Journal of Industrial and Systems Engineering
Vol. 14, No. 3, pp. 33-68
Summer (July) 2022

Sustainable and reliable closed-loop supply chain network design: Normalized normal constraint (NNC) method application

Sajad Amirian[1], Maghsoud Amiri[1*], Mohammad Taghi Taghavifard[1]

[1]*Department of Industrial Management, Faculty of Management and Accounting, Allameh Tabataba'i University, Tehran, Iran*

sajadamirian1362@yahoo.com, amiri@atu.ac.ir, dr.taghavifard@gmail.com

Abstract

The competitive environment of the present age has focused the attention of organizations on meeting the requirements of quality and socially responsible, because organizations that adhere to the quality management framework achieve a higher level of customer satisfaction. In addition, the shorter product life due to the development of technology and changing customer needs reveals the need to pay attention to the concepts of sustainability and reliability in the design of the supply chain network. In this paper, the convergence of sustainability and reliability in supply chains is considered and a model of economic, responsible, and reliable supply chain is comprehensively and efficiently modeled. For this purpose, a nonlinear mixed-integer programming model for the supply chain network design problem is considered as three-objective, multi-product, multi-level, multi-source, multi-capacity, and multi-stage. In this study, the normalized normal constraint (NNC) method is used to solve the proposed multi-objective optimization problem and find Pareto optimal solutions. In addition, numerical examples with random data in different dimensions have been considered to measure the accuracy and overall performance of the proposed model and by changing the various parameters of the model, the sensitivity analysis of target functions has been performed to analyze the model behavior.

Keywords: sustainability, reliability, multi-objective optimization, NNC method, closed loop supply chain network

1- Introduction

Supply chain network design is an interdisciplinary knowledge rooted in sciences such as management, strategy, procurement, and operations research. The supply chain network design issue is a strategic decision that refers to supply chain configuration and as a supply chain management infrastructure issue, it has long-lasting effects on other tactical and operational decisions (Govindan et al., 2017). The highest operating costs of organizations, which are usually not noticeable, are related to wrong decisions in the design and establishment of facilities. To ensure efficient and effective supply chain network design, strategic, tactical, and operational decisions must be optimized in an integrated manner (Shen, 2007). Supply chain integration is recognized as the most important source of competitive advantage (Gulati et al.,

---

*Corresponding author

2012). With increasing competition in the business world and the emergence and development of new technologies, many companies have turned to integration. The need for flexibility, cost reduction, and close and extensive communication between suppliers, manufacturers, and distributors, has led companies to gain a competitive advantage by surviving today in a highly competitive environment by integrating their systems and organization (Chopra and Meindl, 2007).

A supply chain includes all the stages (members of the chain) that are directly or indirectly involved in meeting customer demand. In other words, a product goes through different stages of the chain to reach the consumer. In some of these stages, the product is stored and in others, it is transported, that is, it is a supply chain of a set of warehouses and shipments (Ballou, 2004). Coordinated management and control of supply chain activities can provide quality and reliable products and services to customers quickly and at a minimal cost. Most of the integrated supply chain models presented in previous studies can be categorized as follows: Integrated Buyer-Seller, Integrated production-distribution Planning, Integrated Production-Inventory Planning, Location-Allocation Models (Rizk et al., 2006). These issues are interdependent, so they must be used simultaneously in an integrated manner to minimize costs or benefits in the chain (Chen and Lee, 2004). On the one hand, forward and reverse networks are interdependent due to their interconnection in some parts (for example, recycled materials may re-enter the forward chain). On the other hand, by considering inverse logistics, achieving sustainable production (meaning resource protection and environmental compatibility) is facilitated (Hamidieh et al., 2017). Thus, the integration of forward and reverse flows in the supply chain with the aim of profitability and re-create value of returned products (Gaur et al., 2017; Taleizadeh et al., 2019) and avoiding the sub-optimizations resulting from the separate design of these two networks (Pishvaee & Razmi, 2012; Nurjanni et al., 2017), Highlights the importance of closed-loop supply chain network design (Altmann & Bogaschewsky, 2014).

Today, companies are aware of the role of return materials in reducing production costs, trying to protect the environment by accepting the responsibility of collecting return products. Transportation networks are environmentally friendly by decrease emitting greenhouse gases, especially CO2, Therefore, they play an important role in designing a green supply chain (Pan et al., 2013). The social aspect of supply chains is related to social justice and the rights of stakeholders including employees, customers, and local communities (Eskanderpour et al., 2015). Attention to social and environmental issues has led to the creation of a new concept in business called corporate social responsibility. Recently, governments have paid close attention to community participation and development as a key aspect of social responsibility, especially in developing countries (Lakin & Scheubel, 2017). For example, according to the "Fifth Development Plan of the Islamic Republic of Iran", issues related to job creation and balanced economic development have been significantly welcomed.

The trend of globalization and the tendency to outsource, increasing financial pressures and the intensity of competition, shortening product life and increasing customer expectations, rapid change and technological progress, are the factors leading to integrated logistics and a closed-loop supply chain. The issues of globalization, outsourcing of key activities, stakeholder cooperation, reverse logistics, development of organizational socially responsible, development of advanced technologies, have become more important at the beginning of the 21st century. Hence, most organizations have found that they need to have an overview of business activities, especially in the supply chain and its management (Dakov & Novkov, 2008). The concept of sustainable supply chain and the concept of reliable supply chain are two of these concepts. Traditionally, economic optimization (higher profitability or lower cost) has been a competitive advantage in supply chain network design. Recently, the ability of supply chain continuity as one of the new paradigms in supply chain network design has become more important. Therefore, simultaneous attention to the aspects of sustainability and reliability in supply chain network design, in addition to gaining a long-term competitive advantage, will also have the ability to maintain supply chain. In this research we try to answer the below questions;

1. How can sustainability and reliability considerations be added to a closed loop supply chain network?
2. How can the method of normalized normal constraint (NNC) be applied to solve the mathematical model of CLSC network?

3. How can three objective functions be balanced simultaneously?
4. How can we maximize the profit, maximize the social responsibility and minimize the CO2 emissions?

The aim of the present study is to design a closed-loop supply chain network that is reliable and inexpensive, while emphasizing socially responsible and customer satisfaction. Supply chains can use this model at strategic (determining locations of production, distribution, collection and recycling) and tactical (flow of materials and products in the network) decisions to achieve greater of profitability, socially responsible and reliability. The proposed multi-objective integer complex linear programming optimization model includes flow balance, production, operating capacity, weight and volume constraints of transportation, and demand constraints. Maximizing profits by taking into account environmental impacts as well as maximizing job opportunities created as well as maximizing system reliability, Considers the issue of supply chain sustainability in the form of economic, environmental and social objective functions.

2- Review of research literature

Pishvaei et al. (2014) designed a sustainable drug supply chain network with three economic, environmental, and social objective functions in the medical needle and syringe supply chain under uncertainty. Four factors of socially responsible including local development, job creation, consumer risk, and damage to workers, have been considered in their model. Khalifehzadeh et al. (2015) designed a four-tier supply chain network with the aim of minimizing the operating costs of all elements of the supply chain and maximizing system reliability and addressing deficiencies. A complex integer linear programming model formulates the problem. Pasandideh et al. (2015) presented a linear two-objective mathematical model for a multi-level, multi-product forward supply chain network. In this model, considering cost and reliability as goals, a framework was presented in which warehouses are prone to stochastic breakage due to various environmental factors. Fahimnia and Jabbarzadeh (2016) considered an optimization model including a sustainability performance scoring method and a stochastic fuzzy multi-objective programming approach. Zhalehchian et al. (2016) proposed a model for location routing inventory in a sustainable closed-loop supply chain despite combined uncertainty. Environmental effects include greenhouse gas emissions, fuel consumption, and energy consumption. Job opportunities and economic development as social factors were considered. The uncertain nature of the network was also considered using a possibility programming approach.

Rahmani and Mahoudian (2017) proposed a model for a supply chain network design problem with respect to CO2 emissions and the reliability factor. CO2 emissions were examined from two aspects: carbon emission costs along with fixed and variable costs of location and production (strategic decisions) and CO2 emissions related to transportation and production methods (operational planning). A robust approach has been used to consider uncertain parameters. Yousefi Babadi et al. (2017) for a petrochemical supply chain in uncertain environments, ie despite sabotage risks and less knowledge of parameters, proposed a multi-objective nonlinear programming model. The goal is to minimize total cost and shipping costs by reducing product production. In addition, the developed model identifies the optimal locations for a new distribution center (DC), the central collection and disposal center, as well as the optimal allocation of customer areas to each DC. Zahiri et al (2017), was designed a drug supply chain network under the uncertainty of a sustainable and flexible integer linear programming model with the aim of minimizing the total cost, maximizing social impacts other than building facilities, and minimizing bioremediation measures. A fuzzy random possibility programming approach was used to deal with the uncertainty aspect of the model.

Jabbarzadeh et al (2018), in designing a sustainable and resilient supply chain, used a fuzzy c-means clustering method to evaluate the performance of each supplier. This model was implemented in the plastic pipe industry. Tsao et al. (2018) used a multi-objective mathematical programming model to design a supply chain network in conditions of uncertainty to maximize social benefits and reduce economic costs and environmental impacts. Customer demand uncertainty was assessed using stochastic variables, while overall costs, carbon emissions, job opportunities, and adverse effects were considered using fuzzy numbers. Fattahi and Govindan (2018) examined the design and planning of a biofuel supply chain network by considering the difference in facility capacity due to probable disruptions.

Fakhrzad and Goodarzian (2019) developed a fuzzy multi-objective mixed-integer programming model for a green closed-loop, multi-product, multi-period, multi-level SCND problem. Objective functions include minimizing the total cost, minimizing the gas emission costs caused by the movement of vehicles between centers, and maximizing the reliability of delivery demand based on the reliability of suppliers. To solve the model and show efficiency, they used the famous imperialist competitive algorithm and its new modifications. Li et al. (2019) establish a sustainable and reliable hybrid renewable energy system with reverse osmosis, taking into account different operating scenarios with fluctuations in renewable energy supply and variable water demand designed. Initially, was predicted using recurrent neural networks, future energy supply from renewable sources and water demand to deal with the random behavior of several variables including freshwater demand, ambient temperature, solar radiation, and wind speed. Then, to minimize the total annual costs and greenhouse gas emissions, the multi-criteria optimization method using extended mathematical programming is used. Finally, potential loss of power supply probability was introduced as a tool to measure the stability of the proposed scenarios. The results showed that the potential power drop in the designed system was reduced compared to the base system.

Fazli-Khalaf et al. (2020) considered sustainability and reliability in designing a forward hydrogen supply chain network with three levels of manufacturer, warehouse and customer. To deal with the compositional uncertainty included in the model, a flexible mixed possibility programming method is proposed. A case study has been conducted to implement and analyze the results of the proposed model. Kabadurmus and Erdogan (2020), in a study of a multi-state, multi-level supply chain network design problem with multiple products and components, considered economic, environmental and risk factors. Problem modeled as a mixed linear programming model utilizing a carbon trading plan with limited risk threshold. Supply chain network designed depicts the simultaneous attention to sustainability and reliability. The results of modeling showed that the use of multi-mode transport reduces supply chain costs and carbon emissions. In addition, if the decision maker is risk-averse, the total cost of the supply chain and carbon emissions will increase.

Hosseini-Motlagh et al. (2020) designed a resilient and sustainable power supply chain network in the presence of uncertainty. To this end, they developed a multi-objective optimization model including cost minimization, minimizing resilience measures, and maximizing some aspects of corporate social responsibility. Successive establishment, congestion on electrical lines, distributed generators inadequacy and energy dissatisfaction level were among the flexibility measures. They used a new robust approach to deal with power demand uncertainty based on robust optimization and possibility theory in fuzzy logic. The results of using the proposed model by examining a real case in Iran showed that decision-makers could increase corporate social responsibility and flexibility by 50% and 20%, respectively, by increasing the total cost by 50%. Ahranjani et al. (2020) presented a complex integer linear programming model to design and program bioethanol supply chain networks with several raw materials. In order to create flexibility in the face of existing epistemic uncertainties and the risks of disrupting the supply chain, a stochastic-possibility-based hybrid planning approach has been used. The proposed model minimizes the total expected cost of the supply chain relative to non-disruption and disruption scenarios by setting a limit for greenhouse gas emissions. The performance of the model has been evaluated through a real case study prepared in Iran.

Tirkolaee et al. (2020), in designing a three-tier supply chain including suppliers, central warehouses, and wholesalers, In the first step to select a sustainable supplier, first by ranking the criteria and sub-criteria according to the Fuzzy Analytic Network Process (FANP) method, the relationships between the main criteria with Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL) are identified and finally suppliers prioritized by Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). In the second stage, the weights obtained from supplier prioritization are considered as the input of a three-objective model for the design of the proposed supply chain. The goals are to minimize the cost of the entire chain, maximize the weight value of the products by taking into account the priorities of the suppliers, and maximize the reliability of the supply chain. Finally, the model was solved in a case study of the lamp supply chain using the Weighted Goal Programming (WGP) method. Nosrati and Arshadi Khamseh (2020), considered a two-stage random scheduling model for supply chain network design with two objectives of maximizing reliability based on structural reliability theory and cost minimization with respect to the cost of unauthorized carbon emissions in the entire supply chain. They to optimize the flow between different sectors and the number of orders, the location of factories, warehouses, and recycling centers, despite the stochastic conditions for demand and carbon price, and also, the complexity of the nonlinear integer model, using the Non-dominated Sorting Genetic Algorithm II (NSGAII) to solve the proposed model.

Moradi et al. (2021) studied the issue of supply chain network design of multi-period, multi-product, and multi-level. Judges of retailers, production capacity and transportation costs, and operating costs of distribution centers are considered uncertain parameters. A definite complex integer programming model was proposed with the aim of reducing fixed costs, transportation, and outsourcing costs. In order to control the uncertainties, a robust optimization model was presented. A set of numerical experiments was analyzed using nominal data and realistic data. Results confirm that the proposed robust model performs better than its definitive counterpart does. Ding et al. (2021) examined the design of a supply chain network involving a foreign vendor, several distribution centers, and several retailers, in which a foreign vendor-provided commercial credit distribution centers. In this paper, credit-financing Commercial has reduced the total cost.

Lotfi et al. (2022) proposed a study on a robust optimization model to project the Covid -19 epidemic in Iran and predicted the number of patients from this course. Their study has two main stages. First, they assess the dynamics of the COVID-19. In the second stage, they provide practical suggestions to measure the required resources. They applied convex RO and Mean Absolute Deviation (MAD) to investigate the presented problem. Also, Lotfi et al. (2021a) proposed and designed a viable medical waste chain with risk (CVaR) and robustness considerations. Their network includes health center, waste segregation, waste purchase contractor and landfills. They tried to locate health centers to reduce waste and ship them to the waste purchase contractors, and solve the problem by GAMS CPLEX. To design the location problem for renewable energy centers, they also proposed a research on robust mathematical bi-level programming (Lotfi et al., 2021b). In addition, Pourghader Chobar et al. (2021) presented a problem on a novel multi-objective optimization mathematical model to locate hub centers with dynamic demand and environmental considerations.

Ignorance of responsibility, as well as the inefficiency of different layers of the supply chain, are issues that can impose high costs on the supply chain. Facility malfunctions, for example, may lead to additional transportation costs due to longer distances by customers (Schneider and Daskin, 2005). Given the breakdown of facilities, which is inevitable, the goals of the systems, in addition to the economic dimension, must include accountability and reliability under conditions of uncertainty. Because the supply chain must have responsible, reliable, and cheap facilities. Therefore, the importance of responsibility and reliability in supply chain network design can be clearly explained. A review of the existing literature also reveals a research gap in the implementation of accountability and reliability in supply chain network design. Today, supply chain network design decisions must survive long enough to operate for years or decades under complex and uncertain business environment conditions. Therefore, it is essential that these decisions be made in the presence of uncertainty.

Some previous research have studied the design of supply chain and logistics networks with disruptions in facilities and transportation links separately. However, in some manufacturing industries, there are some supply chain and logistics systems in which all kinds of disruptions can occur. Examples include water and gas pipelines, air and rail network infrastructure, and service delivery systems, including health care and education. Unlike previous works, this study examines the issue of supply chain network design consisting of different facilities as well as transportation routes between them. Some of them are potential, it is necessary to decide which nodes, and potential links should be made. Obviously, modifying the design of the supply chain network and related procurement will be very difficult and costly. Therefore, designing a reliable supply chain network despite several types of disruptions is important.

The models proposed for closed-loop supply chain network design in previous studies are usually modeled as one-objective problems, for a period of time, and considering a product. Table 1 shows the gap in the literature by listing the characteristics of related studies, while providing a more accurate classification of the subject. The contributions and innovations of this research compared to previous studies are as follows:

1. Introduce a new model for the design of multi-objective, multi-level, multi-product, and multi-period closed-loop supply chain networks with strategic planning (e.g., location decision of facilities and their allocation pattern), and Tactical planning (i.e. product flow between facilities of different categories and optimal inventory policy in each distribution center) simultaneous.
2. Assessment the environmental dimension of the model by including the cost of CO2 emissions from all sources (construction of facilities, energy consumption in operational processes and fuel consumed in the transportation network) in the economic objective function (profitability) and constraint allowable carbon emission based on the roof and exchange mechanism.
3. Measuring the social dimension in the objective function of socially responsible to meet the requirements of ISO 26000, taking into account the number of created job opportunities and balanced economic development on both fixed (resulting from the construction of facilities) and variable (per hour of operational activity).
4. Measuring the accuracy of model performance in the objective function of reliability by sending products to customers in sufficient quantities and at the appropriate time, in the form of reliability of selected suppliers and facilities, as well as traveled network routes in the suitable time.
5. Enabling the selection of the efficient best solution from the Pareto optimal set, as well as the possibility of determining the degree of optimality and the importance of different goals for the decision-maker based on the proposed optimization.
6. Reducing the design space and effective coverage of the target space through the uniform distribution of Pareto points on a level using the NNC approach.

Table 1. Comparative analysis of related papers

Researchers	Year	Network Structure	Multi Configuration				Problem Conditions		Sustainability			Emission Policy	Reliability		
			Objective	Product	Period	Transport	Modeling	Uncertainty Type	Economic	Environmental	Social		Index	Entity	Model
20	2015	CL	M	M	S	S	MIP	D	Profit	Score	-	Max	PQ	P	Max
14	2016	OL	M	M	S	M	MILP	S,F	Cost	Score	Score	-	DR	S	SB
24	2017	CL	M	M	S	S	MILP	F,R	Cost	-	DR	-	DT	D	Min
53	2017	OL	S	M	S	M	MILP	R	Cost	E	-	Cap	DR	M,D	SB
66	2017	OL	M	M	M	M	MILP	S,F	Cost	EC	JC	C&T	TD	M	FR
16	2018	OL	S	S	M	M	MILP	S,F	Cost	EC	AT,JC,SA	Cap	CD	W	FR
29	2018	OL	M	S	S	S	MILP	S,F	Cost	Score	Score	-	CD	S,M	FR
15	2019	CL	M	M	M	M	MILP	F	Cost	E	-	Min	DD	S	Max
35	2019	OL	M	S	S	S	MILP	D	Cost	E	-	Min	PD	S	FR
38	2019	OL	S	S	S	S	MILP	D	Cost	EC	-	Tax	DI,MB	M	FR
46	2020	OL	S	M	M	M	MILP	S,F,R	Cost	E	-	Cap	DR	S	SB
18	2020	OL	M	M	M	M	MILP	F,R	Cost	E	JC,SD	Min	DD	M,W	FR
26	2020	OL	M	S	M	S	MILP	F,R	Cost	EC	EG,JC	Min	DeR	M,D,R	Min
30	2020	OL	S	M	S	M	MILP	D	Cost	E	-	C&T	DR	S	FR
61	2020	OL	M	M	M	S	MILP	F	Cost	Score	Score	Max	DD	S,W	FR
63	2020	OL	S	S	M	M	MILP	D	Cost	E	-	Min	DD	S,C	SB
This Study		CL	M	M	M	M	MINLP	F,R	Profit	EC	JC,SD	C&T	DD	S,M,D, CC,RE, R,V	FR

Table guide
Network Structure (OL: Opened-Loop, CL: Closed-Loop)
Configuration (S: Single, M: Multi)
Problem Conditions Uncertainty Type (D: Deterministic, F: Fuzzy, R: Robust, S: Stochastic)
Sustainability Environmental (E: GHG Emission, EC: Emission Cost)
Sustainability Social (AT: Annual Turnover, RD: Responsiveness to Demand, EG: Economic Growth, JC: Job Creation, SA: Social Acceptance, SD: Sick Leaves)
Reliability Index (DR: Disruption Risk/Risk Value, DeR: De-Resiliency, DI: Defective Items, DT: Delivery Time, TD: Technology Disruption, CD: Capacity Disruption, DD: Delivery Demand/Order, PD: Potential Downtime, PQ: Products Quality, MB: Machine Breakdown)
Reliability Entity (S: Supplier, M: Manufacture/Power Plant/Production Process, D: Distribution/Pole Center/Distributed Generators, W: Warehouse/Storage Center, C: Customer/Demand Zone, CC: Collection Center, P: Product/Parts, RE: Recycling Center, R: Route/Line, V: Vehicle)
Reliability Model (SB: Scenario Based, FR: Failure Rate)

3- Problem definition

The main purpose of this research is to provide an efficient model for designing a stable and reliable integrated supply chain network that implements horizontal integration (simultaneous design of direct and reverse networks) and vertical integration (simultaneous strategic and operational decision making) with decision variables. The main ones are choosing the supplier to get the raw material supply contract, finding the best place to establish the potential facility, the flow of materials and products between the facilities and choosing the best vehicle to transport the goods between the routes in the network. The supplier, the optimal location of the facility and the optimal allocation of customers to the facility activated in the supply chain are selected in a way that not only maximizes the profitability of the network but also ensures the system with maximum stability and reliability.

In the intended supply chain, suppliers and recycling centers supply raw materials and delivered to factories. Factories produce the final products and send them to the distribution centers. Distribution centers are also established in the next level in order to store and transfer the products to the final customers, at this level of the chain, it is possible to maintain the products with the condition of leaving the warehouse for maximum a period before the end of life. Customers sell used products to collection centers. Returned products are divided into three categories: valuable, low value and worthless according to their quality status (depending on the time used). Valuable quantities are transferred to recycling centers for recycling, low-value batches are sold to energy recovery centers, and finally, non-valuable quantities are transferred to landfills for safe disposal as waste. Raw materials from recycling of returned products According to the quality of materials used in the recycling process are divided into two parts: raw materials suitable for production and raw materials suitable for sale in the market of recycled raw materials. Figure 1 shows a view of the described supply chain.

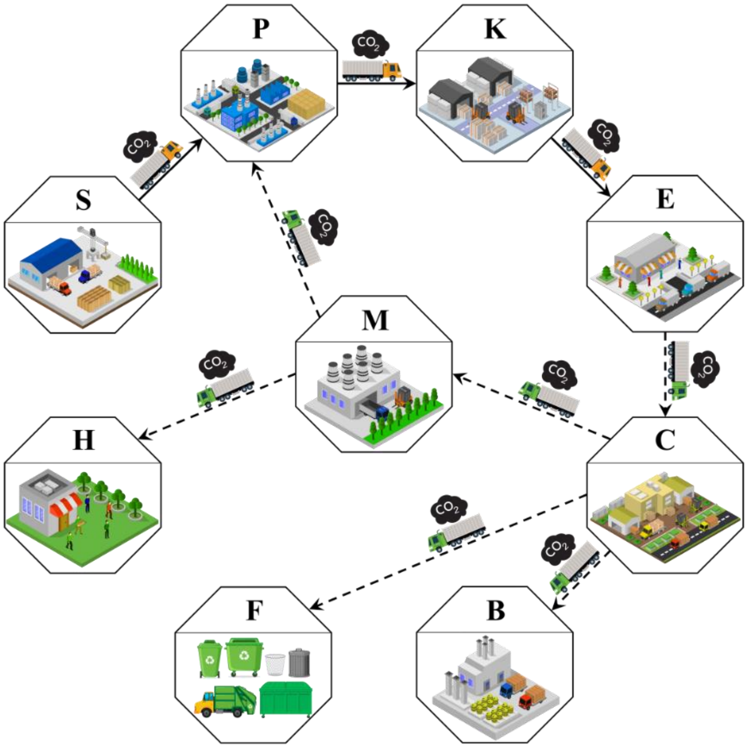

Fig 1. Schematic of a closed-loop supply chain network

Deciding on the type of facilities and products in the design of the supply chain network is of particular importance. This is doubly important for short-lived, perishable products. Perishable products can include drugs or food, and so on. In the present study, a comprehensive model has been attempted by considering all the facilities and the flow between them.

In the proposed model for the research problem, the issue of supply chain sustainability in the form of maximizing profitability by considering environmental impacts along with social responsibility has been considered. Supply chain reliability has been followed by maximizing the collection of reliability of raw material supply, establishing more reliable facilities, and reliability of travel time. Supply chains using this model can make decisions at strategic (determining the places of production, distribution, collection and recycling) and tactical (flow of materials and products in the network). In this section, the research problem is explained as a mathematical model.

Problem modeling

According to the problem statement, modeling the problem of designing a stable and reliable supply chain network as an integer linear mathematical programming model is shown below, which includes the objective functions of maximizing economic profitability and environmental protection (identifying the sustainability of the problem), maximizing responsibility. It is social (represents sustainability) as well as maximizing reliability (represents quality).

Problem assumptions

The assumptions of the problem are as follows.

- ✓ The model is multi-level, multi-product, multi-objective and multi-period.
- ✓ There is no connection between facilities at one level of the chain.
- ✓ Customers are divided into two groups' direct chain (Applicants of final products) and reverse chain (Applicants of recycled raw materials).
- ✓ Demand's lack (Missing) is allowed and unsatisfied demand will be penalized.
- ✓ Not collecting returned products will result in fines for the chain.
- ✓ Only one capacity level is selectable to establish potential centers.
- ✓ Only one type of production technology is implementable for each of the established production centers.
- ✓ Only one type of material is useable to recycle raw materials in each of the established recycling centers.
- ✓ It is possible to use heterogeneous vehicles with limited capacity in road transport between network facilities.
- ✓ The total cost of motivation, collection, and recycling is less than the cost of purchasing new raw materials.
- ✓ Warehouse management system in distribution centers is FIFO.

Mathematical modeling

Before mathematical formulation, it is necessary to defined sets, parameters and decision variables of the problem. However, due to their large size, their full description is given in appendix table 1.

Objective functions

First Objective Function (Profit Maximization): The first objective function of the model (EP) is to maximize supply chain profit, which is the result of the difference between total revenue and total supply chain costs (equation 1). The term TR in the objective function represents the total revenue of the supply chain, which is equal to the revenue from the sale of final products to customers, products returned to the energy recovery center, and recycled materials to other supply chains (equation 2). The term TC stands for supply chain costs, which include fixed costs, operating costs, transportation costs, and costs due to excessive carbon dioxide emissions (equation 3).

$$Maximize\ Z1 = Economic\ Profit\ (EP) = Total\ Revenue\ (TR) - Total\ Cost\ (TC) \tag{1}$$

$$TR = \sum_{t\in T}\left[\sum_{(x,y)\in\Psi_5}\sum_{r\in R} PR_{er}^{t}.\,Q_{xyr}^{t} + \sum_{(x,y)\in\Psi_8}\sum_{r\in R} PR_{br}^{t}\,.\,Q_{xyr}^{t} + \sum_{(x,y)\in\Psi_3}\sum_{a\in A} PR_{ha}^{t}\,.\,Q_{xya}^{t}\right] \tag{2}$$

$$\begin{aligned} TC\ =\ & Fixed\ Cost\ (FC) + Operation\ Cost\ (OC) + Shipping\ Cost\ (SC) \\ & + Emission\ Cost\ (EC) \end{aligned} \tag{3}$$

Fixed costs are denoted by the term FC and include the cost of establishing potential facilities, the cost of contracting with suppliers, and the cost of reopening the route and using vehicles (equation 4).

$$FC = \sum_{u\in U}\left[\sum_{n\in P}\sum_{g\in G} F_n^{gu}.\theta_n^{gu} + \sum_{n\in K} F_n^{u}.\theta_n^{u} + \sum_{n\in C} F_n^{u}.\theta_n^{u} + \sum_{n\in M}\sum_{l\in L} F_n^{lu}.\theta_n^{lu}\right] + \sum_{n\in S}\sum_{a\in A}\sum_{t\in T} F_{na}^{t}.\theta_{na}^{t} + \sum_{(x,y)\in\Psi}\sum_{v\in V}\sum_{t\in T} F_{xy}^{vt}.\pi_{xy}^{vt} \tag{4}$$

Raw material purchase cost, production cost, distribution cost, inspection and separation cost, recycling cost, and disposal cost components of the main costs in the implementation of supply chain operations are. of course, incentive costs (the cost of purchasing and collecting returned products of customers at the end of life), inventory costs (the cost of storing the final products in the warehouse's distribution centers), and fines (fines for not estimating customer demand and penalty for non-collection of returned products) are the components of operating expenses that are included in the term OC. In addition, the cost of providing recycled raw materials to production centers with a negative sign has been reduced from operating costs (equation 5).

$$\begin{aligned} OC = \sum_{t\in T}\Bigg[& \sum_{(x,y)\in\Psi_1}\sum_{a\in A} BC_{sa}^{t}.Q_{xya}^{t} - \sum_{(x,y)\in\Psi_2}\sum_{a\in A} RC_{a}^{t}.Q_{xya}^{t} + \sum_{p\in P}\sum_{r\in R}\sum_{g\in G} PC_{pr}^{gt}.Q_{pr}^{gt} \\ & + \sum_{(x,y)\in\Psi_5}\sum_{r\in R}\sum_{v\in V} KC_{kr}^{t}.Q_{xyr}^{t} + \sum_{k\in K}\sum_{r\in R} HC_{kr}^{t}.I_{kr}^{t} \\ & + \sum_{e\in E}\sum_{r\in R}(EC_{er}^{t}.S_{er}^{t} + OEC_{er}^{t}.QN_{er}^{t}) + \sum_{(x,y)\in\Psi_6}\sum_{r\in R}(CC_{cr}^{t} + OCC_{cr}^{t}).Q_{xyr}^{t} \\ & + \sum_{(x,y)\in\Psi_7}\sum_{r\in R}\sum_{l\in L} MC_{mr}^{lt}.Q_{xyr}^{t} + \sum_{(x,y)\in\Psi_9}\sum_{r\in R} FC_{fr}^{t}.Q_{xyr}^{t}\Bigg] \end{aligned} \tag{5}$$

The term SC indicates the transportation costs (fuel consumption and vehicle use costs) of the supply chain network (equation 6). The cost of fuel will vary depending on the type of vehicle, the amount of cargo transported, and the distance traveled. The cost of using the vehicle is also defined in terms of driving time. Driving time is a function of the average speed of the vehicle and the distance traveled by it.

$$\begin{aligned} SC = \sum_{v\in V}\sum_{t\in T} & \left[\sum_{(x,y)\in\Psi'}\sum_{a\in A} D_{xy}\pi_{xy}^{vt}.\left(\left(\Gamma^{vt}\left(FU1_v + (FU2_v.W_a.Q_{xya}^{t})\right)\right) + (V^{vt}/V^{v})\right)\right] \\ & + \left[\sum_{(x,y)\in\Psi''}\sum_{r\in R} D_{xy}\pi_{xy}^{vt}.\left(\left(\Gamma^{vt}\left(FU1_v + (FU2_v.W_r.Q_{xyr}^{t})\right)\right) + (V^{vt}/V^{v})\right)\right] \end{aligned} \tag{6}$$

The cost of over-limit CO2 emissions in the supply chain is expressed in terms of EC, which is the product of the multiplication of the CO2 emission factor in the difference between the current CO2 emissions and the allowed limit for the CO2 emissions of the supply chain (equation 7). The amount of CO2 emissions in the supply chain will be obtained from the total emissions constant amount due to the establishment of potential facilities (equation 9) and the emissions variable amount due to energy consumed in operational processes and transportation between levels of the chain (equation 10).

$$EC = \Theta\left(CO_2^{CUR} - CO_2^{GOV}\right) \tag{7}$$

$$CO_2^{CUR} = Fixed\ Emission\ CO_2(FEC) + Variable\ Emission\ CO_2(VEC) \tag{8}$$

$$FEC = \sum_{u\in U}\left[\sum_{p\in P}\sum_{g\in G} E_p^{gu}.\theta_p^{gu} + \sum_{k\in K} E_k^{u}.\theta_k^{u} + \sum_{c\in C} E_c^{u}.\theta_c^{u} + \sum_{m\in M}\sum_{l\in L} E_m^{lu}.\theta_m^{lu}\right] \tag{9}$$

$$\begin{aligned} VEC = {} & \epsilon^{j}.\left[Consumption\ Energy\ Operation\ (CEO)\right] \\ & + \epsilon^{l}.\left[Consumption\ Energy\ Shipping\ (CES)\right] \end{aligned} \tag{10}$$

$$\begin{aligned} CEO = \sum_{r\in R}\sum_{t\in T}\Bigg[& \sum_{p\in P}\sum_{g\in G} EP_r^{g}.Q_{pr}^{gt} \\ & + \sum_{(x,y)\in\Psi_5} EK_r.Q_{xyr}^{t} + \sum_{(x,y)\in\Psi_6} EC_r.Q_{xyr}^{t} + \sum_{(x,y)\in\Psi_7}\sum_{a\in A}\sum_{l\in L} EM_a^{l}.\rho_{ar}.Q_{xyr}^{t} \\ & + \sum_{(x,y)\in\Psi_8} EB_r.Q_{xyr}^{t} + \sum_{(x,y)\in\Psi_9} EF_r.Q_{xyr}^{t}\Bigg] \end{aligned} \tag{11}$$

$$\begin{aligned} CES = \sum_{v\in V}\sum_{t\in T} & \left[\sum_{(x,y)\in\Psi'}\sum_{a\in A} D_{xy}.\pi_{xy}^{vt}\left(FU1_v + \left(FU2_v W_a Q_{xya}^{t}\right)\right)\right] \\ & + \left[\sum_{(x,y)\in\Psi''}\sum_{r\in R} D_{xy}.\pi_{xy}^{vt}\left(FU1_v + \left(FU2_v W_r Q_{xyr}^{t}\right)\right)\right] \end{aligned} \tag{12}$$

Measuring the amount of carbon dioxide emissions due to transportation is complex and depends on various factors such as the method of transportation, type of fuel consumed, total product weight and distance traveled (Sundarakani et al., 2010). However, usually in the literature, the calculation of fuel consumption or greenhouse gas emissions has been modeled in a simple and far from reality way. For example, a number of studies (Kim et al., 2009; Hoen et al., 2010; Alkawaleet et al., 2014; and Mirzapour Al-e-hashem and Rekik, 2014) fuel consumption and greenhouse gas emissions in the transport sector of the supply chain only by considering the travel distance have calculated. In a number of studies, fuel consumption and carbon dioxide emissions have been modeled as a function of vehicle speed, freight, and distance traveled (Kuo, 2010; Bektaş and Laporte, 2011; Jabali et al., 2012; Aksoy et al., 2014; Liu et al., 2018).

The second objective function (CSR) pursues the maximization of supply chain social responsibility (equation 13). For this purpose, two criteria of job opportunities are created and the average number of days of sick leave of the personnel is used according to their importance. Both criteria are evaluated from both fixed and variable aspects. The model seeks to establish potential facilities in areas with higher unemployment rates, which in turn creates employment in more deprived areas.

In the expression JC, η_n and job_n are the factors influencing the choice of node node locations. η_n unemployment rate of potential centers, which is the coefficient of the nth region, ie the region with the highest unemployment rate, has a better chance of opening. job_n is also the number of people working in the nth node if it opens, the more it is, the increased possibility of selection nth potential center (equation 14). The term LD also refers to the number of days of sick leave used by employees, which is measured in both fixed and variable forms (equation 15).

$$\begin{aligned} Corporate\ Social\ Responsibility\ (CSR) = {} & \theta_{job} \times \left[Jobs\ Created\ (JC)\right] - \theta_{ltc} \\ & \times \left[Lost\ Days\ (LD)\right] \end{aligned} \tag{13}$$

$$\begin{aligned} JC = \sum_{u\in U}\Bigg(&\sum_{p\in P}\sum_{g\in G}\eta_p.job_p^{gu}.\theta_p^{gu} + \sum_{k\in K}\eta_k.job_k^{u}.\theta_k^{u} \\ &+ \sum_{c\in C}\eta_c.job_c^{u}.\theta_c^{u} + \sum_{m\in M}\sum_{l\in L}\eta_m.job_m^{lu}.\theta_m^{lu}\Bigg) + jt \\ &* \sum_{r\in R}\sum_{u\in U}\sum_{t\in T}\Bigg(\sum_{p\in P}\sum_{g\in G}\frac{TP_r^{g}.Q_{pr}^{gt}}{cap_p^{gu}} + \sum_{p\in P}\sum_{k\in K}\frac{TK_r.Q_{pkr}^{t}}{Cap_k^{u}} + \sum_{e\in E}\sum_{c\in C}\frac{TC_r.Q_{ecr}^{t}}{Cap_c^{u}} \\ &+ \sum_{c\in C}\sum_{m\in M}\sum_{a\in A}\sum_{l\in L}\frac{TM_a^{l}.\rho_{ar}.Q_{cmr}^{t}}{cap_m^{lu}}\Bigg) \end{aligned} \tag{14}$$

$$\begin{aligned} LD = \sum_{u\in U}\Bigg(&\sum_{p\in P}\sum_{g\in G}ltc_p^{gu}.\theta_p^{gu} + \sum_{k\in K}ltc_k^{u}.\theta_k^{u} + \sum_{c\in C}ltc_c^{u}.\theta_c^{u}\sum_{m\in M}\sum_{l\in L}ltc_m^{lu}.\theta_m^{lu}\Bigg) + lt \\ &* \sum_{r\in R}\sum_{u\in U}\sum_{t\in T}\Bigg(\sum_{p\in P}\sum_{g\in G}\frac{TP_r^{g}.Q_{pr}^{gt}}{cap_p^{gu}} + \sum_{p\in P}\sum_{k\in K}\frac{TK_r.Q_{pkr}^{t}}{Cap_k^{u}} + \sum_{e\in E}\sum_{c\in C}\frac{TC_r.Q_{ecr}^{t}}{Cap_c^{u}} \\ &+ \sum_{c\in C}\sum_{m\in M}\sum_{a\in A}\sum_{l\in L}\frac{TM_a^{l}.\rho_{ar}.Q_{cmr}^{t}}{cap_m^{lu}}\Bigg) \end{aligned} \tag{15}$$

The term Reliability is an objective function of maximizing supply chain reliability (equation 16). The term CR indicates the reliability of the supplier in meeting the needs of the manufacturer (equation 17). The term FR indicates the reliability of potential direct chain facilities if established (equation 18). Network travel time reliability is expressed in the TR term (equation 19).

$$\begin{aligned} Maximize\ Z3 &= Reliability \\ &= \lambda_1 \times [Contract\ Reliability\ (CR)] + \lambda_2 \times [Facility\ Reliability\ (FR)] + \lambda_3 \\ &\quad \times [Travel\ time\ Reliability\ (TR)] \end{aligned} \tag{16}$$

$$CR = \sum_{n\in S}\sum_{a\in A}\sum_{t\in T}SR_{sa}.\theta_{sa}^{t} \tag{17}$$

$$FR = \left[1 - \prod_{n\in P}\prod_{g\in G}\prod_{u\in U}\left(1 - RP_n^{gu}\theta_n^{gu}\right)\right] * \left[1 - \prod_{n\in K}\prod_{u\in U}\left(1 - RK_n^{u}\theta_n^{u}\right)\right] \tag{18}$$

$$TR = \sum_{(x,y)\in\Psi}\sum_{v\in V}\sum_{t\in T}\left[w_1\left(1 - Trange_{xy}\right) + w_2\left(Tratio_{xy}\right)\right]\pi_{xy}^{vt} \tag{19}$$

Constraints:

The constraints of the problem are described below. To make the model easier to read, similar constraints are first categorized and then an explanation of each category is provided. This method simplifies the study of the model.

Constraint carbon dioxide emissions:

$$\begin{aligned}
CO_2^{CUR} = {} & \sum_{u\in U}\left[\sum_{p\in P}\sum_{g\in G} E_p^{gu}.\theta_p^{gu} + \sum_{k\in K} E_k^u.\theta_k^u + \sum_{c\in C} E_c^u.\theta_c^u + \sum_{m\in M}\sum_{l\in L} E_m^{lu}.\theta_m^{lu}\right] \\
& + \epsilon^j.\Bigg[\sum_{r\in R}\sum_{t\in T}\Bigg(\sum_{p\in P}\sum_{g\in G} EP_r^g.Q_{pr}^{gt} \\
& + \sum_{(x,y)\in\psi_5} EK_r.Q_{xyr}^t + \sum_{(x,y)\in\psi_6} EC_r.Q_{xyr}^t + \sum_{(x,y)\in\psi_7}\sum_{a\in A}\sum_{l\in L} EM_a^l.\rho_{ar}.Q_{xyr}^t \\
& + \sum_{(x,y)\in\psi_8} EB_r.Q_{xyr}^t + \sum_{(x,y)\in\psi_9} EF_r.Q_{xyr}^t\Bigg)\Bigg] \\
& + \epsilon^l.\Bigg[\sum_{v\in V}\sum_{t\in T}\Bigg(\sum_{(x,y)\in\Psi'}\sum_{a\in A} D_{xy}\pi_{xy}^{vt}\left(FU1_v + \left(FU2_v W_a Q_{xya}^t\right)\right)\Bigg) \\
& + \Bigg(\sum_{(x,y)\in\Psi''}\sum_{r\in R} D_{xy}\pi_{xy}^{vt}\left(FU1_v + \left(FU2_v W_r Q_{xyr}^t\right)\right)\Bigg)\Bigg]
\end{aligned} \tag{20}$$

Constraint (20) determines the amount of carbon dioxide emissions across the planning horizon. It is noteworthy that the construction of potential facilities, operational activities and transportation cause carbon dioxide emissions.

Budget constraints:

$$\sum_{u\in U}\left[\sum_{p\in P}\sum_{g\in G} F_p^{gu}.\theta_p^{gu} + \sum_{k\in K} F_k^u.\theta_k^u + \sum_{c\in C} F_c^u.\theta_c^u + \sum_{m\in M}\sum_{l\in L} F_m^{lu}.\theta_m^{lu}\right] \leq Budget \tag{21}$$

Constraint (21) indicates that the available budget can be invested in the establishment of potential new facilities.

Demand constraints:

$$S_{er}^t = Dem_{er}^t - \sum_{k\in K} Q_{ker}^t, \quad \forall e,r,t \tag{22}$$

$$\sum_{k\in K} Q_{ker}^t \leq Dem_{er}^t, \quad \forall e,r,t \tag{23}$$

The amount of underestimated demand (shortage) of a product is as much as the difference between the actual amount of demand and the amount delivered to customers (response demand) in that period, which is represented by constraint (22). Constraint (23) indicates that the amount of sales may be less than or equal to the amount of actual demand. Unpredicted demand in a period is considered lost.

Allocation constraints:

$$\sum_{g\epsilon G}\sum_{u\in U}\theta_{p}^{gu}\leq 1,\quad \forall p \tag{24}$$

$$\sum_{u\in U}\theta_{k}^{u}\leq 1,\quad \forall k \tag{25}$$

$$\sum_{u\in U}\theta_{c}^{u}\leq 1,\quad \forall c \tag{26}$$

$$\sum_{l\epsilon L}\sum_{u\in U}\theta_{m}^{lu}\leq 1,\quad \forall m \tag{27}$$

Constraints (24) to (27) is related to establishment conditions of potential facilities. Therefore, there is maximum of one capacity level and one type of production technology for production center (24), maximum of one capacity level for distribution (25) and collection centers (26), maximum of one capacity level and one type of material for recycling center (27).

Facility capacity constraints:

$$\sum_{p\in P}Q_{spa}^{t}\geq b_{sa}.\theta_{sa}^{t},\quad \forall s,a,t \tag{28}$$

$$\sum_{p\in P}Q_{spa}^{t}\leq Cap_{sa}.\theta_{sa}^{t},\quad \forall s,a,t \tag{29}$$

$$\sum_{r\in R}TP_{r}^{g}.Q_{pr}^{gt}\leq \sum_{u\in U}Cap_{p}^{gu}.\theta_{p}^{gu},\quad \forall p,g,t \tag{30}$$

$$\sum_{e\in E}\sum_{r\in R}TK_{r}.Q_{ker}^{t}\leq \sum_{u\in U}Cap_{k}^{u}.\theta_{k}^{u},\quad \forall k,t \tag{31}$$

$$\sum_{r\in R}v_{r}.I_{kr}^{t}\leq \sum_{u\in U}VCap_{k}^{u}.\theta_{k}^{u},\quad \forall k,t \tag{32}$$

$$\sum_{e\in E}\sum_{r\in R}TC_{r}.Q_{ecr}^{t}\leq \sum_{u\in U}Cap_{c}^{u}.\theta_{c}^{u},\quad \forall c,t \tag{33}$$

$$\sum_{c\in C}\sum_{a\in A}\sum_{r\in R}\sum_{l\in L}TM_{a}^{l}.\rho_{ar}.Q_{cmr}^{t}\leq \sum_{l\in L}\sum_{u\in U}Cap_{m}^{lu}.\theta_{m}^{lu},\quad \forall m,t \tag{34}$$

Constraints (28) to (34) relate to the capacity of the facility. The minimum amount of raw material supply in case of selecting and obtaining a contract with the supplier is determined according to the limit (28) and the maximum capacity of the supplier is determined by the constraint (29). Constraint (30) with the impact of production technology used in production centers, expresses their maximum production capacity. The maximum operating capacity and storage capacity of distribution centers are shown in constraints (31) and

(32), respectively. The maximum operating capacity of collection centers is also constraint (33). The maximum recycling capacity of raw materials in recycling centers is expressed by constraint (34) according to the role of materials used in recycling operations.

Flow balance constraints:

$$\sum_{g\in G} Q_{pr}^{gt} = \sum_{k\in K} Q_{pkr}^{t}, \quad \forall p,r,t \tag{35}$$

$$\sum_{s\in S} Q_{spa}^{t} + \sum_{m\in M} Q_{mpa}^{t} = \sum_{r\in R}\sum_{g\in G} q_{ar}.\, Q_{pr}^{gt}, \quad \forall p,a,t \tag{36}$$

$$I_{kr}^{t} = I_{kr}^{t-1} + \sum_{p\in P} Q_{pkr}^{t} - \sum_{e\in E} Q_{ker}^{t}, \quad \forall k,r,t \tag{37}$$

$$I_{kr}^{t} = 0, \quad \forall k,r,t,t=1 \tag{38}$$

$$\sum_{e\in E}\sum_{d=t}^{\min(t+D_r-1,T)} Q_{ker}^{d} - \sum_{p\in P}\sum_{t\in T} Q_{pkr}^{t} \geq 0, \quad \forall k,r,t,t\neq T \tag{39}$$

$$\sum_{p\in P} Q_{mpa}^{t} = \sum_{c\in C}\sum_{r\in R} \sigma_a.\, \rho_{ar}.\, Q_{cmr}^{t}, \quad \forall m,a,t \tag{40}$$

$$\sum_{h\in H} Q_{mha}^{t} = \sum_{c\in C}\sum_{r\in R} (1-\sigma_a).\, \rho_{ar}.\, Q_{cmr}^{t}, \quad \forall m,a,t \tag{41}$$

$$QR_{er}^{t} = \sum_{d=0}^{D_r} \omega_r^d.\left(Dem_{er}^{t-d} - S_{er}^{t-d}\right), \quad \forall e,r,t,t\geq D_r \tag{42}$$

$$QR_{er}^{t} = 0, \quad \forall e,r,t,t<D_r \tag{43}$$

$$\sum_{c\in C} Q_{ecr}^{t} \leq QR_{er}^{t}, \quad \forall e,r,t \tag{44}$$

$$QN_{er}^{t} = QR_{er}^{t} - \sum_{c\in C} Q_{ecr}^{t}, \quad \forall e,r,t \tag{45}$$

$$\sum_{e\in E} \beta_r.\, Q_{ecr}^{t} = \sum_{b\in B} Q_{cbr}^{t}, \quad \forall c,r,t \tag{46}$$

$$\sum_{e\in E} \gamma_r.\, Q_{ecr}^{t} = \sum_{m\in M} Q_{cmr}^{t}, \quad \forall c,r,t \tag{47}$$

$$\sum_{e\in E} Q_{ecr}^{t} = \sum_{m\in M} Q_{cmr}^{t} + \sum_{b\in B} Q_{cbr}^{t} + \sum_{f\in F} Q_{cfr}^{t}, \quad \forall c,r,t \tag{48}$$

According to constraint (35), all production products are transferred to distribution centers, in fact, it is not possible to store the product in production centers. Constraint (36) states that the raw materials required for the production of products are supplied through suppliers or recycling centers. The inventory of final products in the warehouse of distribution centers is constraint to (37), and the constraint (38) is the amount of this inventory in the first planning period is considered zero. Constraint (39) states that products delivered to the distribution center must reach the customer no later than one period before the end of their service life, so that they can be used at the appropriate time (before expiration). In other words, the maximum storage time of inventory in the distribution center warehouse is one period less than the end of its life. Constraints (40) and (41) indicate at what rate the raw materials from the recycling of returned products are transported to the production centers and the market for recycled raw materials, respectively. Constraint (42) indicates that expired products are returned at different rates depending on the service life (uptrend). The important point is that the maximum total rate of return in years of use is one. Under constraint (43), products will not be returned before the end of their life. According to constraint (44), the reverse chain may not be able to collect all returned products from customers. The amount of uncollected returned products is shown in constraint (45). Constraints (46), (47) and (48) specify the amount of products collected that have energy recovery, recyclable and waste value, respectively.

Transport capacity constraints:

$$\sum_{a \in A} v_a . Q_{xya}^{t} \leq vcap^{v} . \pi_{xy}^{vt}, \quad \forall (x,y) \in \Psi', v, t \tag{49}$$

$$\sum_{r \in R} v_r . Q_{xyr}^{t} \leq vcap^{v} . \pi_{xy}^{vt}, \quad \forall (x,y) \in \Psi'', v, t \tag{50}$$

$$\sum_{a \in A} w_a . Q_{xya}^{t} \leq wcap^{v} . \pi_{xy}^{vt}, \quad \forall (x,y) \in \Psi', v, t \tag{51}$$

$$\sum_{r \in R} w_r . Q_{xyr}^{t} \leq wcap^{v} . \pi_{xy}^{vt}, \quad \forall (x,y) \in \Psi'', v, t \tag{52}$$

Transport capacity constraints ensure that when using a particular vehicle, the amount of material and product transport must be less than the maximum volumetric capacity (49 and 50) and the maximum weight capacity (51 and 52) of the vehicle.

Travel time constraints:

$$\tau_{xy}^{vt} = \left(L_{xy} + U_{xy}\right)/2, \quad \forall (x,y) \in \Psi, v, t \tag{53}$$

$$Trange_{xy} = \frac{\left(Tmax_{xy} - Tmin_{xy}\right)}{Tmax_{xy}}, \quad \forall (x,y) \in \Psi \tag{54}$$

$$Tratio_{xy} = \frac{Tmid_{xy}}{Tmax_{xy}}, \quad \forall (x,y) \in \Psi \tag{55}$$

$$Tmax_{xy} = \frac{D_{xy}}{L_{xy}}, \quad \forall (x,y) \in \Psi \tag{56}$$

$$Tmin_{xy} = \frac{D_{xy}}{U_{xy}}, \quad \forall (x,y) \in \Psi \tag{57}$$

$$Tmid_{xy} = \frac{\left(Tmax_{xy} + Tmin_{xy}\right)}{2}, \quad \forall (x,y) \in \Psi \tag{58}$$

Constraint (53) indicates the average speed of a vehicle of type v on the route between origin x and destination y in period t. Respectively, ratio of the difference between the maximum and minimum travel time to the maximum travel time between facilities in constraint (54), ratio of the average travel time to the maximum travel time between facilities in constraint (55), maximum and minimum travel time in constraints (56 and 57), and the average travel time in constraint (58) has been shown.

Logical constraints:

$$\theta_{sa}^{t}, \theta_{p}^{gu}, \theta_{k}^{u}, \theta_{c}^{u}, \theta_{m}^{lu}, \pi_{xy}^{vt} \in \{0,1\} \tag{59}$$

$$Q_{xya}^{vt}, Q_{xyr}^{vt}, Q_{pr}^{gt}, I_{kr}^{t}, QR_{xr}^{t}, QN_{er}^{t}, S_{er}^{t}, CO_2^{CUR} \geq 0 \tag{60}$$

Relationships (59) and (60) indicate the necessary logical constraints on discrete and continuous decision variables, respectively.

4- Solution method

In a multi-objective optimization problem, there is no single optimal solution, and several different optimal solutions can be generated so that each combined solution is implemented between the objective functions. These optimal answers are called Pareto answers. The Pareto Front Cloud for a multi-objective optimization problem with three objective functions is shown in figure (2). In this case, the 3D target space becomes a single-page cloud.

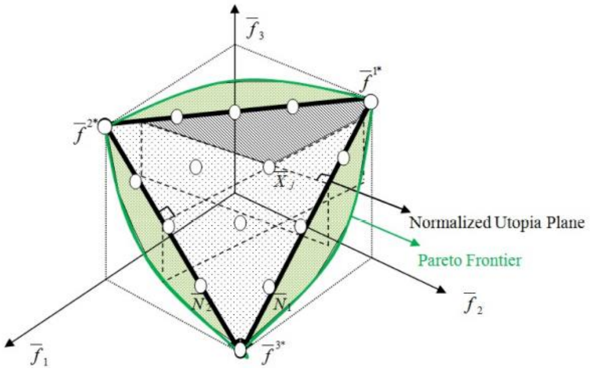

Fig 2. NNC method for a three-objective optimization problem

Often, the NNC method reports a set of Pareto optimal solutions rather than a single optimal solution (Ahmadigorji et al., 2017). The NNC method is one of the methods for obtaining efficient solutions with uniform distribution on the Pareto boundary in multi-objective problems, which was proposed in 2003 by Messac et al (Messac and Mattson, 2004). This method produces less localized non-Pareto and Pareto points than the Normal Boundary Intersection (NBI) method. Hence, it is more stable (Das and Dennis, 1998). The NNC method, despite its structural similarity to the NBI method, also benefits from the features of the epsilon constraint method (Mavrotas, 2009). The difference is that first, the objectives become normal, and then by applying new constraints in each step, the optimal solution is followed. The ability of this method to provide a well-distributed set of all Pareto solutions in the multi-objective supply chain network design literature certified in several studies (Wang et al., 2011; Sahraeian et al., 2013; Cascini et al., 2014; Gong et al., 2017; Tao et al., 2020). By uniformly distributing the solutions at the Pareto boundary, it becomes easier for the decision-maker to choose the optimal solution. Unfortunately, the Pareto solutions presented in most methods are not well-distributed (Das and Dennis, 1998; Ismail-Yahaya and Messac, 2002; Messac and Mattson, 2002). In addition, the NNC method does not require an initial weight for each objective (Wang et al., 2011). Overall, these capabilities provide the proposed approach to finding more preferred multi-objective solutions over other multi-objective optimization methods, such as sum weighted, conventional epsilon constraint, and enhanced epsilon constraint.

The process of the NNC approach to solving multi-objective optimization problems can be summarized as follows (Rahmani and Amjadi, 2018):

Step 1: The optimality of each objective function is denoted by u^{i*}, which is obtained by solving a single-objective problem according to equation (61).

$$u^{i*} = arg\,min\ f_i(u) \\ subject\ to: \begin{cases} \emptyset(u) = 0 i = 1,2,\dots,n \\ \psi(u) \leq 0 \end{cases} \tag{61}$$

Using the solutionsu^{i*}, the anchor points f^{i*} are generated as relation (62).

$$f^{i*} = \left[f_1^{i*}\ f_2^{i*} \dots f_n^{i*}\right]^T,\ i = 1,2,\dots,n = \left[f_1\left(u^{i*}\right)\ f_2\left(u^{i*}\right)\ \dots\ f_n\left(u^{i*}\right)\right]^T,\ i = 1,2,\dots,n \tag{62}$$

By connecting the anchor points in the target space, a super plan is created, which is called the ideal super plan.

Step 2: To avoid affecting the optimization process, the objective functions of the problem must be normalized. For this normalization, the NNC method uses the best and worst designs of objective functions under the headings of utopia point and pseudo-nadir point. The utopia point is denoted by f^u and is the point in the answer space that contains the best results of the objective function (see equation 63).

$$f^u = [f_1^u\ f_2^u \dots f_n^u]^T = [f_1(u^{1*})\ f_2(u^{2*})\ \dots\ f_n(u^{n*})]^T \tag{63}$$

The pseudo-nadir is denoted by f^N, which has the worst answer for the objective function, and is defined as equation (64).

$$f^N = [f_1^N\ f_2^N \dots f_n^N]^T f^N = [f_1^N\ f_2^N \dots f_n^N]^T \tag{64}$$

So that

$$f_i^N = \max\{f_i(u^{1*})\ f_i(u^{2*})\ \dots\ f_i(u^{n*})\},\ i = 1,2,\dots,n \tag{65}$$

In this way, each objective function is normalized based on the formula in equation (66).

$$\bar{f}_i = \frac{f_i - f_i^U}{f_i^N - f_i^U},\ i = 1,2,\dots,n \tag{66}$$

So that $\bar{f}_i$ is the normalized form of f_i. In figure 3, for a three-objective optimization problem, the normalized objective functions $\bar{f}_1$, $\bar{f}_2$, and $\bar{f}_3$ coordinate the target space and $\bar{f}^{1*}$, $\bar{f}^{2*}$, and $\bar{f}^{3*}$ anchors are normalized.

Step 3: The normalized ideal plane cloud vectors, denoted by $\overline{N}_k$, are calculated according to equation (67).

$$\overline{N}_k = \bar{f}^{n*} - \bar{f}^{k*},\ k = 1,2,\dots,n-1 \tag{67}$$

Each vector $\overline{N}_k$ shows the direct direction from the normalized anchor point k ($\bar{f}^{k*}$) to the normalized anchor point n ($\bar{f}^{n*}$). Figure 1 shows the direction of the vector $\overline{N}_1$ from $\bar{f}^{1*}$ to $\bar{f}^{3*}$ and the direction $\overline{N}_2$ from $\bar{f}^{2*}$ to $\bar{f}^{3*}$.

Step 4: A normalized distance (δ_k) is defined for a certain number of divisions (m_k) in the vector $\overline{N}_k$ (equation 68).

In the NNC method, each m_k corresponding to m_1 be calculated as equation (69).

$$\delta_k = \frac{1}{m_k - 1}, \quad k = 1,2,\dots,n-1 \tag{68}$$

$$\frac{m_k}{\|\bar{N}_k\|} = \frac{m_1}{\|\bar{N}_1\|}, \quad k = 1,2,\dots,n-1 \tag{69}$$

Step 5: The points of the ideal super high, denoted by $\bar{X}_j$, are in the normalized ideal super high as equation (70).

$$\bar{X}_j = \sum_{k=1}^{n} \alpha_{kj}.\bar{f}^{k*} \tag{70}$$

So that $0 \leq \alpha_{kj} \leq 1$ and $\sum_{k=1}^{n} \alpha_{kj} = 1$.

Step 6: The Pareto optimal solution for each point of the ideal super plan is obtained by solving the problem of single-objective optimization in equation (71).

$$\begin{gathered} \min \bar{f}_n(u) \\ \emptyset(u) = 0, \;\; \psi(u) \leq 0 \\ \bar{N}_k.\left(\bar{f} - \bar{X}_j\right) \leq 0, \;\; k = 1,2,\dots,n-1 \\ \bar{f} = \left[\bar{f}_1(u), \bar{f}_1(u), \dots, \bar{f}_n(u)\right]^T \end{gathered} \tag{71}$$

5- Problem solving and numerical results

To solve the mathematical model presented in the previous step, first for the problem of optimizing the mathematical model, the problem of designing a closed-loop supply chain network, considering the stability and reliability, we consider 10 numerical samples that have different dimensions. Then we solve numerical problems using Gomez software and NNC normalized constraint method.

As can be seen, with the increase in the size of the problem, the number of suppliers, the number of factories, distribution centers and other problem sets gradually increases and the complexity and difficulty of solving the problem increases.

Table 2. Dimensions of numerical problems

No. Problem	Facilities						
	S	P	K	E	C	M	T
1	2	2	2	4	2	2	2
2	3	3	2	5	2	3	3
3	4	4	3	6	3	3	3
4	4	4	3	7	3	5	4
5	5	5	4	7	3	6	4
6	5	6	4	8	4	6	4
7	6	7	5	9	5	7	4
8	6	7	6	10	5	7	5
9	7	9	8	11	6	8	5
10	8	10	8	12	6	9	6

Other parameters of experimental problems are generated randomly through uniform distributions. After reporting the initial data of the problems and the results obtained, the next section presents mathematical model validation and sensitivity analysis.

5-1- Problem solving

To solve the present problem, 10 numerical problems with different dimensions have been designed using Gomez software in Table 4. In this table, the second column shows the optimal supply chain profit values. The third column also shows the level of social responsibility and the fourth column shows the objective function of supply chain reliability. The purpose of the problem, which is to maximize the three objective functions mentioned in the planning horizon, for the different levels of numerical problems is shown in Table 4 below. In Problem 1, the number of suppliers, factories, customers, collection centers and periods is less than in other problems, so the amount of objective functions in Problem 1 is less than in other problems with higher dimensions. The same is true of other numerical problems. Because increasing the number of production centers and suppliers helps to increase the production of products and consequently the profit from revenues. In addition, as the dimensions of the problem increase, the values of social responsibility and reliability increase.

Table 3. Optimal values of objective functions for numerical problems

No. Problem	Objective Functions EconomicProfit (first)	Social Responsibility (second)	Reliability (third)
1	9246070.47	449.2	2.06
2	9733520.18	815.6	2.53
3	10162336.98	1089.66	2.72
4	10841225.33	1093.79	2.77
5	11285947.43	1169.33	2.95
6	11636521.79	1257.97	3.14
7	12265364.89	1396.76	3.66
8	12896348.38	1451.23	3.98
9	13366985.29	1499.77	4.24
10	13969553.72	1525.43	4.72

In the following, the rate of change of each of the objective functions in numerical problems is shown in the form of relevant graphs. According to the following figure, it can be seen that the supply function profit function of the supply chain increases with increasing dimensions of numerical problems at a fixed rate. The reason is the increase of some problem parameters and the growth of the value of the objective function.

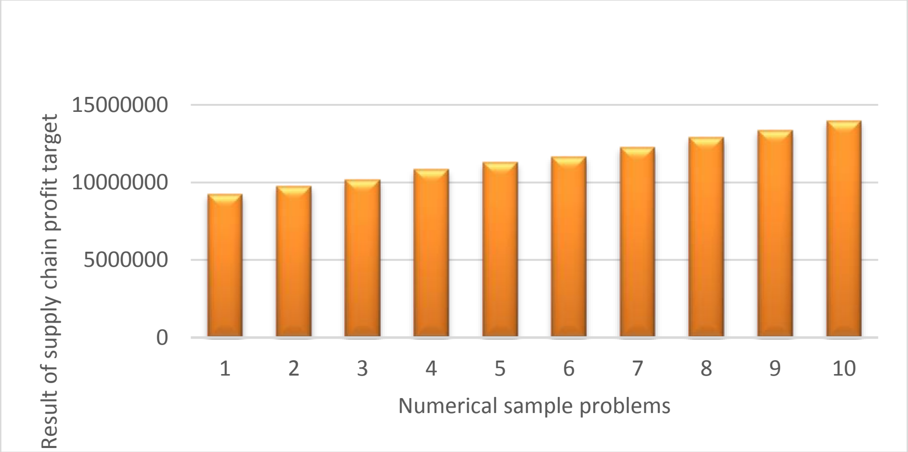

Fig 4. Value of supply chain profit target function in numerical problems

According to the following figure, it is shown that the objective function of social responsibility initially increases at a higher rate, and in larger dimensions, the value of this objective function almost reaches a certain value and has not increased significantly.

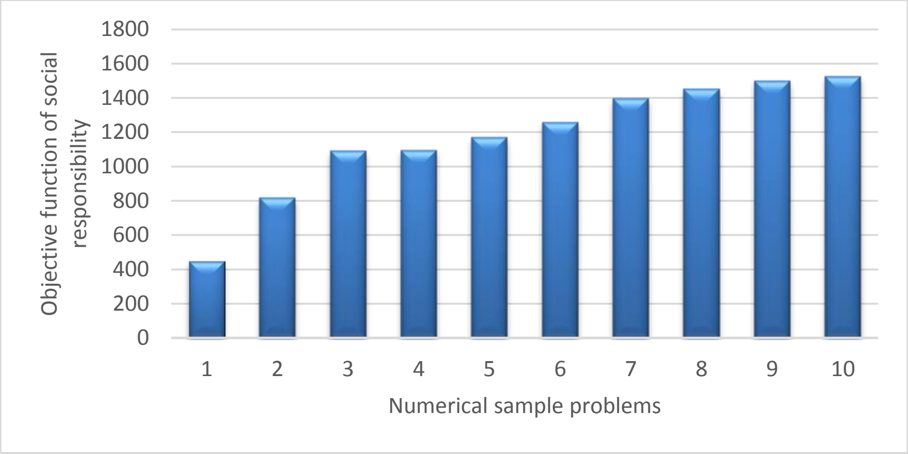

Fig 5. The value of the objective function of social responsibility in numerical issues

As shown below for the reliability objective function, it can be seen that the value of this objective function grows at a lower rate for smaller dimensions, while it increases at a higher rate for larger dimensions. In medium-sized problems, the value of this objective function is almost constant.

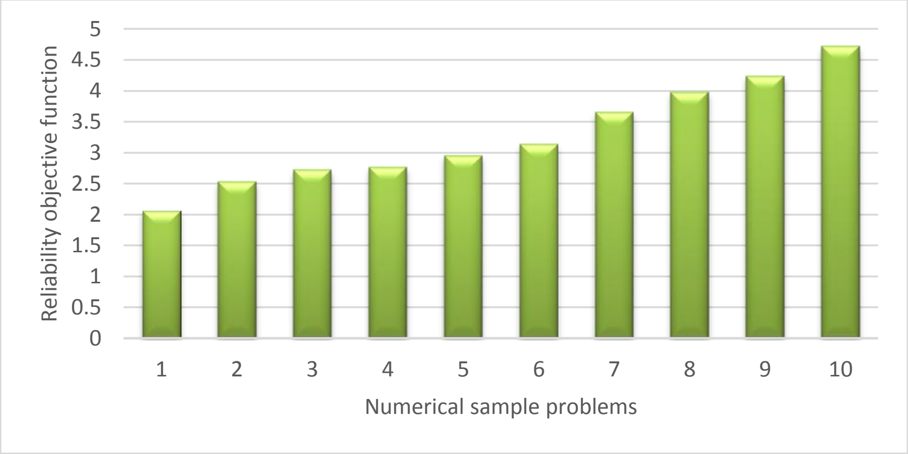

Fig 6. Value of the reliability objective function in numerical problems

Also shown below is the time to solve each of the numerical problems. Since the dimensions of numerical problems increase and problems have three objective functions and also the method of solving the normalized constraint in Gomez software has complexities, solving problems in Gomez software requires considerable time.

Table 4. Execution time of numerical problems

No. Problem	1	2	3	4	5	6	7	8	9	10
Execution time (seconds)	22360	23580	26335	28954	33651	36227	38996	41259	43653	45789

6- Numerical sensitivity analysis

In this section, we intend to validate the model and examine the model behavior in more detail by changing the model parameters such as first-hand customer demand e of product r in period t, penalty of uncollected product r returned from customer e in period t, supplier capacity s In the supply of raw material a in each period, and the amount of carbon dioxide emissions by vehicle v per liter of fuel consumption to examine the behavior of the first, second and third objective function of the model, namely supply chain profit, social responsibility and reliability. The following diagram shows the results of the analysis of the sensitivity of the supply chain profit target function to changes in the demand parameter and it can be concluded that with increasing demand in the problem, the value of the supply chain profit function increases.

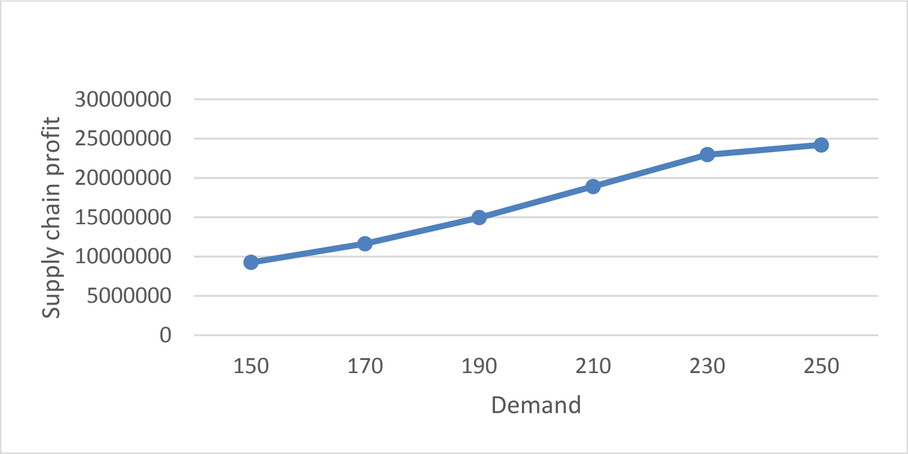

Fig 7. Sensitivity analysis chart of supply chain profit target function to demand changes

In the following, the analysis of the sensitivity of the objective function of social responsibility to changes in the demand parameter is shown and it can be concluded that with increasing demand in the problem, the value of this objective function decreases.

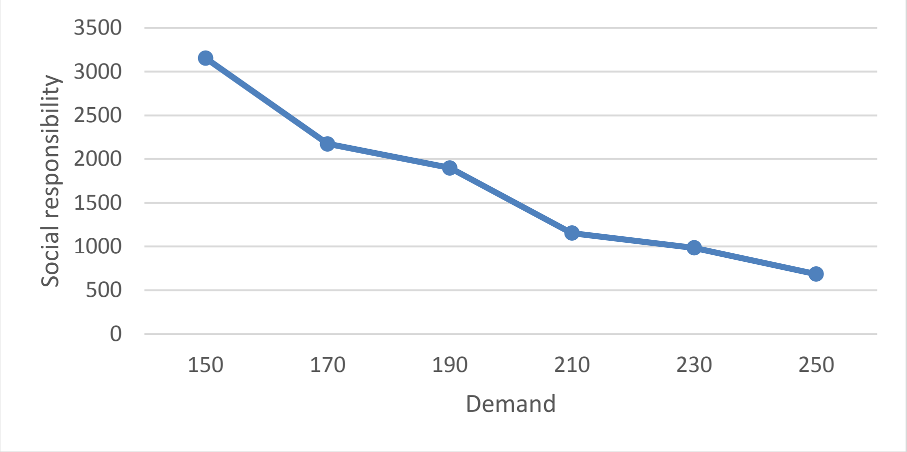

Fig 8. Diagram of sensitivity analysis of the objective function of social responsibility to changes in demand

In the following, we examine the behavior of the demand function of reliability to demand. Figure 8 shows the value of the reliability objective function for different amounts of demand. From the diagram in figure 9, it can be inferred that the value of the reliability objective decreases with increasing demand.

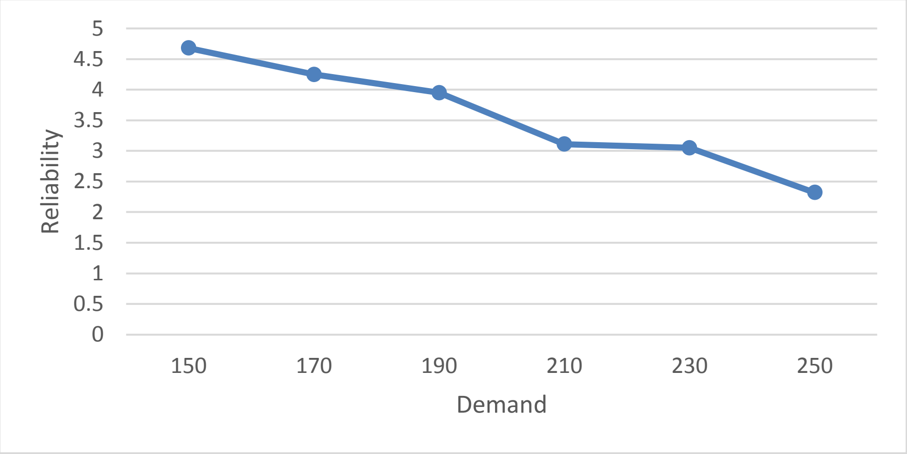

Fig 9. Sensitivity analysis diagram of the objective function of reliability to changes in demand

Figure 10 shows the value of the supply chain profit target function for different amounts of fines. From the diagram in figure 10, it can be inferred that by increasing the penalty, the value of the supply chain profit target decreases at a declining rate.

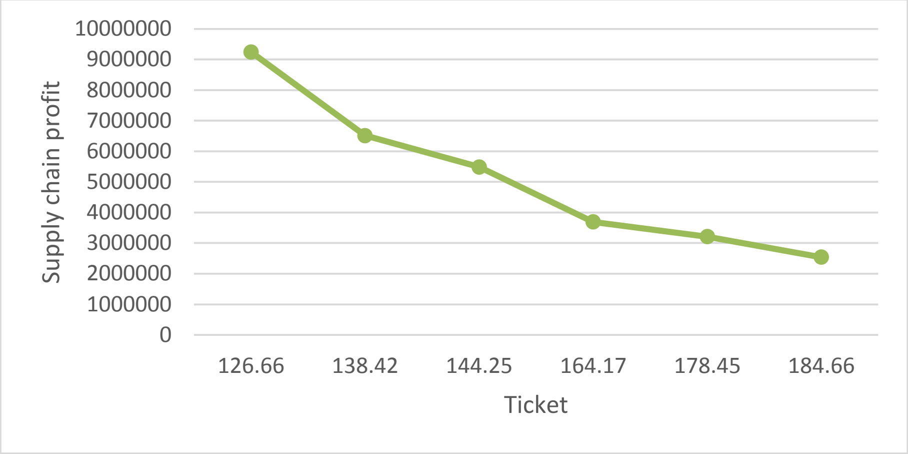

Fig 10. Sensitivity analysis chart of supply chain profit target function to penalty changes

The chart below shows the value of the objective function of social responsibility in exchange for different amounts of fines. From the diagram in figure 11, it can be inferred that with increasing fines, the amount of the objective function of social responsibility decreases.

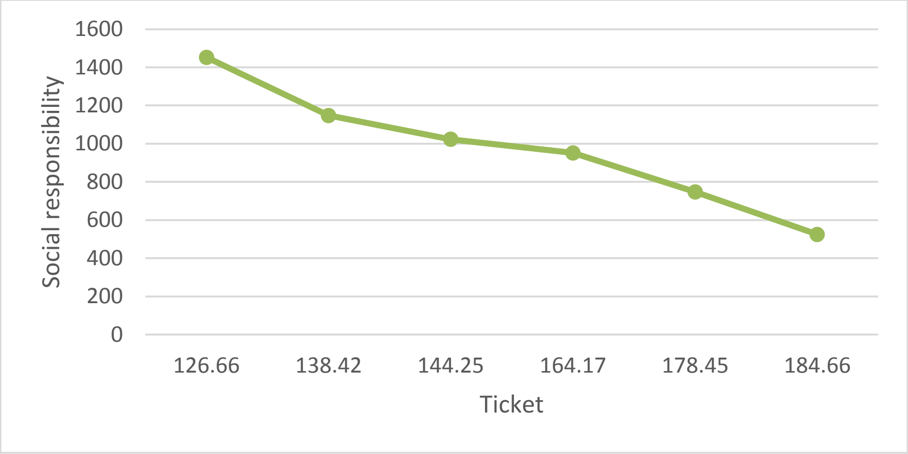

Fig 11. Sensitivity analysis diagram of the objective function of social responsibility towards penalty changes

In the following, we examine the behavior of the reliability objective functions in relation to the penalty parameter. Figure 12 shows the value of the objective function of reliability for different amounts of fines. From the diagram in figure 11, it can be inferred that the amount of reliability decreases with increasing fines.

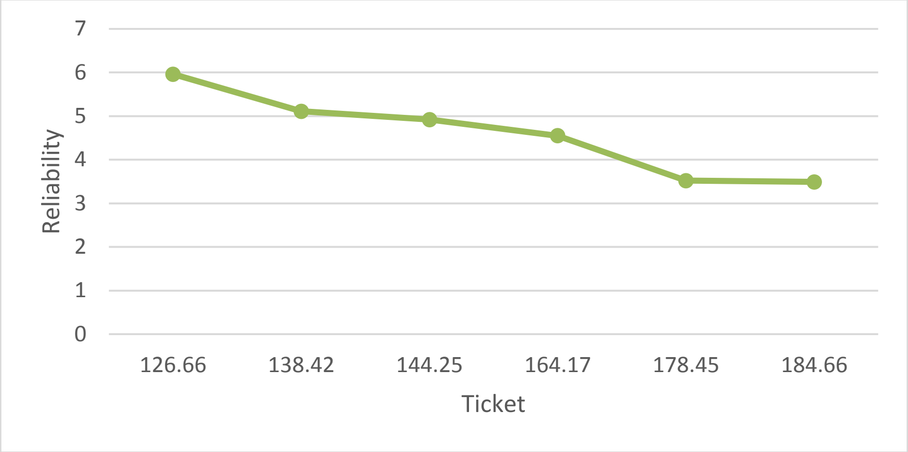

Fig 12. Sensitivity analysis chart of the reliability objective function for penalty changes

Figure 13 shows the value of the supply chain profit target function for different amounts of supplier capacity. From the diagram in figure 13, it can be inferred that as the supply capacity increases, the value of the supply chain profit function increases.

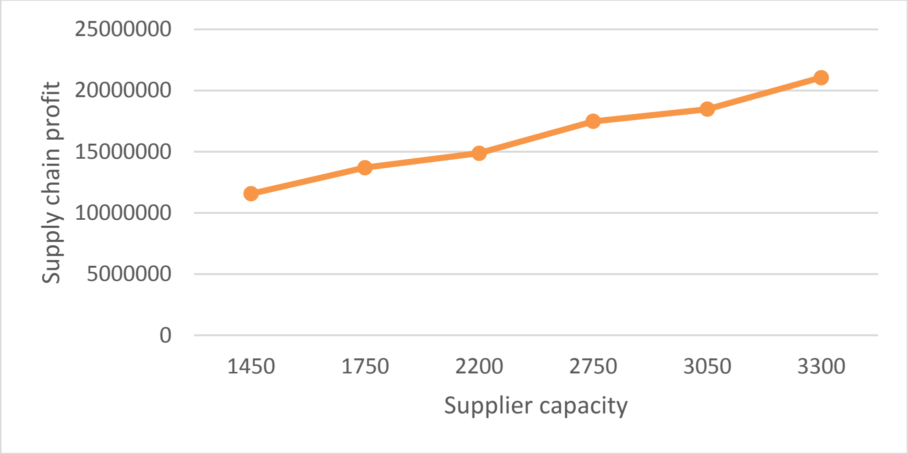

Fig 13. Sensitivity analysis diagram of supply chain profit target function to changes in supplier capacity

Figure 14 shows the value of the objective function of social responsibility in exchange for different amounts of supplier capacity. From the diagram in figure 14, it can be inferred that as the capacity of the supplier increases, the value of the social responsibility function remains almost constant.

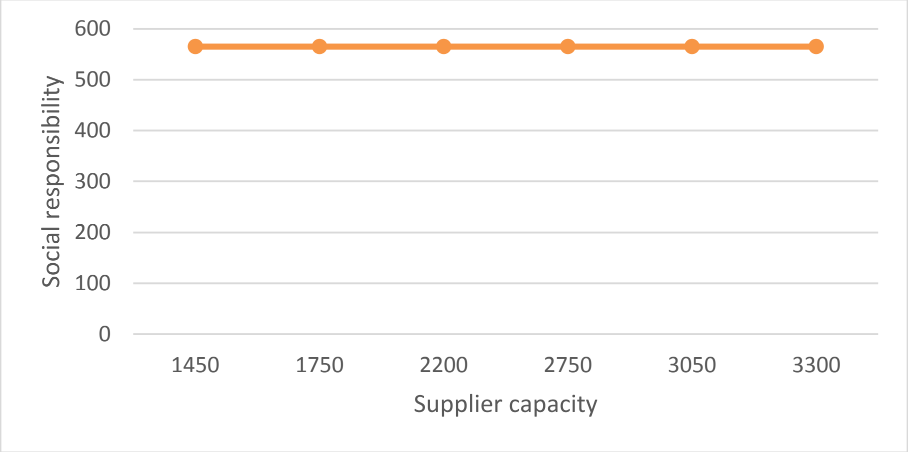

Fig 14. Sensitivity analysis diagram of the objective function of social responsibility towards changes in supplier capacity

Figure 15 shows the value of the reliability objective function for different values of supplier capacity. From the diagram in figure 15 it can be inferred that as the supply capacity increases, the value of the reliability objective function increases with the ascending rate.

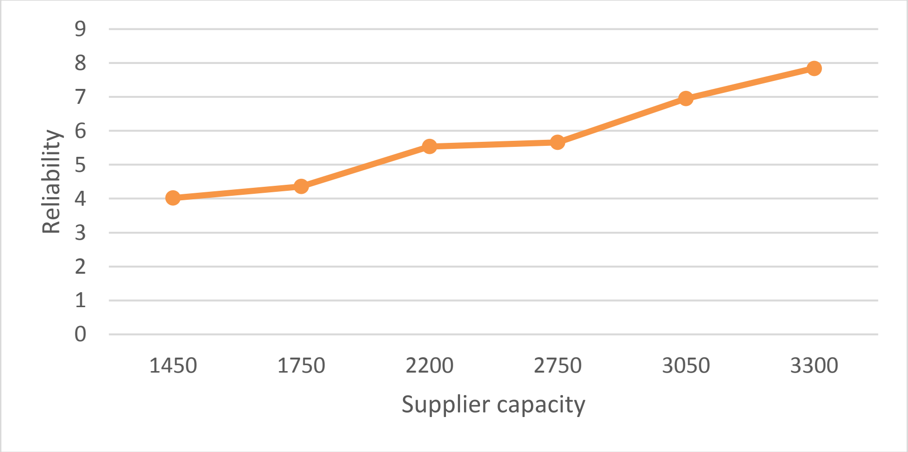

Fig 15. Sensitivity analysis diagram of the reliability objective function in response to changes in supplier capacity

Figure 16 shows the sensitivity analysis of the value of the supply chain profit target function for different values of the carbon dioxide emission parameter. From the diagram in figure 16, it can be inferred that by increasing the carbon dioxide emission parameter, the value of the supply chain profit target function decreases.

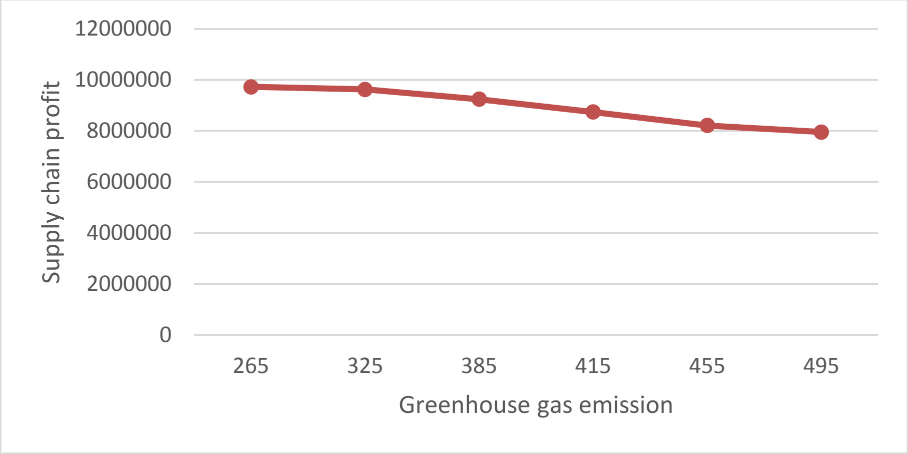

Fig 16. Sensitivity analysis diagram of supply chain profit target function to changes in carbon dioxide emissions

Figure 17 shows the sensitivity analysis of the value of the social responsibility objective function for different values of the carbon dioxide emission parameter. From the diagram in figure 17, it can be inferred that by increasing the carbon dioxide emission parameter, the value of the objective function of social responsibility decreases.

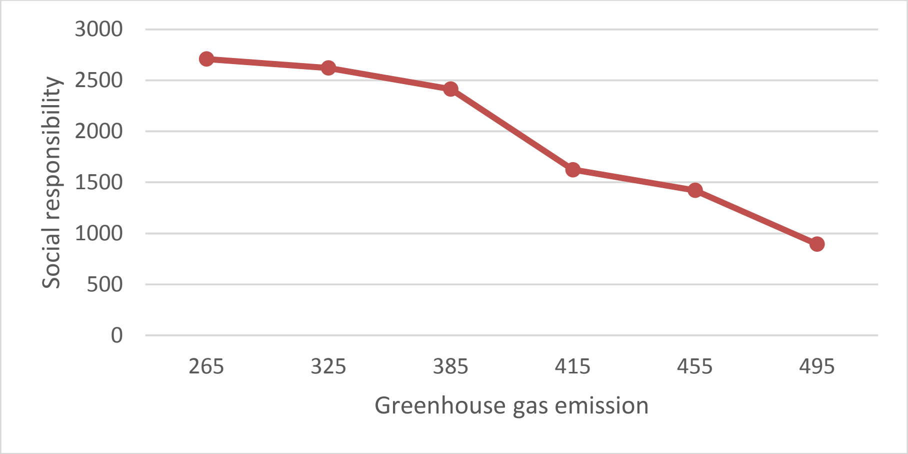

Fig 17. Sensitivity analysis diagram of the objective function of social responsibility for changes in carbon dioxide emissions

Figure 18 shows the sensitivity analysis of the value of the reliability objective function for different values of the carbon dioxide emission parameter. From the diagram in figure 18 it can be inferred that by increasing the carbon dioxide emission parameter, the value of the reliability objective function remains almost constant.

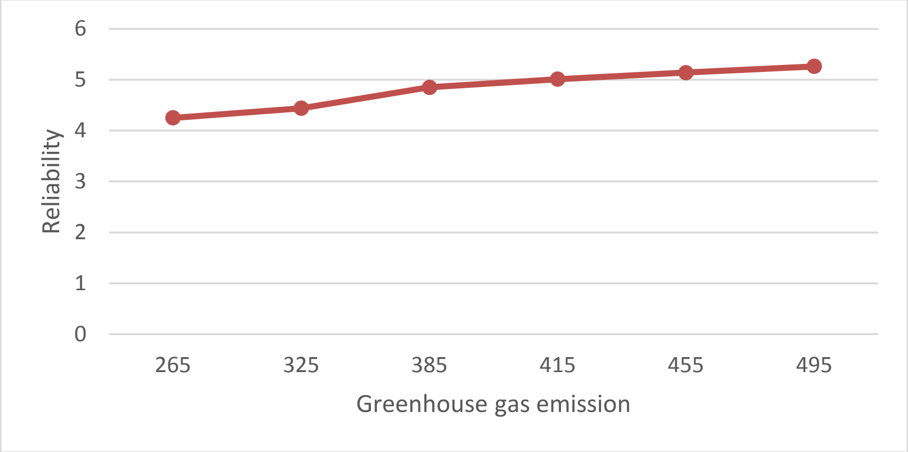

Fig 18. Sensitivity analysis diagram of the reliability objective function for changes in carbon dioxide emissions

7- Conclusions and suggestions for future research

In this research, we have designed and presented a mathematical model of closed-loop supply chain network design, which includes considerations of sustainability and reliability, social responsibility and economic benefits. A nonlinear mixed-integer mathematical programming model was designed for the supply chain network design problem in three objectives: multi-product, multi-level, multi-source, multi-capacity and multi-stage. Since the mathematical model is a multi-objective optimization model, it is necessary to use appropriate multi-objective optimization methods to solve it. For this reason, the Normalized Normal (NNC) constraint method was used and Gomez software was used to solve the mathematical model. Also, numerical examples with random data in different dimensions to measure the accuracy and overall performance of the proposed model are considered and by changing the various parameters of the model, sensitivity analysis of target functions is performed to model behavior and all three-supply chain profit target functions. Social and reliability to be analyzed. Because the mathematical model and the NNC solution method have complexities, solving it in Gomez software took considerable time. The values of the execution time of the problem were reported for different dimensions, and as the dimensions of the problem increase, the execution time also increases. Be. For different dimensions of numerical problems, the values of objective functions were also reported and it was observed that with increasing dimensions of numerical problems, the values of supply chain profit, reliability and social responsibility also increase.

To validate the designed optimization model, we analyzed the numerical sensitivity of various parameters of demand, fines, greenhouse gas emissions and supplier capacity, and the results were presented. It was observed that with increasing the demand parameter, the amount of profit of the issue also increases while reliability and social responsibility decrease. By increasing the penalty parameter, the amount of profit target function, reliability and social responsibility decreases. When the supplier capacity parameter increases, the problem profit and reliability increase while social responsibility remains constant. Finally, as the emission parameter increases, the value of the target function decreases profit and social responsibility, while the value of the target function of reliability remains almost constant.

For future research, suggestions can be made to improve the present study. For example, strong meta-heuristic approaches such as particle swarm optimization and multi-objective colonial competition can be used to solve the designed problem, and the results of problem solving with different methods can be compared. In addition, the issue of vehicle routing or forklifts in production centers can be modeled on the issue. In addition, data uncertainty can be used on parameters such as demand to bring the situation closer to the real world.

Reference

Ahmadigorji, M., Amjady, N., & Dehghan, S. (2017). A robust model for multiyear distribution network reinforcement planning based on information-gap decision theory. IEEE Transactions on Power Systems, 33(2), 1339-1351.

Aksoy, A., Küçükoğlu, İ., Ene, S., & Öztürk, N. (2014). Integrated emission and fuel consumption calculation model for green supply chain management. *Procedia-Social and Behavioral Sciences*, *109*, 1106-1109.

Alkawaleet, N., Hsieh, Y. F., & Wang, Y. (2014). Inventory routing problem with CO 2 emissions consideration. In *Logistics operations, supply chain management and sustainability* (pp. 611-619). Springer, Cham.

Altmann, M., & Bogaschewsky, R. (2014). An environmentally conscious robust closed-loop supply chain design. *Journal of Business Economics*, *84*(5), 613-637.

Ballou, R. H. (2004). Business logistics, supply chain management. Upper Saddle River, NJ: 5. internat. Aufl.

Bektaş, T., & Laporte, G. (2011). The pollution-routing problem. *Transportation Research Part B: Methodological*, *45*(8), 1232-1250.

Cascini, A., Mora, C., Pareschi, A., & Ferrari, E. (2014). Multi-objective Optimisation modelling for green supply chain management. Proceedings of XIX Summer School AIDI “Francesco Turco”, Industrial Mechanical Plants. Senigallia (AN), Italy.

Chen, C. L., & Lee, W. C. (2004). Multi-objective optimization of multi-echelon supply chain networks with uncertain product demands and prices. *Computers & Chemical Engineering*, *28*(6-7), 1131-1144.

Chen, Z. L. (2004). Integrated production and distribution operations. In *Handbook of quantitative supply chain analysis* (pp. 711-745). Springer, Boston, MA.

Chopra, S., & Meindl, P. (2007). Supply chain management. Strategy, planning & operation. In *Das summa summarum des management* (pp. 265-275). Gabler.

Dakov, I., & Novkov, S. (2008, May). Sustainable Supply chain management–Scope, activities and interrelations with other concepts. In *5th International Conference on Business and Management* (pp. 16-17).

Das, I., & Dennis, J. E. (1998). Normal-boundary intersection: A new method for generating the Pareto surface in nonlinear multicriteria optimization problems. *SIAM journal on optimization*, *8*(3), 631-657.

Eskandarpour, M., Dejax, P., Miemczyk, J., & Péton, O. (2015). Sustainable supply chain network design: An optimization-oriented review. *Omega*, *54*, 11-32.

Fahimnia, B., & Jabbarzadeh, A. (2016). Marrying supply chain sustainability and resilience: A match made in heaven. *Transportation Research Part E: Logistics and Transportation Review*, *91*, 306-324.

Fakhrzad, M. B., & Goodarzian, F. (2019). A fuzzy multi-objective programming approach to develop a green closed-loop supply chain network design problem under uncertainty: modifications of imperialist competitive algorithm. RAIRO-Operations Research, 53(3), 963-990.

Fattahi, M., & Govindan, K. (2018). A multi-stage stochastic program for the sustainable design of biofuel supply chain networks under biomass supply uncertainty and disruption risk: A real-life case study. *Transportation Research Part E: Logistics and Transportation Review*, *118,* 534-567.

Fazli-Khalaf, M., Mirzazadeh, A., & Pishvaee, M. S. (2017). A robust fuzzy stochastic programming model for the design of a reliable green closed-loop supply chain network. *Human and ecological risk assessment: an international journal*, *23*(8), 2119-2149.

Fazli-Khalaf, M., Naderi, B., Mohammadi, M., & Pishvaee, M. S. (2020). Design of a sustainable and reliable hydrogen supply chain network under mixed uncertainties: A case study. *International Journal of Hydrogen Energy*, *45*(59), 34503-34531.

Gaur, J., Amini, M., & Rao, A. K. (2017). Closed-loop supply chain configuration for new and reconditioned products: An integrated optimization model. Omega, 66, 212-223.

Ghayebloo, S., Tarokh, M. J., Venkatadri, U., & Diallo, C. (2015). Developing a bi-objective model of the closed-loop supply chain network with green supplier selection and disassembly of products: the impact of parts reliability and product greenness on the recovery network. *Journal of Manufacturing Systems*, *36*, 76-86.

Gong, D. C., Chen, P. S., & Lu, T. Y. (2017). Multi-objective optimization of green supply chain network designs for transportation mode selection. Scientia Iranica, 24(6), 3355-3370.

Govindan, K., Fattahi, M., & Keyvanshokooh, E. (2017). Supply chain network design under uncertainty: A comprehensive review and future research directions. *European Journal of Operational Research*, *263*(1), 108-141.

Gulati, R., Puranam, P., & Tushman, M. (2012). Meta-organization design: Rethinking design in interorganizational and community contexts. *Strategic management journal*, *33*(6), 571-586.

Hamidieh, A., Naderi, B., Mohammadi, M., & Fazli-Khalaf, M. (2017). A robust possibilistic programming model for a responsive closed loop supply chain network design. *Cogent Mathematics*, *4*(1), 1329886.

Hoen, K. M. R., Tan, T., Fransoo, J. C., & Houtum, G. (2010). Effect of carbon emission regulations on transport mode selection in supply chains [Z]. *Eindhoven: Eindhoven University of Technology*.

Hosseini-Motlagh, S. M., Samani, M. R. G., & Shahbazbegian, V. (2020). Innovative strategy to design a mixed resilient-sustainable electricity supply chain network under uncertainty. Applied Energy, 280, 115921.

Ismail-Yahaya, A., & Messac, A. (2002). Effective generation of the Pareto frontier using the normal constraint method. In 40th AIAA Aerospace Sciences Meeting & Exhibit (p. 178).

Jabali, O., Van Woensel, T., & De Kok, A. G. (2012). Analysis of travel times and CO2 emissions in time-dependent vehicle routing. Production and Operations Management, 21(6), 1060-1074.

Jabbarzadeh, A., Fahimnia, B., & Sabouhi, F. (2018). Resilient and sustainable supply chain design: sustainability analysis under disruption risks. International Journal of Production Research, 56(17), 5945-5968.

Kabadurmus, O., & Erdogan, M. S. (2020). Sustainable, multimodal and reliable supply chain design. *Annals of Operations Research*, *292*(1), 47-70.

Khalifehzadeh, S., Seifbarghy, M., & Naderi, B. (2015). A four-echelon supply chain network design with shortage: Mathematical modeling and solution methods. *Journal of Manufacturing Systems*, *35*, 164-175.

Kim, J., Xu, M., Kahhat, R., Allenby, B., & Williams, E. (2009). Designing and assessing a sustainable networked delivery (SND) system: Hybrid business-to-consumer book delivery case study. *Environmental science & technology*, *43*(1), 181-187.

Kuo, Y. (2010). Using simulated annealing to minimize fuel consumption for the time-dependent vehicle routing problem. *Computers & Industrial Engineering*, *59*(1), 157-165.

Lakin, N., & Scheubel, V. (2017). *Corporate community involvement: The definitive guide to maximizing your business' societal engagement*. Routledge.

Li, Q., Loy-Benitez, J., Nam, K., Hwangbo, S., Rashidi, J., & Yoo, C. (2019). Sustainable and reliable design of reverse osmosis desalination with hybrid renewable energy systems through supply chain forecasting using recurrent neural networks. *Energy*, *178*, 277-292.

Li, Y., Liu, B., & Huan, T. C. T. (2019). Renewal or not? Consumer response to a renewed corporate social responsibility strategy: Evidence from the coffee shop industry. *Tourism Management*, *72*, 170-179.

Liu, J., Feng, Y., Zhu, Q., & Sarkis, J. (2018). Green supply chain management and the circular economy: Reviewing theory for advancement of both fields. *International Journal of Physical Distribution & Logistics Management*.

Lotfi, R., Kheiri, K., Sadeghi, A., & Babaee Tirkolaee, E. (2022). An extended robust mathematical model to project the course of COVID-19 epidemic in Iran. Annals of Operations Research, 1-25.

Lotfi, R., Kargar, B., Gharehbaghi, A., & Weber, G. W. (2021a). Viable medical waste chain network design by considering risk and robustness. Environmental Science and Pollution Research, 1-16.

Lotfi, R., Mardani, N., & Weber, G. W. (b. Robust bi-level programming for renewable energy location. International Journal of Energy Research, 45(5), 7521-7534.

Marchi, B., Zanoni, S., Zavanella, L. E., & Jaber, M. Y. (2019). Supply chain models with greenhouse gases emissions, energy usage, imperfect process under different coordination decisions. *International Journal of Production Economics*, *211*, 145-153.

Mavrotas, G. (2009). Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. *Applied mathematics and computation*, *213*(2), 455-465.

Max Shen, Z. J. (2007). Integrated supply chain design models: a survey and future research directions. *Journal of Industrial & Management Optimization*, *3*(1), 1.

Messac, A., & Mattson, C. A. (2002). Generating well-distributed sets of Pareto points for engineering design using physical programming. Optimization and Engineering, 3(4), 431-450.

Messac, A., & Mattson, C. A. (2004). Normal constraint method with guarantee of even representation of complete Pareto frontier. AIAA journal, 42(10), 2101-2111.

Messac, A., Ismail-Yahaya, A., & Mattson, C. A. (2003). The normalized normal constraint method for generating the Pareto frontier. *Structural and multidisciplinary optimization*, *25*(2), 86-98.

Mirzapour Al-e-hashem, S. M. J., & Rekik, Y. (2014). Multi-product multi-period Inventory Routing Problem with a transshipment option: A green approach. *International Journal of Production Economics*, *157*, 80-88.

Moradi, S., & Sangari, M. S. (2021). A robust optimisation approach for designing a multi-echelon, multi-product, multi-period supply chain network with outsourcing. *International Journal of Logistics Systems and Management*, *38*(4), 488-505.

Mousavi Ahranjani, P., Ghaderi, S. F., Azadeh, A., & Babazadeh, R. (2020). Robust design of a sustainable and resilient bioethanol supply chain under operational and disruption risks. *Clean Technologies and Environmental Policy*, *22*(1), 119-151.

Nosrati, M., & Khamseh, A. (2020). Reliability optimization in a four-echelon green closed-loop supply chain network considering stochastic demand and carbon price. *Uncertain Supply Chain Management*, *8*(3), 457-472.

Nurjanni, K. P., Carvalho, M. S., & Costa, L. (2017). Green supply chain design: A mathematical modeling approach based on a multi-objective optimization model. *International Journal of Production Economics*, *183*, 421-432.

Pan, F., & Nagi, R. (2013). Multi-echelon supply chain network design in agile manufacturing. *Omega*, *41*(6), 969-983.

Pasandideh, S. H. R., Niaki, S. T. A., & Asadi, K. (2015). Bi-objective optimization of a multi-product multi-period three-echelon supply chain problem under uncertain environments: NSGA-II and NRGA. *Information Sciences*, *292*, 57-74.

Pishvaee, M. S., Razmi, J., & Torabi, S. A. (2012). Robust possibilistic programming for socially responsible supply chain network design: A new approach. *Fuzzy sets and systems*, *206*, 1-20.

Pishvaee, M. S., Razmi, J., & Torabi, S. A. (2014). An accelerated Benders decomposition algorithm for sustainable supply chain network design under uncertainty: A case study of medical needle and syringe supply chain. *Transportation Research Part E: Logistics and Transportation Review*, *67*, 14-38.

Pourghader Chobar, A., Adibi, M. A., & Kazemi, A. (2021). A novel multi-objective model for hub location problem considering dynamic demand and environmental issues. Journal of Industrial Engineering and Management Studies, 8(1), 1-31.

Rahmani, D., & Mahoodian, V. (2017). Strategic and operational supply chain network design to reduce carbon emission considering reliability and robustness. *Journal of Cleaner Production*, *149*, 607-620.

Rahmani, S., & Amjady, N. (2018). Improved normalised normal constraint method to solve multi-objective optimal power flow problem. IET generation, transmission & distribution, 12(4), 859-872.

Rezaei Kallaj, M., Abolghasemian, M., Moradi Pirbalouti, S., Sabk Ara, M., & Pourghader Chobar, A. (2021). Vehicle Routing Problem in Relief Supply under a Crisis Condition considering Blood Types. Mathematical Problems in Engineering, 2021.

Rizk, N., Martel, A., & D'Amours, S. (2006). Multi-item dynamic production-distribution planning in process industries with divergent finishing stages. Computers & Operations Research, 33(12), 3600-3623.

Sahraeian, R., Bashiri, M., & Taheri-Moghadam, A. (2013). Capacitated multimodal structure of a green supply chain network considering multiple objectives. International Journal of Engineering Transactions B: Applications, 9(26).

Snyder, L. V., & Daskin, M. S. (2005). Reliability models for facility location: the expected failure cost case. *Transportation Science*, *39*(3), 400-416.

Sundarakani, B., De Souza, R., Goh, M., Wagner, S. M., & Manikandan, S. (2010). Modeling carbon footprints across the supply chain. *International Journal of Production Economics*, *128*(1), 43-50.

Taleizadeh, A. A., Haghighi, F., & Niaki, S. T. A. (2019). Modeling and solving a sustainable closed loop supply chain problem with pricing decisions and discounts on returned products. *Journal of cleaner production*, *207*, 163-181.

Tao, J., Shao, L., Guan, Z., Ho, W., & Talluri, S. (2020). Incorporating risk aversion and fairness considerations into procurement and distribution decisions in a supply chain. International Journal of Production Research, 58(7), 1950-1967.

Tirkolaee, E. B., Mardani, A., Dashtian, Z., Soltani, M., & Weber, G. W. (2020). A novel hybrid method using fuzzy decision making and multi-objective programming for sustainable-reliable supplier selection in two-echelon supply chain design. *Journal of Cleaner Production*, *250*, 119517.

Tsao, Y. C., Thanh, V. V., Lu, J. C., & Yu, V. (2018). Designing sustainable supply chain networks under uncertain environments: Fuzzy multi-objective programming. *Journal of Cleaner Production*, *174*, 1550-1565.

Wang, B., Zhang, H., Yuan, M., Guo, Z., & Liang, Y. (2020). Sustainable refined products supply chain: a reliability assessment for demand-side management in primary distribution processes. *Energy Science & Engineering*, *8*(4), 1029-1049.

Wang, F., Lai, X., & Shi, N. (2011). A multi-objective optimization for green supply chain network design. Decision support systems, 51(2), 262-269.

Yousefi-Babadi, A., Tavakkoli-Moghaddam, R., Bozorgi-Amiri, A., & Seifi, S. (2017). Designing a reliable multi-objective queuing model of a petrochemical supply chain network under uncertainty: a case study. *Computers & Chemical Engineering*, *100*, 177-197.

Zahiri, B., Zhuang, J., & Mohammadi, M. (2017). Toward an integrated sustainable-resilient supply chain: A pharmaceutical case study. Transportation Research Part E: Logistics and Transportation Review, 103, 109-142.

Zhalechian, M., Tavakkoli-Moghaddam, R., Zahiri, B., & Mohammadi, M. (2016). Sustainable design of a closed-loop location-routing-inventory supply chain network under mixed uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, *89*, 182-214.

Appendix A

Nomenclature	Icon	Description
Sets		
Main Sets	S	Set of raw materials suppliers, $s \in S$
	P	Set of potential production centers, $p \in P$
	K	Set of potential distribution centers, $k \in K$
	E	Set of customer fixed points, $e \in E$
	C	Set of potential collection centers, $c \in C$
	M	Set of potential recycling centers, $m \in M$
	H	Set of fixed points of recycled raw materials market, $h \in H$
	F	Set of safe disposal centers, $f \in F$
	B	Set of energy recovery centers, $b \in B$
	A	Set of raw materials, $a \in A$
	R	Set of products, $\mathrm{r} \in \mathrm{R}$
	L	Set of materials used to recycle products, $\mathrm{l} \in \mathrm{L}$
	G	Set of technologies in production centers, $g \in \mathrm{G}$
	U	Set of capacity level $\mathrm{u} \in \mathrm{U}$
	V	Set of vehicles, $\mathrm{v} \in \mathrm{V}$
	T	Set of period, $t \in T$
Hybrid Sets	N	Set of network nodes, $N \in \{s, p, k, e, c, m, b, f, h\}$
	Ψ	Set of Network arcs, $\Psi(\mathrm{x}, \mathrm{y}) \in \{\Psi_1: (s, p), \Psi_2: (p, m), \Psi_3: (m, h), \Psi_4: (p, k), \Psi_5: (k, e), \Psi_6: (e, c), \Psi_7: (c, m), \Psi_8: (c, b), \Psi_9: (c, f)\}$
	Ψ'	Set of carrying raw materials arcs, $\Psi' \subset \Psi$; $\Psi' \in \{\Psi_1, \Psi_2, \Psi_3\}$
	Ψ''	Set of carrying products arcs, $\Psi'' \subset \Psi$; $\Psi'' \in \{\Psi_4, \Psi_5, \Psi_6, \Psi_7, \Psi_8, \Psi_9\}$
Parameters		
Selling Prices	PR_{er}^{t}	Selling price of one unit product r for first-hand customer e in time period t
	PR_{br}^{t}	Selling price of one unit returned product r at the energy recovery center b in time period t
	PR_{ha}^{t}	Selling price of one unit raw material a at market of recycled raw materials h in time period t
Fixed Costs	F_{p}^{gu}	Fixed cost of establishing one production center p with technology g and capacity level u
	F_{k}^{u}	Fixed cost of establishing one distribution center k with capacity level u
	F_{c}^{u}	Fixed cost of establishing one collection center c with a capacity level u
	F_{m}^{lu}	Fixed cost of establishing one recycling center m using materials l and capacity level u
	F_{sa}^{t}	Fixed cost to make one contract with supplier s for prepare raw material a in time period t
	F_{v}^{t}	Fixed cost of using vehicle v in time period t
	Θ	Fixed cost for one unit carbon dioxide emissions over of allowable limit
Unit Costs	BC_{sa}^{t}	Purchasing cost of one unit new raw material a from supplier s in time period t
	RC_{a}^{t}	Savings cost of one unit recycled raw material a in time period t
	PC_{pr}^{gt}	Producing cost of one unit product r at the production center p with technology g in time period t
	KC_{kr}^{t}	Distributing cost of one unit product r at the distribution center k in time period t
	HC_{kr}^{t}	Holding cost of one unit product r at the distribution center k in time period t
	EC_{er}^{t}	Penalty cost of not satisfy one unit customer demand e of product r in time period t
	OEC_{er}^{t}	Penalty cost for non-collection of one unit returned product r from customer e in time period t
	CC_{cr}^{t}	Separating and packing cost of one unit returned product r at the collection center c in time period t
	OCC_{cr}^{t}	Incentive cost to purchase and collect of one unit returned product r at the collection center c in time period t
	MC_{mr}^{lt}	Recycling cost of one unit returned product r at the recycling center m with materials l in time period t
	FC_{fr}^{t}	Safe disposal cost of one unit returned product r at the disposal center f in time period t
	V_{v}^{t}	Cost of per one fuel liter consumed by vehicle v in time period t
	F_{d}^{t}	Driver's wages per hour of driving in time period t
Capacities	Cap_{sa}	Capacity of supplier s for supply raw material a
	Cap_{p}^{gu}	Capacity of production center p with technology g and capacity level u
	Cap_{k}^{u}	Capacity of distribution center k with capacity level u
	$VCap_{k}^{u}$	Storage capacity of distribution center k with capacity level u
	Cap_{c}^{u}	Capacity of collection center c with capacity level u
	Cap_{m}^{lu}	Capacity of recycling center m using materials l and capacity level u
	$wcap^{v}$	Weight capacity of vehicle v
	$vcap^{v}$	Volume capacity of vehicle v

CO2	CO_2^{GOV}	Determine of amount allowable of carbon dioxide emissions in supply chain network by government
	E_p^{gu}	Fixed amount of carbon dioxide emissions due to establishing one production center p with technology g and capacity level u
	E_k^u	Fixed amount of carbon dioxide emissions due to establishing one distribution center k with capacity level u
	E_c^u	Fixed amount of carbon dioxide emissions due to establishing one collection center c with a capacity level u
	E_m^{lu}	Fixed amount of carbon dioxide emissions due to establishing one recycling center m using materials l and capacity level u
	ϵ^j	Carbon dioxide emissions per one unit of energy consumed (g⁄kwh)
	ϵ^l	Carbon dioxide emission rate at per one liter fuel consumed (g⁄L)
Energy & Fuel	EP_r^g	Energy consumed to produce one unit of product r with technology g (kwh)
	EK_r	Energy consumed to distribute one unit of product r (kwh)
	EC_r	Energy consumed to collect one unit of returned product r (kwh)
	EM_a^l	Energy consumed to produce one unit of recycled raw material a with using of materials l (kwh)
	EB_r	Energy consumed to recover energy from one unit of returned product r (kwh)
	EF_r	Energy consumed to dispose one unit of returned product r (kwh)
	$FU1_v$	Fuel consumed per one unit distance for vehicle v without load
	$FU2_v$	Extra fuel consumption per unit of distance traveled by vehicle v with one unit load
Employment	θ_{job}	Importance coefficient of creating job opportunities
	job_p^{gu}	Number of created fixed job opportunities due to establishing one production center p with technology g and capacity level u
	job_k^u	Number of created fixed job opportunities due to establishing one distribution center k with capacity level u
	job_c^u	Number of created fixed job opportunities due to establishing one collection center c with capacity level u
	job_m^{lu}	Number of created fixed job opportunities due to establishing one recycling center m using materials l and capacity level u
	η_p	Unemployment ratio at the production center p
	η_k	Unemployment ratio at the distribution center k
	η_c	Unemployment rate at the collection center c
	η_m	Unemployment ratio at the recycling center m
	jt	Variable rate of creating job opportunities per hour of operational activity
Sick Leave	θ_{ltc}	Importance coefficient of sick leaves
	ltc_p^{gu}	Number of sick leaves due to job damage with establishing one production center p with technology g and capacity level u
	ltc_k^u	Number of sick leaves due to job damage with establishing one distribution center k with capacity level u
	ltc_c^u	Number of sick leaves due to job damage with establishing one collection center c with capacity level u
	ltc_m^{lu}	Number of sick leaves due to job damage with establishing one recycling center m with using materials l and capacity level u
	lt	Variable rate of sick leaves per one hour of operational activity
Reliability	λ_1	Importance coefficient of supplier's reliability
	λ_2	Importance coefficient of reliability for the establishment of potential facilities in forward chain; $N \in \{p, k\}$
	λ_3	Importance coefficient of reliability of travel time for supply chain network; $\Psi(x, y)$
	SR_{sa}	Reliability of supplier s in supplying raw material a
	RP_p^{gu}	Reliability of production center p with technology g and capacity level u
	RK_k^u	Reliability of distribution center k with capacity level u
	$Trange_{xy}$	Ratio of the difference between the maximum and minimum travel time to the maximum travel time for supply chain network; $\Psi(x, y)$
	$Tratio_{xy}$	Ratio of average travel time to maximum travel time for supply chain network; $\Psi(x, y)$
	w_1	Weight factor $Trange_{xy}$
	w_2	Weight factor $Tratio_{xy}$
Coefficients of Distance, Time, Weight and Volume	D_{xy}	The distance between each pair of nodes in the supply chain
	D_r	Maximum life of product r
	TP_r^g	Time required for produce one unit of product r using technology g
	TK_r	Time required for distributed one unit of product r
	TC_r	Time required for collected one unit of product r
	TM_a^l	Time required for recycled one unit of raw material a
	w_a	Weight of one unit raw material a
	w_r	Weight of one unit product r
	v_a	Volume of one unit raw material a
	v_r	Volume of one unit product r
Other Coefficients	b_{sa}^t	Minimum amount supply of raw material a by supplier s in time period t
	DEM_{er}^t	Demand of primary market e for product r in time period t
	DEM_{ha}^t	Demand for raw material a in the secondary market h in time period t
	q_{ar}	Required amount of raw material a in produce one unit product r; $\sum_{a \in A} q_{ar} = 1, \;\; \forall r \in R$

	ρ_{ar}	Recycled amount raw material a per one unit of returned product r; $\sum_{a\in A}\rho_{ar} = 1,\ \ \forall r \in R$
	β_r	Percentage of returned and collected product r with energy recovery value
	γ_r	Percentage of returned and collected product r with recycling value; $\beta_r + \gamma_r < 1,\ \ \forall r$
	σ_a	Percentage of recycled raw material a with able to reuse at the production of products
	ω_r^d	Return rate for end of life product r after d years of used; $$\sum_{d=0}^{D_r} \omega_r^d \leq 1$$
	L_{xy}	The lower limit of velocity in the path between x and y
	U_{xy}	The upper limit of velocity in the path between x and y
	τ_{xy}^v	The average speed of vehicle v in the route x to y; $\tau_{xy}^v = \left(L_{xy} + U_{xy}\right)/2$
	$Budget$	Total budget available for establishing of potential facilities
Decision Variables		
Binary Variables	θ_{sa}^t	Binary variable; If concluded a supplying contract for raw material a with the supplier s in period t equal to 1, otherwise 0
	θ_p^{gu}	Binary variable; If established a production center p with technology g and capacity level u equal to 1, otherwise 0
	θ_k^u	Binary variable; If established a distribution center k with capacity level u equal to 1, otherwise 0
	θ_c^u	Binary variable; If established a collection center c with capacity level u equal to 1, otherwise 0
	θ_m^{lu}	Binary variable; If established a recycling center m using materials l and capacity level u equal to 1, otherwise 0
	π_{xy}^{vt}	Binary variable; If traveled route x to y by vehicle v in period t equal to 1, otherwise 0
Continuous Variables	Q_{xya}^t	Quantity of raw material a shipped between two facility $(x, y) \in \Psi'$in time period t
	Q_{xyr}^t	Quantity of product r shipped between two facility $(x, y) \in \Psi''$in time period t
	Q_{pr}^{gt}	Quantity of product r is produced in the production center p with technology g in time period t
	I_{kr}^t	Inventory quantity of product r that maintained in distribution center k in time period t
	QR_{xr}^t	Quantity of returned product r by customer e in time period t
	QN_{er}^t	Quantity of product r that by customer e in period t returned but not collected
	S_{er}^t	Lack quantity of product r for customer e in time period t
	CO_2^{CUR}	Quantity of carbon dioxide emissions in the supply chain (tons)