establishment variables ($Me_f^{Ca_f}$) are determined as zero and one values based on the sum of the total capacity of customers and also the minimum fixed cost of evaluation and selection and the sum of the total capacity of customers as well as the minimum fixed cost of facility establishment, respectively. In the second phase, the values of the decision variables mentioned above, enter the deterministic mathematical model as a predetermined parameter and are solved by the TH method. Therefore, the number of integer variables of the mathematical model, followed by the solution time, is significantly reduced. The general steps of the proposed multi-objective two-phase algorithm are as follows:

### Phase (I): Facility Location

**Step 1:** The sum of total demand entered by customers is identified.
**Step 2:** The matrix of production center establishment costs for different locations is ranked from low to high based on establishment costs. The same ranking for suppliers is done based on the fixed costs of supplier evaluation and selection.

**Step 3:** According to the ranking of establishment costs and evaluation costs as well as customers' total demands, variables $SS_{s_1}$, $Me_f^{Ca_f}$ are selected as input parameters to establish or conclude the contract, and the value of their decision variable is set to 1. This process continues until all customers' total demands are satisfied.
**Step 4:** After satisfying the termination condition in the third step, the values of the remaining decision variables are set to 0.
**Step 5:** The values of the decision variables determined in the third and fourth steps form a binary vector.

**Phase (II): Product Transportation**

**Step 6:** The suppliers selected to conclude the contract and the appropriate locations selected to establish production centers enter the deterministic mathematical model as input parameters in the form of a binary vector. (thus, the number of binary variables is significantly reduced.)
**Step 7:** The reduced uncertain mathematical model is solved so that how to allocate demand zones to production centers, the utilized transportation roads, the amount of transportation of products in different routes, and other mathematical model decision variables is obtained.

The main structure of the proposed multi-objective two-phase algorithm is presented in Fig. 2.

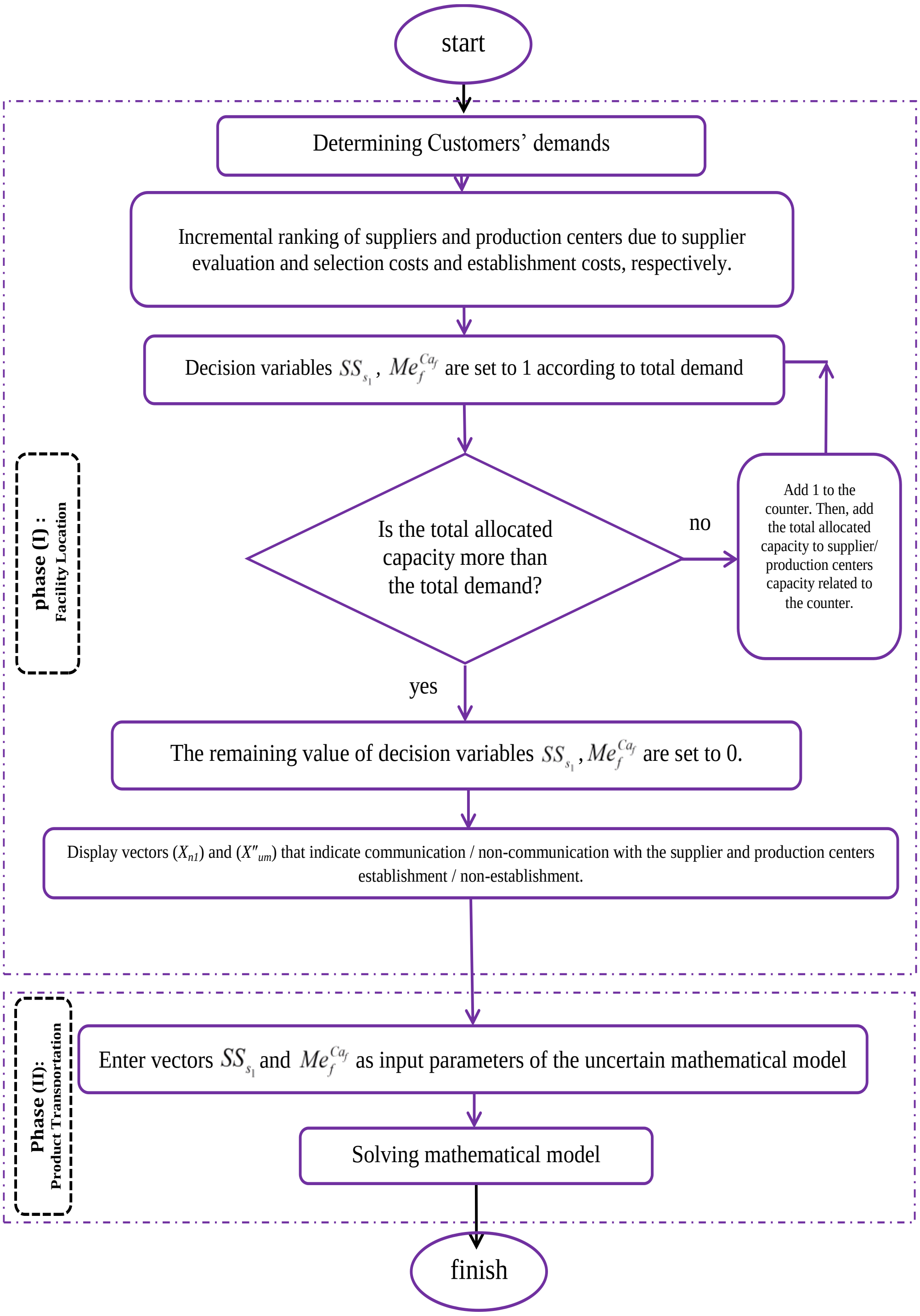



**Fig 2.** The main structure of the multi-objective two-phase heuristic algorithm.

In order to better illustrate the implementation process of the mentioned two-step heuristic algorithm, a small example of the first phase, i.e. supplier selection and facility location is presented below;

First, it is assumed that there exist 8 demand points by their amount of demand as Fig. 3.

| *cu* | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | |
|---|---|---|---|---|---|---|---|---|---|
| *Customer Demand* | 12 | 5 | 19 | 24 | 31 | 9 | 17 | 14 | 131 |

**Fig. 3.** The customer nodes and their demand in example.

It is also assumed that there are 6 potential primary suppliers to select the best ones and also 6 potential areas to identify and locate the production facilities.

It is noted that the number of production facilities and suppliers required should be selected based on the number of demand mentioned in the example, ie demand equal to 131, therefore it can be said:

A. **Supplier Selection**: potential suppliers and their capacities are shown in Fig. 4 (For ease of display, supply capacity is the capacity related to the demand, for example, if a product requires 5 units of raw material *q* and 3 units of raw material *p*, the sum of these 8 units is one unit demand is taken into account. In other words, the displayed capacities are final products and not the raw materials).

In this section, in the first step, based on the cost of selecting suppliers, all the bid options are sorted from minimum to maximum, then considering that the number of requests must be met equal to 131 (because the shortage is not allowed) is observed. Of the total capacity of 371, suppliers 4, 6 and 1 with a capacity of 43, 38 and 50, respectively, meet a total of 131 demand, so given that the three suppliers 4, 6 and 1 demand Meet and have the lowest bid cost, so they are selected as the final suppliers, in other words, in the desired tender, suppliers 2, 3 and 5 are removed from the model.

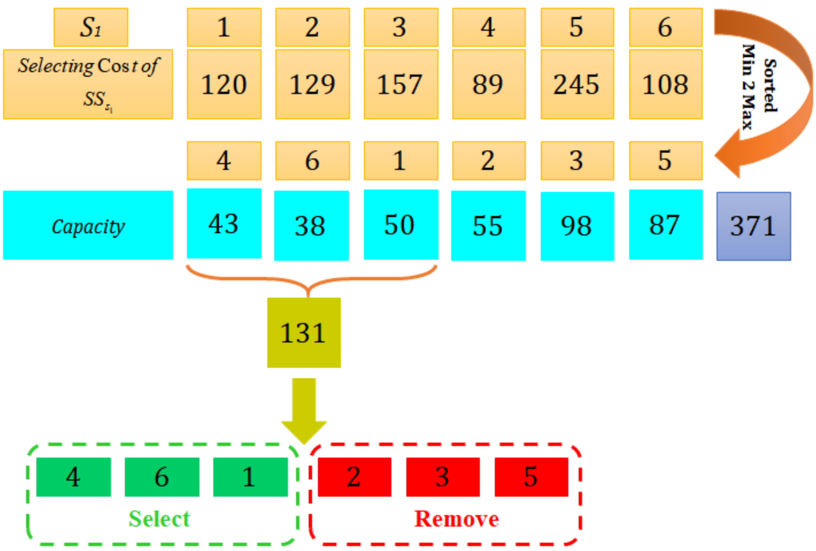



**Fig. 4.** The phase I of proposed heuristic algorithm in example – Supplier selection section

B. **Facility Location**: potential area of production centers and related areas are shown in Fig. 5. To find the best locations, at first, based upon the cost of installation of the production centers, all the areas are sorted from minimum to maximum, then considering that the number of requests must be met equal to 131 (because the shortage is not allowed) is observed. Of the total capacity of 371, locations 2, 4, 6 and 1 with a capacity of 23, 29, 36 and 43, respectively, meet a total of 131 demand, so given that the four locations 2, 4, 6 and 1 demands meet and have the lowest installation costs, they are selected as the final locations for production centers, in other words, in the desired tender, areas 3 and 5 are removed from the model.

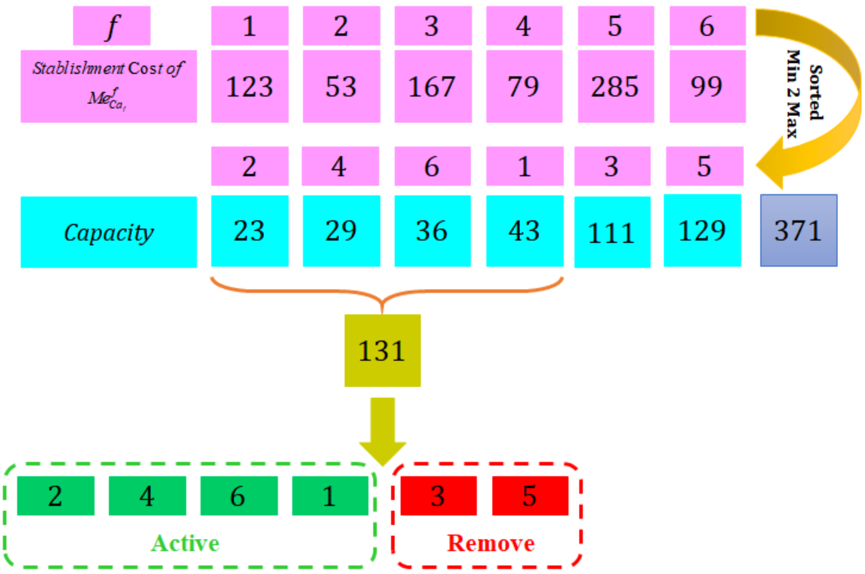



**Fig. 5.** The phase I of proposed heuristic algorithm in example – production center location section.

According to Figs. 3 to 5 as well as explanations A and B, where suppliers 1, 6 and 4 were selected and potential points 1, 6, 4 and 2 were selected to installation production centers, the values of these variables were fixed and As a parameter, the model is run at a higher speed with fewer binary variables, followed by the simplification of some complex constraints.

The applicability of the proposed heuristic algorithm is tested on some test problems which their obtained solutions are reported in Table 2 and Fig. 6. Problem size is evaluted as $|Ro|\times|S_1|\times|Cu|\times|Co|\times|F|\times|Re|\times|Di|\times|S_2|$. As seen, on average, with a 4.39% change in the final objective function, the solution time is reduced to 67.47%; i.e., by ignoring the negligible change in the final objective function, the model solution time is significantly reduced.

**Table 2.** Comparison of objective function values and solution time obtained by two algorithms.

| Problem Instances | Problem Size | Cplex solver | | Hybrid solution algorithm | | Difference percentage | |
|---|---|---|---|---|---|---|---|
| | | Objective | Cpu time (Secs) | Objective | Cpu time (Secs) | Objective (%) | Cpu time (%) |
| 1 | 5 | 0.2561 | 24.14 | 0.2372 | 28.45 | 7.35 | -17.85 |
| 2 | 12 | 0.2882 | 35.45 | 0.2644 | 36.65 | 8.26 | -3.39 |
| 3 | 24 | 0.3243 | 58.54 | 0.2993 | 42.15 | 7.70 | 28.00 |
| 4 | 36 | 0.3649 | 98.47 | 0.3420 | 44.51 | 6.27 | 54.80 |
| 5 | 48 | 0.4106 | 124.15 | 0.3871 | 49.32 | 5.73 | 60.27 |
| 6 | 54 | 0.4621 | 168.87 | 0.4321 | 52.12 | 6.49 | 69.14 |
| 7 | 64 | 0.5199 | 257.25 | 0.4983 | 58.41 | 4.17 | 77.29 |
| 8 | 72 | 0.5851 | 364.54 | 0.5653 | 61.24 | 3.38 | 83.20 |
| 9 | 78 | 0.6584 | 754.15 | 0.6342 | 66.84 | 3.68 | 91.14 |
| 10 | 84 | 0.6959 | 942.12 | 0.6734 | 71.62 | 3.24 | 92.40 |
| 11 | 90 | 0.7356 | 1254.45 | 0.7150 | 99.14 | 2.80 | 92.10 |
| 12 | 140 | 0.7775 | 3600 | 0.7591 | 105.31 | 2.37 | 97.07 |
| 13 | 164 | 0.8218 | 3600 | 0.8060 | 128.54 | 1.93 | 96.43 |
| 14 | 180 | 0.8687 | 3600 | 0.8558 | 145.74 | 1.48 | 95.95 |
| 15 | 240 | 0.9182 | 3600 | 0.9086 | 164.21 | 1.04 | 95.44 |
| **Average** | | **0.5791** | **1232.142** | **0.5585** | **76.95** | **4.39** | **67.47** |

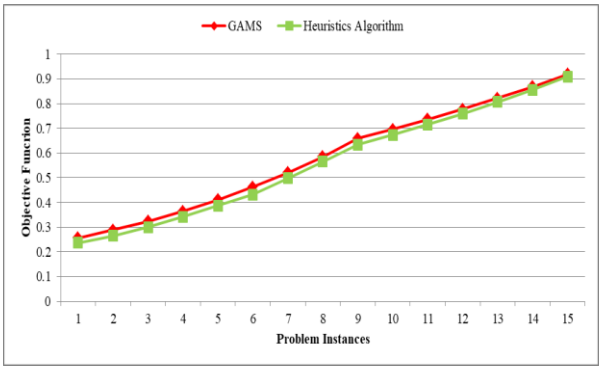



**Fig. 6-a.** Comparison of objective function value; Hybrid solution algorithm vs. GAMS software**.**

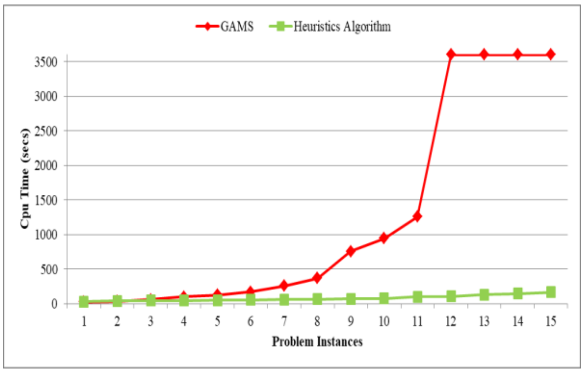



**Fig. 6-b.** Comparison of solution time; the Hybrid solution algorithm vs. GAMS software.

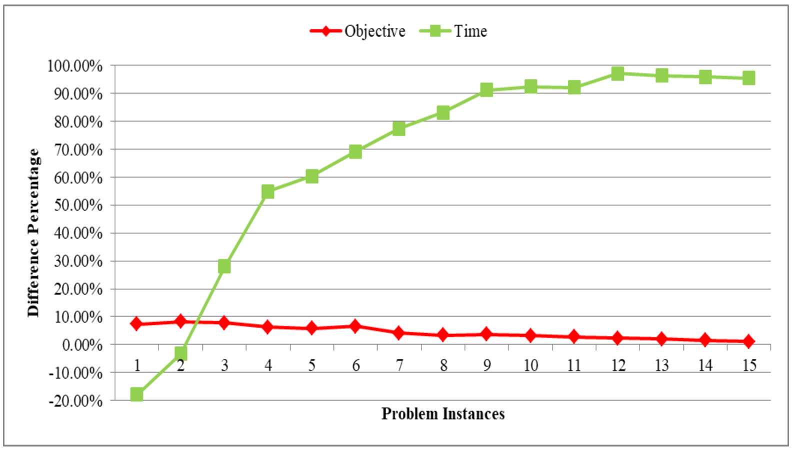



**Fig. 6-c.** Comparison of the percentage of the difference between objective function value and solution time; the Hybrid solution algorithm vs. GAMS software.

## Practical example

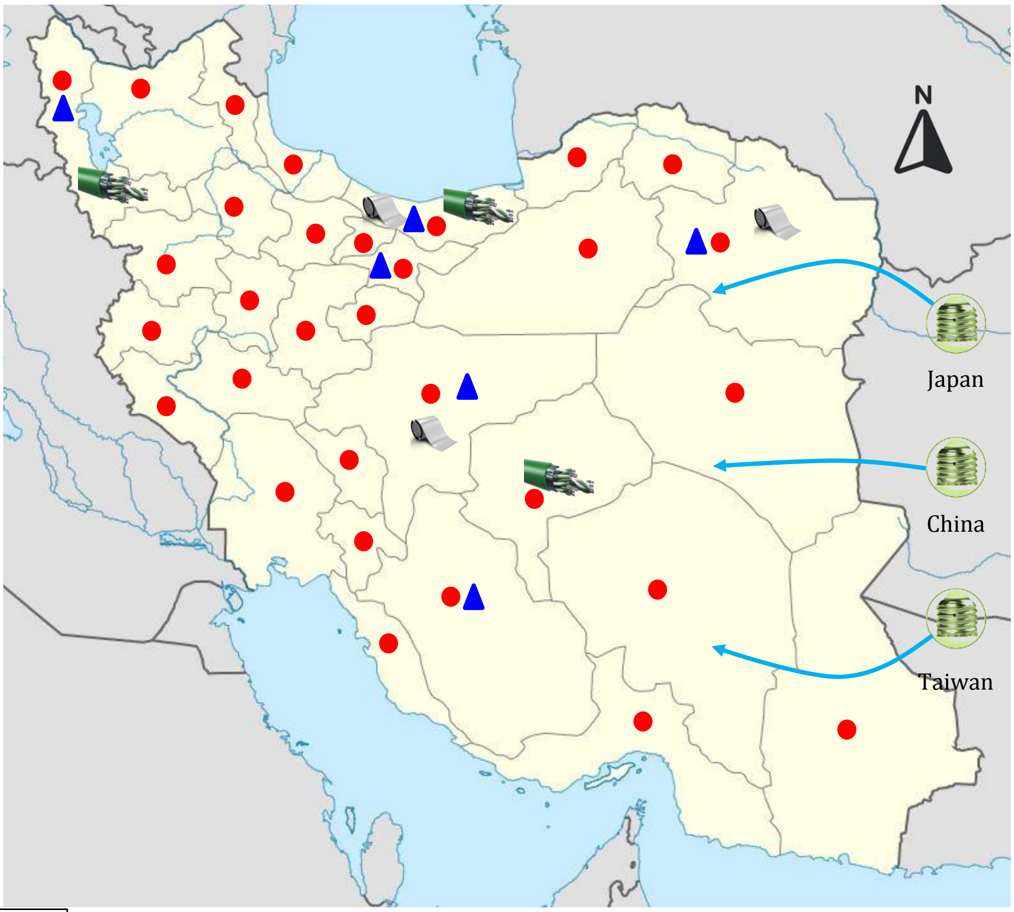
A practical example in the lighting projectors industry is presented in Iran to demonstrate the applicability of the proposed model. In this RSCL-SCN, using five raw materials, two final products, single-lens and two-lens projectors, are produced. Because of product failures, the customer can return after purchase. Once it is returned, the product is repaired and enters the target market again as a second-rate product.

The main suppliers of raw materials in China, Japan, and Taiwan (sockets and lens), Isfahan, Mazandaran, and Khorasan Razavi (iron and aluminium sheets) and Mazandaran, Yazd, and Western Azerbaijan (cable and wire) are considered. In the case of occurrence of any disruption for each supplier, the other two suppliers are intended as the backup, which can operate of course with extra operational cost.

After production, the final products are sent to 30 provinces of Iran as target markets. Moreover, the potential locations for establishing production, collection, repair, and disposal centers have been considered in seven provinces of Isfahan, Tehran, Fars, Khorasan Razavi, Western Azerbaijan, Yazd, and Mazandaran.

All capacity levels of different facilities are assumed to be low, medium, and high qualitatively and modularly. 12 scenarios are considered with the aim of covering 12 months of one working year to deal with the environmental uncertainty in the parameters as well as the possible disruption.

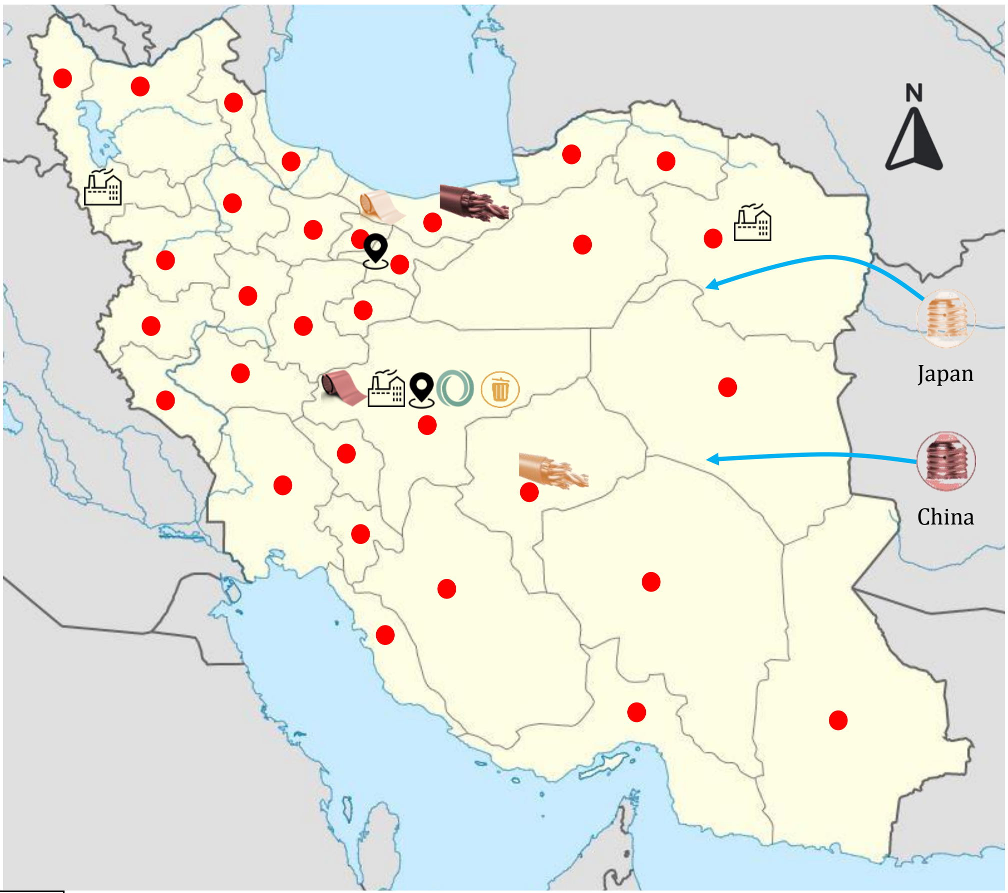
Fig. 7 represents the potential locations for establishing facilities schematically. Since it is evident that establishing transportation roads among all facilities and target markets is possible, those are eliminated to avoid the complexity of the shape.




| Legend | |
|---|---|
| | Potential centers of supplying first raw materials (sockets and lenses) |
| | Potential centers of supplying second raw materials (iron and aluminum sheets) |
| | Potential centers of supplying first raw materials (Cable and wire) |
| | Potential locations of establishing the production, collection, repair and disposal centers |
| | Demand centers |

**Fig. 7.** Potential locations for established facilities.

The model is solved using the required data of the practical example and the proposed algorithm was run by a CPLEX solver in GAMS 32 software on a computer with a Core 2 Due @ 2.0 GHz and 8 GB RAM operating with windows 10.0. The final output of the practical example is shown in Fig. 8.




| Legend | |
|---|---|
| | Main supplier of first raw materials (sockets and lenses) |
| | Backup supplier of first raw materials (sockets and lenses) |
| | Bain supplier of second raw materials (iron and aluminum sheets) |
| | Backup supplier of second raw materials (iron and aluminum sheets) |
| | Main supplier of first raw materials (Cable and wire) |
| | Backup supplier of first raw materials (Cable and wire) |
| | Potential locations for establishing the production, collection, repair, and disposal centers |
| | Demand centers |
| | Established production centers |
| | Established collection centers |
| | Established repair centers |
| | Established disposal centers |

**Fig. 8.** The final output of the practical example.

According to Fig. 8, the main suppliers of first, second, and third raw materials optimally have been selected China, Mazandaran, and Isfahan, respectively; while the backup suppliers have been selected Japan, Yazd, and Mazandaran respectively. Production centers have been established in Isfahan, Khorasan Razavi, and Western Azerbaijan provinces, collection centers in Tehran and Isfahan provinces and repair, recycling and disposal centers have been established in Isfahan province. Furthermore, the value of the economic objective function is equal to 565.857552 monetary units (MU). The CL-SCN environmental score is 658.07, while it is 608.93 in the social dimension. Eventually, the value of the final Torabi-Hosseini objective function is equal to 0.658.

## Sensitivity analysis

In this section, sensitivity analysis is conducted on critical parameters of the model. The parameters importance of satisfaction level lower bound of objective functions ($\eta$), percentage of repairable products ($REP$), environmental and social performance scores ($EI_{s_1}^{re,f}$ ,$SI_{s_1}^{ro,f}$ ), and operative capacity of production center ($Cap_f^{Ca_f}$ ) play a prominent role in RSCL-SCN. Therefore, the trend of changes in the objective function is analyzed based on changing these parameters.

### Importance of satisfaction level lower bound of objective functions ($\eta$)

One of the effective parameters on the TH method and consequently on the proposed model is the parameter $\eta$. Fig. 9 shows the trend of objective function changes based on changing this parameter. It is observed that, as $\eta$ increases, the value of the ultimate objective function decreases. As seen, the decreasing gradient has become steeper at point 0.4.

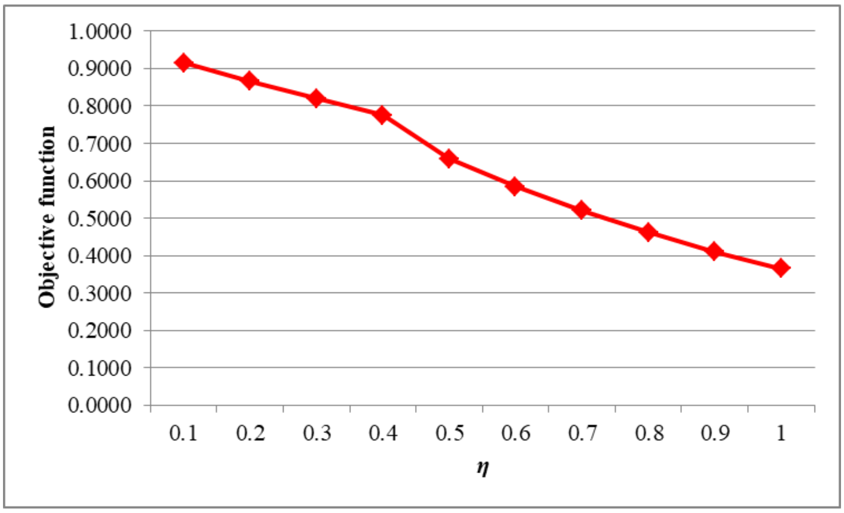



**Fig 9.** The trend of changes of objective function based on changing the importance of satisfaction level lower bound of objective functions ($\eta$)

### Percentage of repairable products ($REP_\theta$)

Fig. 10 demonstrates the trend of changes of objective function based on changing REP$_\theta$. As seen, as $REP_\theta$ increases, the value of ultimate objective function TH increases because an increase in $REP$ value leads to an increase in the percentage of returned products, and consequently, the negative impacts of all three objective functions have increased. It is observed that the best $REP$ which concluded the minimum value of objective, is equal to 10%. From 10% to 60%, the trend of the chart is ascending, but at the point of 70%, it is observed that the trend of the chart has changed and decreased, and then from 80% to 100%, this trend has been ascending again. It can be seen that despite the downtrend at the 70% point, the value of the objective function at this point is still higher than the 10% point.

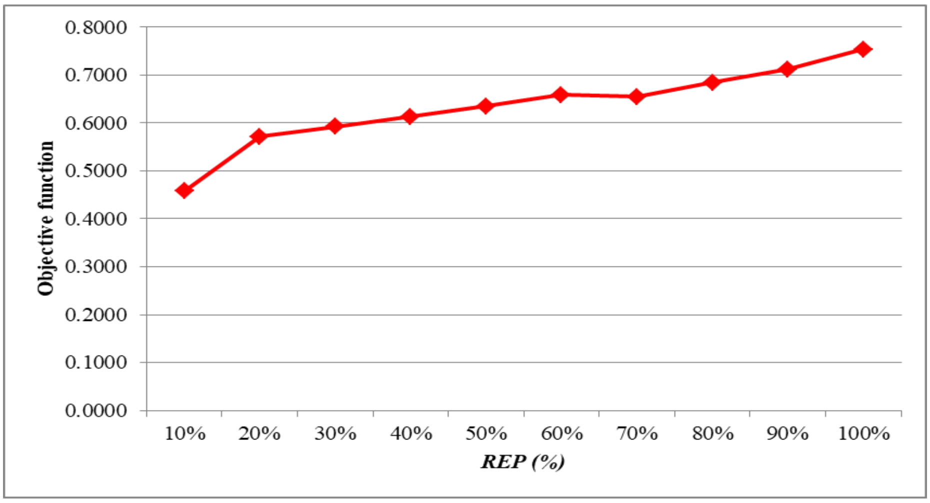



**Fig. 10.** The trend of objective function changes based on changing the percentage of repairable products (*REP* $_\theta$).

### Environmental and social performance scores ( $EI_{s_1}^{re,f}$ ,$SI_{s_1}^{ro,f}$ )

Fig. 11 shows the trend of objective function changes based on changing $EI_{s_1}^{re,f}$ ,$SI_{s_1}^{ro,f}$ . It is observed that, as parameters $EI_{s_1}^{re,f}$ ,$SI_{s_1}^{ro,f}$ increase, the value of ultimate objective function TH grows. However, as seen, the growth rate of the objective function based on $SI_{s_1}^{ro,f}$ changes is more considerable, which demonstrates that the proposed model is more sensitive to social performance scores.

Regarding Fig. 11, it is observed that with increasing values of $EI_{s_1}^{re,f}$ ,$SI_{s_1}^{ro,f}$ , the slope of the graph related to social issues is steeper than the slope of the environmental graph, which means that these values have a more significant effect on the social objective function than the environmental objective function. It is also concluded that the diagram related to the environmental objective function has an almost constant and upward trend, but the diagram related to the social objective function has a local minimum point in the amount of 0.5. This in itself indicates that the values of the scores have a greater impact on the social objective function than the environmental objective function.

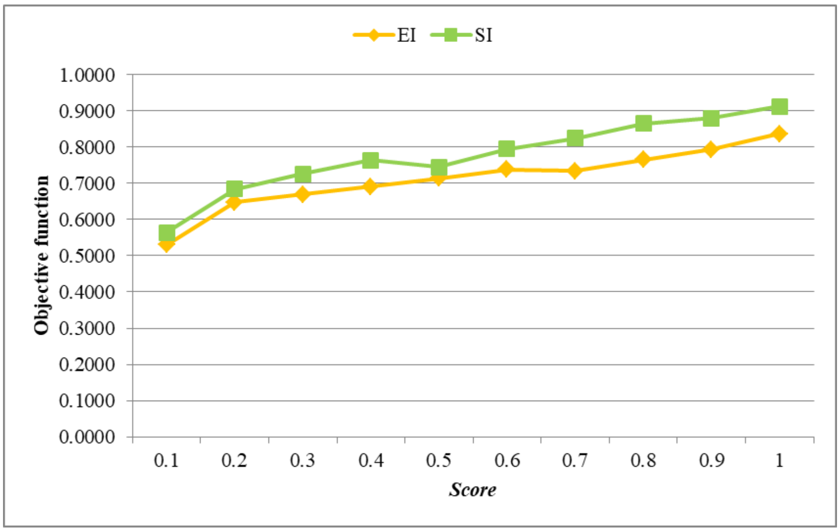



**Fig. 11.** The trend of objective function changes based on changing environmental and social performance scores ($EI_{s_1}^{re,f}$ ,$SI_{s_1}^{ro,f}$ ).

## Conclusions and future research directions

This paper designed a resilient CL-SCN concerning sustainable development considerations in an uncertain environment. Generally, this problem considered six categories of decisions, including the selection of suppliers, establishing facilities at different echelons, capacity planning of established facilities, determining the production volume, amount of products transferred between different six echelons (supplier, manufacturer, collection, repair, disposal, and customers) and the shortage level in the CL-SCN. Due to the possibility of disruption in suppliers, the proposed model used the backup supplier approach to deal with this disruption. Also, factors such as facing a shortage, lost sale costs, uncertainty in some parameters, and occurrence of disruption in suppliers and transportation roads were considered to make the model more flexible and applicable due to the real-world conditions. Then, the model was converted to a single-objective model using the Torabi-Hassini method, and a two-phase Hybrid solution algorithm was adopted to solve the model for large-sized instances. Eventually, a practical example in the lighting projectors industry was presented in Iran to demonstrate the applicability of the proposed model. By solving the example, it is seen that 3 primary suppliers and 3 backups are selected, and 3 production centers, 2 collection centers and 1 repair, recycling and disposal centers have been established. The value of the economic objective function is equal to 565.857552 monetary units (MU). The CL-SCN environmental score is 658.07, while it is 608.93 in the social dimension. Eventually, the value of the final multi-objective function is equal to 0.658.

In concluding this study, the authors faced several challenges and limitations, the most important of them are as: after modeling the problem, various problems were encountered to validate the model, in some cases the model was infeasible, and this issue caused a lot of researchers to spend time re-examining and modifying the model. Another important limitation of the present article was the lack of access to real data to solve a real case study, so the authors had to estimate some of the data needed.

The main future research directions to complete this study are considering suppliers and 3PL logistic services to deal with possible disruption, adopting exact solution algorithms such as Benders Decomposition, considering exchange rates in export and import process, paying attention to shortage policies by using an applicable method such as PBO. Also, it is suggested to scholars, apply the introduced model in other industries and services like oil industry, etc.

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