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Creating a comprehensive sustainable supply chain optimization model that aligns with stakeholder requirements and ecological factors

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Abstract

In today's growing world, the Green Supply Chain (GSC) is a new approach to include environmental impacts and economic goals in a supply chain network. This paper continues previous research studies by designing a new green supply chain network considering different social, economic, environmental, service level, and shortage aspects. This study introduces a fresh, comprehensive tradeoff model that considers factors such as overall expenses, quality of service, environmental pollution levels, and societal impacts within a sustainable supply chain. The proposed model is formulated as a multi-product multi-objective mixed-integer programming model to assist in planning a green supply chain. The suggested model has three objective functions: maximizing social responsibility, minimizing the cost of carbon dioxide (CO2) emissions, and minimizing economic costs. The model allows for shortages in the form of backorders and seeks to maximize service level in addition to the mentioned objective functions. Robust Possibilistic Programming (RPP) was employed to deal with the problem's uncertain input parameters in the solution approach. Also, a multi-objective model of the problem was solved using Fuzzy Goal Programming (FGP). To examine and evaluate the model in a simple framework, the proposed mathematical model of the problem was implemented in an industrial unit in the real world, and the results obtained from it were analyzed. Among the results that the output of the model provides to managers and decision-makers, it is possible to mention the determination of the optimal amount of production of each product in the manufacturing plants, quantity of products and parts transported between facilities, and also the determination of the of network's carbon emissions which is equal to 51.59 tons.

Keywords: green supply chain; social responsibility; service level; robust possibilistic programming; fuzzy goal programming.

Paper Type: Original Research

1. Introduction

Technology development and economic growth in recent years have improved people's living conditions and lifestyles while posing substantial social and environmental problems (Darbari et al., 2019). Greenhouse gas emissions have increased significantly since the 19th century. Due to the rapid and ever-increasing growth of human society and the economic development of economies worldwide, products and services are increasingly used, which releases environmental pollutants (Lamb et al., 2021). The increase of carbon in the Earth's atmosphere increases yearly, which increases the natural greenhouse effect and warms the planet (Anderson et al., 2016). Beyond just economic factors, rising worries about the effects on the environment and global and governmental regulations have drawn scholarly attention to the GSC issues (Ivanov et al., 2019). Governmental and international organizations have passed regulations requiring businesses to handle environmental challenges due to environmental pollution and accelerated global warming (Golinska & Romano, 2012). The matter of global warming is caused by global efforts to reduce carbon concentrations (Leung et al., 2014). The Paris Agreement of 2015 determined that the global temperature increase would be less than 2°C (Lamb et al., 2021). Today, over time, government laws, environmental pressures, and the growth of people's awareness have made companies and organizations increasingly choose "green" (environmentally friendly) plans as strategic weapons in today's competitive world (Min & Kim, 2012). Supply chain management is the term used to describe the effective and efficient management of the movements of goods, information, and capital among the many supply chain participants, including retailers, distributors, manufacturers, suppliers, and customers. (Chopra et al., 2013). Therefore, organizations very soon put environmental protection and related strategies as an innovation in the priority of their plans. The supply chain

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considerably affects the environment, including releasing pollutants, the risk to public health, etc. Today, organizations try to minimize the adverse environmental effects by considering the concerns caused by releasing environmental pollutants. This integration is now known as the concept of "green supply chain management" (Tseng et al., 2019). Today, the world community understands that sustainable development is achieved when limited and non-renewable resources are used optimally. The damage to the environment is also reduced. This awareness has started a movement in organizations and companies to integrate environmental protection activities with supply chain management. This paper seeks to provide a model for the design of the green supply chain network to minimize the costs of the entire network, taking into account environmental considerations along with other goals defined for it. In this research, an attempt has been made to present a model concerning social, environmental, and economic dimensions.
This paper presents efficient methods and new optimization models to promote green supply chain planning. For this purpose, we focus on four aspects based on the studied cases, Figure 1. As a first perspective, it focuses on a multi-objective optimization model that minimizes the costs of the entire system. The second perspective emphasizes the environmental aspect that minimizes carbon emission costs under a carbon tax policy. According to the ISO 26000 standard, the third perspective focuses on collective social responsibility as a sustainability aspect of the social standard. Participatory social responsibility carries social satisfaction and social and environmental concerns. The last aspect emphasizes customer satisfaction and service level. The service level expresses the ability to meet customer requests and needs with the inventory on hand, an essential indicator of the supply chain's capacity and effectiveness.

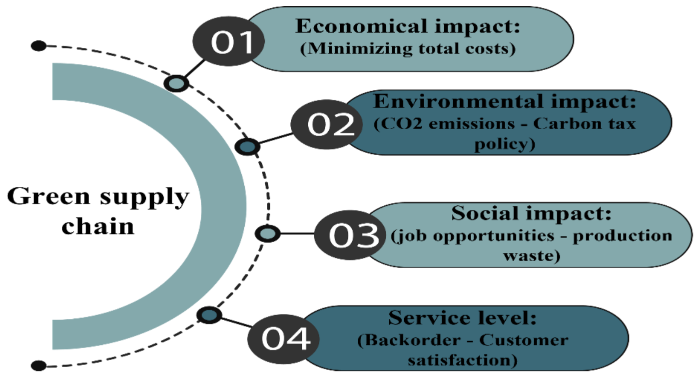

Figure 1. An overview of the four main perspectives (focus area) considered in this paper

This paper seeks to develop new methods, models, and optimization strategies for GSCP. Supply chain coordinators, production and operations managers, and manufacturers can use the methods and models proposed in this research. This study is a new integrated optimization for sustainability aspects and the tradeoff between costs, carbon emissions, and service level in supply chain management. The remainder of the paper is structured as follows. We discuss relevant studies in the literature in Section 2 of this article. Part 3 presents the problem definition and model formulation. The solution approach is then described in Section 4. Next, Section 5 discusses the outcomes of applying the model to a real industrial case and sensitivity analysis. The study's conclusion and future research directions are covered in Section 6, the last section.

2. Literature review

Companies face challenges in evaluating and configuring their systems and strategies to improve services and reduce costs. There has been a growing focus on supply chain management in recent years, with particular attention being paid to the green supply chain management concept, which incorporates environmental concerns (Malviya & Kant, 2015; Ramezani et al., 2014). Research in this area has increasingly emphasized minimizing carbon emissions and other environmental impacts. One key objective of this research has been to develop sustainable supply chain models that consider various factors, including overall expenses, quality of service, environmental pollution levels, and societal impacts. For instance, Pishvaee et al. (2012) aimed to create a network that minimized environmental impacts and total costs. Also, a fuzzy approach is developed. In the research conducted by Fahimnia et al. (2015) present a mixed integer programming model for supply chain management at the tactical planning level. Garg et al. (2015) a non-linear integer programming problem is presented. The model's objectives include optimizing the total profit and minimizing the carbon footprint. Sazvar et al. (2016) modeled a sustainable supply chain by simultaneously considering social, environmental, and economic goals in a Cut Flowers industry case study. In a study by Rezaee et al. (2017), they explored a green supply chain within the context of carbon trading. This model is associated with uncertainty in product demand and carbon price. From the findings of this research, it can be pointed out that a higher carbon price makes the supply chain greener, but these two cases do not necessarily have a linear relationship. In their research, Soleimani et al. (2017) address the issue of designing a closed-loop supply chain. This model aims to increase the chain's overall profit; social responsibility concerns include

losing business days and maximizing customer demand for new and recycled products. Mohammed et al. (2017) proposed an optimization model for a multi-period, multi-product design problem. This model examines the impact of different carbon policies on operational and strategic decisions. According to Ghomi-Avili et al. (2018), a novel approach was introduced to develop a highly efficient closed-loop network that can best withstand unpredictable disruptions. In the research of Attari & Torkayesh (2018), a three-level supply chain network with fuzzy demand values is proposed. A case study has been done on Iran’s mining industry. Sadeghi Rad & Nahavandi's (2018) article presents integrated mathematical programming for a closed-loop green supply chain. The objective functions include minimizing economic cost and environmental impact and maximizing customer satisfaction. In their research, Zarbakhshnia et al. (2019) have designed and planned a forward and reverse green supply chain network. This study used the epsilon-constraint approach for solving. In the research of Zhen et al. (2019), decisions about environmental levels and potential facility capacity levels are jointly considered. To solve the model, a Lagrangian relaxation method is presented. Mardan et al. (2019) have presented a mathematical model for a multi-product, multi-period, and multi-objective green supply chain. In their paper, Yavari & Geraeli (2019) the design of the supply chain network for perishable products was studied. Biuki et al. (2020) dealt with supply chain management concerning challenges such as sustainability, location, routing, and inventory control in their research. Yu & Solvang (2020) presented a multi-objective model for closed-loop supply chain network design in their paper. This model aims to strike a balance between cost-effectiveness and environmental performance. In the research of Abdi et al. (2020), an innovative approach to designing a green supply chain network is presented. Porkar et al. (2020) discuss optimizing a logistics network for profit, green plan score, and quality, including the green waste score. This paper uses Multi-objective Particle Swarm Optimization and NSGA-II for its solution approach. In their research, Homayouni et al. (2021) have investigated a green supply chain considering carbon policies and types of vehicles under uncertainty. In the article by Khorshidvand et al. (2021), a multi-objective Mixed-Integer Linear Programming (MOMILP) is formulated to maximize social satisfaction and profit and minimize total CO2 emissions in the entire chain. Wang & Wan (2022) present a multi-product and multi-period problem with dependent demand for greenness and price. Golpîra & Javanmardan (2022) investigated a sustainable closed-loop supply chain considering various carbon policies. Boskabadi et al. (2022) proposed a fuzzy mathematical model for a complex supply chain distribution network. Hasan et al. aimed to minimize CO2 emission and network costs and maximize profit per capita in their model. Guo et al. (2023) create a complex mathematical model to reduce supply chain costs, energy use, CO2 emissions, and waste generation while addressing disruption risk. The impact of uncertain carbon prices and demand on aluminum supply chain strategy and tactics are investigated in a stochastic mixed-integer linear programming model, and stochastic carbon price scenarios are analyzed.
Continuing the previous works, this research seeks to develop an integrated green supply chain model of retailers, distribution centers, manufacturers, and suppliers. This research seeks to provide a green supply chain network by considering the combination of things such as maximizing the level of customer service, minimizing the costs of carbon dioxide emissions, maximizing social responsibility, along with minimizing the typical costs of the supply chain network in the form of a multi-level, multi-period and multi-product supply chain. The main contributions of the present study include: paying attention to the environmental consideration, services level, and social responsibility and developing a MILP model in a multi-echelon GSC. Table 1 shows the contributions of this study together with a list of the most relevant studies in this area.

Table 1. Classification of literature review in terms of problem assumptions, parameters, and solution approach

Researcher	Objective function		Characteristics of the problem						Sustainability aspect			Shortage		Solution approach
	Single	Multi	Single product	Multi-product	Single period	Multi-period	Linear	Non-linear	Economic	Social	Environmen-tal	Backorder	Lost sale	
(Pishvaee, Torabi, et al., 2012)		*	*		*		*		*		*			Fuzzy mathematical programming
(Fahimnia et al., 2015)		*		*		*		*	*		*	*		Cross entropy (CE)
(Garg et al., 2015)		*	*		*			*	*		*			Heuristic
(Sazvar et al., 2016)		*		*		*		*	*	*	*	*	*	Compromise programming
(Rezaee et al., 2017)	*			*	*		*		*		*			**AMPL / CPLEX**
(Soleimani et al., 2017)		*		*		*		*	*	*	*			Genetic algorithm
(Mohammed et al., 2017)		*		*		*	*		*		*			Robust optimization approach
(Ghomi-Avili et al., 2018)		*	*			*		*	*		*			Epsilon constraint Method
(Attari & Torkayesh, 2018)		*	*			*		*	*		*			Bender’s decomposition algorithm

(Sadeghi Rad & Nahavandi, 2018)	*		*		*		*	*	*	*			**Metric -LP CPLEX**
(Zarbakhshnia et al., 2019)	*		*	*		*		*		*			Epsilon constraint
(Zhen et al., 2019)	*		*	*		*		*		*			Lagrangian relaxation
(Mardan et al., 2019)	*		*		*	*		*		*			**LP-Metric**
(Yavari & Geraeli, 2019)	*		*		*	*		*		*			Heuristic
(Biuki et al., 2020)	*		*		*	*		*	*	*	*		Metaheuristic
(Yu & Solvang, 2020)	*		*	*		*		*		*			Stochastic programming
(Abdi et al., 2020)	*		*		*	*		*		*		*	Metaheuristic
(Porkar et al., 2020)	*		*		*		*	*		*			Metaheuristic algorithm
(Homayouni et al., 2021)	*		*		*		*	*		*		*	Robust optimization
(Khorshidvand et al., 2021)	*		*		*	*		*	*	*			Lagrangian relaxation /
(Wang & Wan, 2022)	*		*		*	*		*		*	*		Metaheuristic
(Golpîra & Javanmardan, 2022)	*	*		*		*		*	*	*			Exact method
(Boskabadi et al., 2022)	*		*		*		*	*	*	*			NSGA-II / MOPSO
(Hasan et al., 2023)	*		*		*		*	*		*	*		Hyper-heuristic algorithms
(Guo et al., 2023)	*		*	*		*		*		*			Stochastic programming
This study	*		*		*	*		*	*	*	*		RPP / FGP

In summary, it can be said that the aspects of innovation and newness of the current research are the simultaneous consideration of all the assumptions and the following cases together:

- We present a mixed integer linear programming model, multi-period, multi-objective, multi-product, and multi-levels, as a four-level green supply chain, including suppliers, production centers, product distributors, and retailers.
- We are considering the expectations and needs of major stakeholders (shareholders and owners, employees, customers, local community, government, environment) of the supply chain network.
- We are considering objectives for minimizing carbon emissions and social responsibility using fuzzy goal programming under the carbon tax policy.
- Considering shortage (in the form of backlogged orders) in the model and minimizing these backlogged orders and consequently maximizing the service level.

3. Model formulation

3.1. Problem description

The following section presents a network design model under uncertain conditions. The proposed model is a multi-product, multi-period, multi-objective, multi-level green supply chain. This network includes raw material and component suppliers, product factories, distribution centers, and retailers. Raw materials and consumable parts are transported from supply centers to final product manufacturers in this multi-level supply chain network. Different types of products are produced in production centers and then sent to distributors. Distributors then distribute the products between different retail outlets. The outline of the proposed green supply chain can be seen in Figure 2. In this research, two primary emission sources for CO2 in the supply network of the proposed model have been determined: a) the amount of carbon dioxide emission from the transportation system that moves raw materials, parts, and products between different levels of the network b) the amount of carbon dioxide emission from facilities Product manufacturers and distribution centers. The proposed model has three objective functions. The first objective function includes the model's economic aspects and represents the system's overall costs. These costs include ordering costs, purchasing raw materials and parts, fixed and variable costs of producing products, maintenance costs, transportation costs of materials and products, and shortages. The second objective function incorporates environmental aspects and minimizes the carbon emission cost of the entire network under the carbon tax policy. The third objective function represents the model's social aspect and sustainability in response to its stakeholders' expectations and needs (employees - local community). It maximizes the number of job opportunities created. In the proposed model, shortage (back order) is allowed. Part of the demand for products cannot be answered in that period and be postponed to the following periods as back orders, and the model seeks to minimize this shortage and then maximize the service.

In this model, the parameters, purchase cost, ordering cost, transportation cost, variable cost of production, cost of backorders, and demand, are assumed to be uncertain. Suppliers have a specific and limited capacity to supply raw materials and consumable parts. The rest of the assumptions considered for the proposed mathematical model are as follows:

- An integrated green supply chain will be investigated within a limited and defined production planning horizon that includes several periods.
- The proposed model includes several different products that result from the assembly of several parts.
- Each producer has a specific capacity to produce each product.
- Different types of parts are shipped from some selected suppliers to the assembly plants. Then, different products are offered by assembling different sets of parts. Finished products are shipped to a collection of distribution centers and then distributed to various retailers.
- There are capacity constraints for shipping products between levels of the network.
- The capacity of all the mentioned centers is limited.
- Distribution centers can hold inventory, but retailers prefer not to. In addition, manufacturers prefer to have inventory related to primary parts.

Each potential supplier has a specific and limited capacity to provide different parts in each period and can provide all kinds of parts.

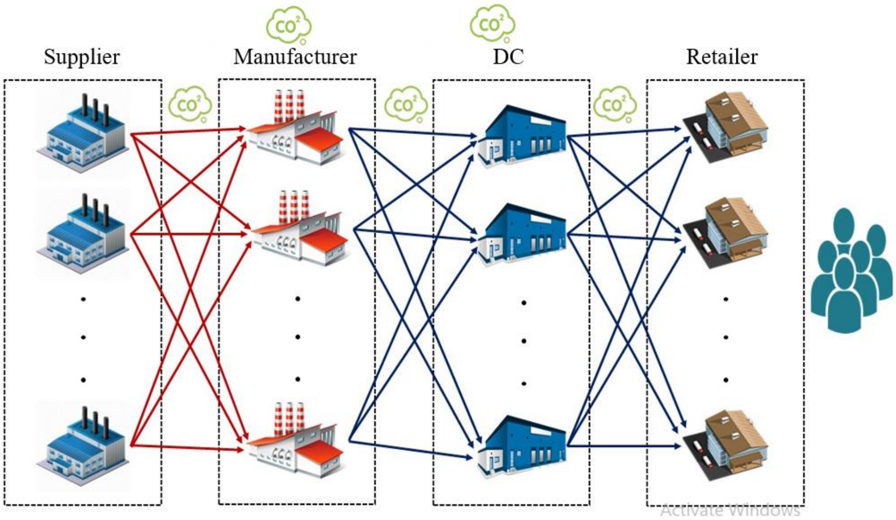

Figure 2. Proposed green supply chain network

3.2. Sets

q	Index of parts	$q \in Q$
p	Index of products	$p \in P$
i	Index of suppliers	$i \in I$
j	Index of manufacturers	$j \in J$
k	Index of distribution center	$k \in K$
l	Index of retailer center	$l \in L$
$t, t^{'}$	Index of periods	$t, t^{'} \in Tt, t^{'} = 1, \ldots, t, \ldots, T$

3.3. Parameters

$\widetilde{D}_{plt}$	The demand of retailer (l) for the product (p) in period (t)
Dis_{ij}	Distance, in a kilometer, between supplier (i) and manufacturer (j)
Dis_{jk}	Distance, in a kilometer, between the manufacturer (j) and distribution center (k)
Dis_{kl}	Distance, in a kilometer, between distribution center (k) and retailer center (l)
Cav_{qij}	Maximum capacity of the part (q) transfer from the supplier (i) to the manufacturer (j)
Cav_{pjk}	Maximum capacity of product (p) transfer from manufacturing center (j) to distribution center (k)
Cav_{pkl}	Maximum capacity of product (p) transfer from the distribution center (k) and retailer center (l)
$\widetilde{M}_{qi}$	The selling price of part (q) the supplier (i) offers. (Iranian Rial)
H_{qj}	Holding cost per unit part (q) in manufacturer (j). (Iranian Rial)
H_{pk}	Holding cost per unit product (p) in manufacturer (j). (Iranian Rial)
$\tilde{G}_q$	Cost of transfer part (q) per unit distance. (Iranian Rial)
$\tilde{G}_p$	Cost of transfer product (p) per unit distance. (Iranian Rial)
$\tilde{O}_j$	Ordering cost for the manufacturer (j). (Iranian Rial)
$\tilde{O}_k$	Ordering cost for the distribution center (k). (Iranian Rial)
$\tilde{O}_l$	Ordering cost for the retailer center (l). (Iranian Rial)
CP_{pj}	Fixed cost of production of the product (p) at manufacturing center (j). (Iranian Rial)
$\tilde{C}V_{pj}$	The variable cost of production of the product (p) at the manufacturing center (j). (Iranian Rial)
$\tilde{C}B_{pl}$	Backorder product cost (p) at retailer center (l). (Iranian Rial)
$C^{(op)}$	Cost of job opportunities created in manufacturing center (j). (Iranian Rial)
VQ_{qjt}	Maximum capacity of manufacturing center (j) to hold the part (q) in period (t)
VP_{pk}	Maximum capacity of distribution center (k) to hold product (p)
Pa_{pj}	Maximum capacity of production of the product (p) at manufacturing center (j)
Pb_{qi}	Maximum capacity of supply of part (q) by the supplier (i)
fa_{qp}	Coefficient of consumption part (q) in the product (p)

$\mu^{(P)}$	CO2 emission factor per electric energy consumption. (tons/kWh)
$\mu^{(R)}$	CO2 emission factor for transportation per kilometer. (tons/km)
E_{pj}	Energy consumption (kWh) for producing a unit of product (p) in the manufacturing center (j)
E_{pk}	Energy consumption (kWh) for processing a unit of product (p) in the distribution center (k)
$F^{(Co_2)}$	An estimated average of the carbon tax. (Iranian Rial/tons)
$\alpha^{(min)}$	Minimum service level in retailer centers
AJ_{pj}	The number of jobs created if setup the production line of product (p) in the manufacturing center (j)
WP_{pj}	Average wastes generated production of the product (p) in manufacturing center (j)
$\phi^{(job)}$	The weighting factor of produced job opportunities
$\phi^{(wste)}$	The weighting factor of generated wastes
TDL	Electricity transmission and distribution network losses

3.4. Decision variables

X_{pjt}	Quantity of product (p) produced at manufacturing center (j) in period (t)
A_{qijt}	Quantity of part (q) shipped from the supplier (i) to manufacturing center (j) in period (t)
B_{pjkt}	Quantity of product (p) shipped from manufacturing center (j) to distribution center (k) in period (t)
C_{pklt}	Quantity of product (p) shipped from the distribution center (k) to retailer center (l) in period (t)
W_{plt}	Quantity of product (p) ordered by retailer center (l) at the end of the period (t)
Ua_{qjt}	Quantity of inventory part (q) at the end of the period (t) in the manufacturing center (j)
Ub_{pkt}	Quantity of inventory product (p) at the end of the period (t) in the distribution center (k)
α_{plt}	Service level in the retailer center (l) for the product (p) in the period (t)
λa_{kl}	1 If retailer center (l) orders the distribution center (k); 0 otherwise
λb_{jk}	1 If distribution center (k) orders the manufacturing center (j); 0 otherwise

λc_{ijt}	1 1 If manufacturing center (j) orders the supplier (i) in period (t); 0 otherwise
θ_{pjt}	1 If the production of the product (p) in the manufacturing center (j) is set up in the period (t); 0 otherwise

3.5. Objective functions

The components of the mathematical model are described below:

3.5.1. The first objective function (economic objective)

$$\begin{aligned} & MinTotalCosts: \\ & TCOST = TA + TB + TC + TD \end{aligned} \tag{1}$$

$$\begin{aligned} TA = & \sum_{q=1}^{Q}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \tilde{G}_q . Dis_{ij} . A_{qijt} + \sum_{q=1}^{Q}\sum_{j=1}^{J}\sum_{t=1}^{T} H_{qj} . Ua_{qjt} \\ & + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \tilde{O}_j . \lambda c_{ijt} + \sum_{q=1}^{Q}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} \tilde{M}_{qi} . A_{qijt} \end{aligned} \tag{2}$$

$$\begin{aligned} TB = & \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} \tilde{G}_p . Dis_{jk} . B_{pjkt} \\ & + \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{t=1}^{T} CP_{pj} . \theta_{pjt} + \tilde{C}V_{pj} . X_{pjt} + \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{t=1}^{T} AJ_{pj} . \theta_{pjt} \, . C^{(op)} \end{aligned} \tag{3}$$

$$\begin{aligned} TC = & \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} \tilde{G}_p . Dis_{kl} . C_{pklt} \\ & + \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{t=1}^{T} H_{pk} . Ub_{pkt} + \sum_{j=1}^{J}\sum_{k=1}^{K} \tilde{O}_k . \lambda b_{jk} \end{aligned} \tag{4}$$

$$TD = \sum_{p=1}^{P}\sum_{l=1}^{L}\sum_{t=1}^{T} \tilde{C}B_{pl} . W_{plt} + \sum_{k=1}^{K}\sum_{l=1}^{L} \tilde{O}_l . \lambda a_{kl} \tag{5}$$

Equation (1) represents the economic objective function of the proposed model that minimizes the costs of the entire supply chain network. This objective function consists of four subsections. The section (TA) includes the costs of a) parts transportation costs from different suppliers to product manufacturing centers, b) holding cost of inventory of parts in product production centers, c) ordering costs for the manufacturing centers, and d) costs of purchasing parts from different suppliers. The component (TB) respectively indicates a) transportation costs of products from product manufacturing centers to distribution centers, b) fixed costs of setting up products production lines in manufacturing centers, c) variable costs of producing products in manufacturing plants, d) the cost of employing workforce due to setting up a product production line in manufacturing centers. The component (TC) also includes: a) the cost of transporting products from distribution centers to retailer centers, b) holding cost of the inventory of products in distribution centers, c) ordering costs for the distribution center, and finally, the component (TD) includes: backorders costs of products in retail centers and b) ordering cost for retail centers.

3.5.2. The second objective function (environmental impact)

$$MinTotalCO_2emissionscosts:$$
$$TCO2: F^{(Co_2)}.CO_2^{Emissions}$$
$$CO_2^{Emissions}: \left(\begin{array}{l} \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{t=1}^{T}\frac{\mu^{(P)}.E_{pj}.X_{pjt}}{1-TDL} + \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\frac{\mu^{(P)}.E_{pk}.B_{pjkt}}{1-TDL} \\ +\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T}\mu^{(R)}.Dis_{ij}.\lambda c_{ijt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\mu^{(R)}.Dis_{jk}.\lambda b_{jk} \\ +\sum_{k=1}^{K}\sum_{l=1}^{L}\mu^{(R)}.Dis_{kl}.\lambda a_{kl} \end{array} \right) \tag{6}$$

Equation (6) shows the environmental objective function based on the carbon tax policy for two types of emission sources specified in the network. The environmental objective function in this model minimizes the carbon dioxide emission costs of chain activities under the carbon tax policy. In the carbon tax policy, companies and organizations pay taxes on the number of greenhouse gases emitted by their activities. The carbon tax policy directly imposes a price as a tax on the emission of greenhouse gases. In other words, each ton of carbon dioxide equivalent has a price. Companies and organizations with this type of carbon policy must pay a specific tax for each unit of environmental pollution released from supply chain activities. The first line calculates the number of emissions in production centers and distribution centers, respectively. The second and third lines calculate the number of emissions caused by the transportation of parts and products between facilities throughout the network.

3.5.3. The third objective function (corporate social responsibility (CSR))

$$MaxSocial\ responsibility:$$
$$TSOCIAL: \phi^{(job)}\left(\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{t=1}^{T}AJ_{pj}.\theta_{pjt}\right) - \phi^{(wste)}\left(\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{t=1}^{T}X_{pjt}.WP_{pj}\right) \tag{7}$$

The importance of corporate social responsibility has been increasing in recent years. Companies have recently become more attentive to their corporate social responsibility with increasing public concerns about environmental and social issues. Accordingly, how corporate social responsibility can facilitate companies' sustainable development has become a critical issue in this field (Ji & Miao, 2020). Equation (7) shows the objective function of the proposed model from the social dimension, which is concerned with the stakeholders' interests. This model seeks to maximize social responsibility. In equation (7), the first term shows the number of job opportunities created due to the setup of the product production line in the manufacturing center. The second term also calculates the production waste from the manufacturing and assembly of products in the product manufacturing center.

3.6. Constraints

Inventory balance constraints:

$$W_{plt} = W_{p,l,t-1} + \widetilde{D}_{plt} - \sum_{k=1}^{K} C_{pklt}\ \forall p, l, (t \geq 2) \tag{8}$$

$$W_{plt} = \widetilde{D}_{plt} - \sum_{k=1}^{K} C_{pklt}\ \forall p, l, (t = 1) \tag{9}$$

$$Ub_{pkt} = Ub_{p,k,t-1} + \sum_{j=1}^{J} B_{pjkt} - \sum_{l=1}^{L} C_{pklt}\ \forall p, k, (t \geq 2) \tag{10}$$

$$Ub_{pkt} = \sum_{j=1}^{J} B_{pjkt} - \sum_{l=1}^{L} C_{pklt}\ \forall p, k, (t = 1) \tag{11}$$

$$Ua_{qjt} = Ua_{q,j,t-1} + \sum_{i=1}^{I} A_{qijt} - \sum_{p=1}^{P} fa_{qp}.X_{pjt}\ \forall q, j, (t \geq 2) \tag{12}$$

$$Ua_{qjt} = \sum_{i=1}^{I} A_{qijt} - \sum_{p=1}^{P} fa_{qp}.X_{pjt}\ \forall q, j, (t = 1) \tag{13}$$

$$\sum_{k=1}^{K} B_{pjkt} = X_{pjt} \forall p, j, t \tag{14}$$

Equations (8) and (9) show the equilibrium limit of product inventory in the retailer's center for different products, written separately for periods (t) and (t ≥ 2). Also, according to this equation, the amount of shortage of each product in each period can be obtained by deducting the demand for that product from the total receipts of the product from different distributors in addition to the back orders of the previous period. Equations (10) and (11) indicate the equilibrium limit of product flow for each distribution center in each period, which is written separately for periods (t) and (t ≥ 2). This equation balances the volume of incoming products from different manufacturers, the volume of products shipped to different retailers, and the stock in stock. Relationship (12) and (13) shows the equilibrium limit of the inventory of primary parts and manufactured products in each period and for each production center. This equation balances the number of primary parts received from different suppliers, the number of products produced in the production center, and the inventory in the warehouse. Equation (14) guarantees that each production center sends all the final products produced to different distribution centers in each period and does not hold any inventory of the final products produced.

Capacity constraints:

$$\sum_{j=1}^{J} A_{qijt} \leq Pb_{qi} \forall q, i, t \tag{15}$$

$$Ua_{qjt} \leq VQ_{qjt} \forall q, j, t \tag{16}$$

$$Ub_{pkt} \leq VP_{pk} \forall p, k, t \tag{17}$$

$$C_{pklt} \leq \lambda a_{kl}.Cav_{pkl} \forall p, k, l, t \tag{18}$$

$$B_{pjkt} \leq \lambda b_{jk}.Cav_{pjk} \forall p, j, k, t \tag{19}$$

$$A_{qijt} \leq \lambda c_{ijt}.Cav_{qij} \forall q, i, j, t \tag{20}$$

$$X_{pjt} \leq \theta_{pjt}.M^{(\infty)} \forall p, j, t \tag{21}$$

$$\sum_{q=1}^{Q} A_{qijt} \leq \lambda c_{ijt}.M^{(\infty)} \forall i, j, t \tag{22}$$

$$X_{pjt} \leq Pa_{pj} \forall p, j, t \tag{23}$$

$$\sum_{j=1}^{J} \theta_{pjt} \leq 1 \forall p, t \tag{24}$$

Equation (15) shows the ability of different suppliers to supply parts. According to this equation, each supplier has a limited capacity to supply various primary parts needed by production centers. Equation (16) shows the storage capacity of production centers for keeping primary parts. Equation (17) shows the storage capacity for keeping the final products in the distribution centers. Equation (18) shows the capacity limit for transporting finished products from the distribution center to the retail center. Equation (19) shows the capacity limit to transport the final products produced from the production center to the distribution center in each period. Equation (20) shows the capacity limit for transporting parts and raw materials from the supply center to the product manufacturing center in each period. Equation (21) states whether the production of products is started in manufacturing plants or not. In other words, this equation guarantees that only production centers are allowed to produce a product for which the production line of that product has been set up and prepared. The relationship (22) shows suppliers can only send primary parts to production centers if they receive an order. In other words, this equation ensures that suppliers ship parts only to the manufacturing centers from which they receive orders. Equation (23) refers to the maximum production capacity in production centers. Producers are limited in their ability to make each product in each period. Equation (24) ensures that only one product can be launched and made per production center per period.

Service level constraints:

$$\alpha_{plt} = 1 - \frac{W_{plt}}{\sum_{t'=1}^{t} \widetilde{D}_{plt'}} \forall p, l, t \tag{25}$$

$$\alpha^{(min)} \leq \alpha_{plt} \leq 1 \forall p, l, t \tag{26}$$

Today, customer satisfaction is essential for organizations and companies. Service level is a measure to evaluate the performance of organizations and companies in obtaining customer satisfaction. Service level can be defined as the percentage of demand that is satisfied during a specific period. The level of service indicates the ability to respond to the demands and needs of customers according to the inventory in hand. Based on the definition of the problem and the assumptions, in the proposed model of this research, shortage (backorder) is allowed, and part of the demand for products cannot be answered in that period and be postponed to the following periods in the form of backorders. Accordingly, relation (25) maximizes the level of service in each retail store for each product and each period. The relationship (26) shows that the level of service is between the minimum interval of the service level and the number one. This equation limits the level of service and customer satisfaction between its upper and lower limits. Here, the minimum amount of the service level is determined by asking experts and retail centers and specifies that the retail stores are only allowed to have a certain amount of shortage in each period.

Sign constraints:

$$X_{pjt}, W_{plt}, B_{pjkt}, C_{pklt}, A_{qijt}, Ub_{pkt}, Ua_{qjt} \in Z^{+} \cup \{0\} \tag{27}$$

$$\theta_{pjt}, \lambda b_{jk}, \lambda a_{kl}, \lambda c_{ijt} \in \{0,1\} \tag{28}$$

$$\alpha_{plt} \in R^{+} \tag{29}$$

Equations (27) to (29) define the decision variables of the mathematical model of the problem. These equations show the type of problem decision variables and the range of virtual values they can have been shown.

4. Robust probabilistic programming approach (RPP)

4.1. Uncertainty

Controlling and managing the parameters of the mathematical model of the problem is one of the key and essential issues in planning and optimizing supply chain networks; in some cases, it is impossible to determine the exact and definite value of these parameters, and they are unpredictable. To bring the mathematical optimization models closer to real-world conditions and to increase the efficiency of the mathematical model of the problem, some parameters of the mathematical model, such as the demand for the product and the cost parameters, are considered under conditions of uncertainty and uncertainty. The symbol (~) above some parameters indicates the presence of uncertainty in it. In this section, the uncertainty in the green supply chain of the proposed model has been examined, and the robust possibility planning approach has been used to deal with the uncertainty. In the design of the proposed green supply chain network model, they are taking into account the fact that parameters such as product demand, the purchase cost of raw materials and parts, transportation cost, production cost, and shortage cost have dynamic and fluctuating nature and it is difficult to determine the exact amount of these parameters. Also, due to reasons such as the unavailability or unreliability of previous data, the value of these parameters is estimated by asking expert experts and relying on their experience.

4.2. Possibilistic programming model

A possibilistic programming approach is used to face cognitive uncertainties. One of the essential methods of the possibilistic programming approach is Possibilistic chance-constrained programming (PCCP). PCCP is one of the main approaches to solving optimization problems with various uncertainties. According to this method, decision-makers and model designers ensure that the probability of establishing and meeting a specific limitation is higher than a satisfaction level. In other words, the decision maker and model designer can determine a minimum satisfaction level as a security margin to satisfy the possible constraints. This approach uses different types of fuzzy numbers (triangular, trapezoidal) (Kargar et al., 2020; Pishvaee, Razmi, et al., 2012; Talaei et al., 2016; Zahiri et al., 2014). In this section, first, to reduce the complexity of modeling and ease of formulation, a simple supply chain model is considered for analysis, which can be seen in relation (30). This supply chain model is assumed to have uncertainty in the objective function coefficients and constraints. In one way, the non-deterministic parameters of the model have a trapezoidal distribution.

$$\begin{aligned} & MinZ = fy + cx \\ & st: \\ & Ax \geq d \\ & Bx = d \\ & Sx \leq Ny \\ & x \geq 0 \\ & y \in \{0,1\} \end{aligned} \tag{30}$$

The parameters (f, c, d, N) are indeterminate in the above model. The trapezoidal possibility distribution is used to model non-deterministic parameters in this problem. Four points define the trapezoidal likelihood function. Figure 3 shows the trapezoidal possibility distribution for the uncertainty parameter$\tilde{d} = (d_{(1)}, d_{(2)}, d_{(3)}, d_{(4)})$.

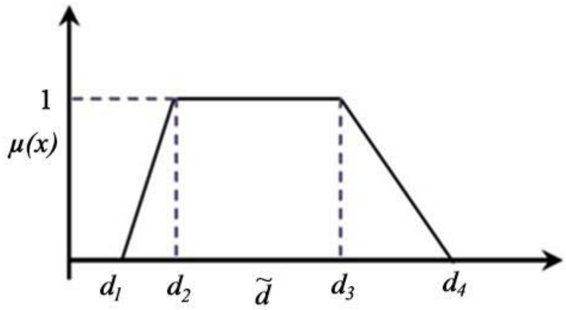

Figure 3. The trapezoidal possibility distribution of fuzzy parameter ($\tilde{d}$) (Pishvaee, Razmi, et al., 2012)

In creating the basic mathematical model of PCCP, the "expected value" factor is used to model and face uncertain parameters of the objective function. Also, the necessity (Nec) scale is used to deal with the uncertainty in the parameters of model limitations. The mathematical model of PCCP is equivalent to the initial non-deterministic mathematical model can be seen in relation (31).

$$\begin{aligned} & MinE[Z] = E[\tilde{f}]y + E[\tilde{c}]x \\ & st: \\ & Nes\{Ax \geq \tilde{d}\} \geq \alpha_1 \\ & Nes\{Bx = \tilde{d}\} \geq \alpha_2 \\ & Nes\{Sx \leq \tilde{N}y\} \geq \alpha_3 \\ & x \geq 0 \\ & y \in \{0,1\} \end{aligned} \tag{31}$$

In the above Possibilistic programming model$(\alpha_1, \alpha_2, \alpha_3)$ are the minimum satisfaction levels of the Possibilistic constraints specified by the decision maker or the model designer. In other words, they show how much it is possible to establish restrictions. It also$E[Z]$ shows the average value of the objective function. Also, according to the theory of Necessity, Nes indicates the degree of necessity. Now the deterministic model is equivalent to the Possibilistic programming model in equation (32).

$$
\begin{aligned}
&MinE[Z] = \left(\frac{f_{(1)} + f_{(2)} + f_{(3)} + f_{(4)}}{4}\right)y + \left(\frac{c_{(1)} + c_{(2)} + c_{(3)} + c_{(4)}}{4}\right)x \\
&st: \\
&Ax \geq (1-\alpha_1)d_{(3)} + \alpha_1 d_{(4)} \\
&Bx \leq \frac{\alpha_2}{2} d_{(3)} + (1-\frac{\alpha_2}{2})d_{(4)} \\
&Bx \geq \frac{\alpha_2}{2} d_{(2)} + (1-\frac{\alpha_2}{2})d_{(1)} \\
&Sx \leq \big((1-\alpha_3)N_{(2)} + \alpha_3 N_{(1)}\big)y \\
&x \geq 0 \\
&y \in \{0,1\}
\end{aligned}
\tag{32}
$$

4.3. RPP model

The RPP model is presented in this section, and its differences and advantages with the possibilistic programming model are stated. For this purpose, in equation (33), a robust possibilistic model for the sample problem in relation (30) is written.

$$
\begin{aligned}
&MinZ: E[Z] + \eta(Z[Z]_{max}()) \\
&+\pi_1\big(d_{(4)} - (1-\alpha_1)d_{(3)} - \alpha_1 d_{(4)}\big) \\
&+\pi_2\left(\frac{\alpha_2}{2} d_{(3)} + (1-\frac{\alpha_2}{2})d_{(4)} - d_{(3)}\right) \\
&+\pi_2\left(d_{(2)} - \frac{\alpha_2}{2} d_{(2)} - (1-\frac{\alpha_2}{2})d_{(1)}\right) \\
&+\pi_3\big((1-\alpha_3)N_{(2)} + \alpha_3 N_{(1)} - N_{(1)}\big) \\
&st: \\
&E[Z] = \left(\frac{f_{(1)} + f_{(2)} + f_{(3)} + f_{(4)}}{4}\right)y + \left(\frac{c_{(1)} + c_{(2)} + c_{(3)} + c_{(4)}}{4}\right)x \\
&Z(4)_{(4)_{max}} \\
&Ax \geq (1-\alpha_1)d_{(3)} + \alpha_1 d_{(4)} \\
&Bx \leq \frac{\alpha_2}{2} d_{(3)} + (1-\frac{\alpha_2}{2})d_{(4)} \\
&Bx \geq \frac{\alpha_2}{2} d_{(2)} + (1-\frac{\alpha_2}{2})d_{(1)} \\
&Sx \leq \big((1-\alpha_3)N_{(2)} + \alpha_3 N_{(1)}\big)y \\
&x \geq 0 \\
&y \in \{0,1\} \\
&0.5 \leq \alpha_1, \alpha_2, \alpha_3 \leq 1
\end{aligned}
\tag{33}
$$

The objective function in the above robust possibilistic model includes average performance, optimality robustness, and Feasibility Robustness. The first term of the objective function contains the expected value of the objective function using the average values of the uncertain parameters of the model. In other words, this part of the objective function focuses on minimizing the system's average total costs. The second term of the objective function refers to optimality robustness, and the penalty cost for the deviation is higher than the expected amount for the objective function. This section minimizes the distance and the difference between the maximum possible value for the objective function and its average value. Parameter (η) is the objective function's weight coefficient and determines the second term's weight or dominance compared to other terms in the objective function. The remaining terms in the objective function are related to the concept of Feasibility Robustness. In these expressions, according to the possible amount of excessive deviation in the model's limitations with non-deterministic parameters, the penalty amount has been estimated. In other words, the existence of these terms in the objective function minimizes the distance of the right-hand side of the constraints from their worst possible value. Also, the existence of these expressions in the objective function optimizes the constraints' confidence level. Like the possibility model, there is no need for many time-consuming repetitions to determine the optimal confidence level. In these equations, the parameters (π_1, π_2, π_3) represent the penalty for violating the uncertainty constraints in the possibilistic model (Kargar et al., 2020; Pishvaee, Razmi et al., 2012; Talaei et al., 2016; Zahiri et al., 2014). The RPP model of the current research is presented as follows.

$$\begin{aligned}
&MinTotalCosts:\\
&MTCOST: E[TCOST] + \eta(TCOST[TCOST]_{max}())\\
&+\varepsilon_1 \sum_{p=1}^{P}\sum_{l=1}^{L}\sum_{t=2}^{T}\left((1-\frac{\theta 1}{2})D4_{plt} + \frac{\theta 1}{2}D3_{plt} - D3_{plt}\right)\\
&+\varepsilon_1 \sum_{p=1}^{P}\sum_{l=1}^{L}\sum_{t=2}^{T}\left(D2_{plt} - (1-\frac{\theta 1}{2})D1_{plt} - \frac{\theta 1}{2}D2_{plt}\right)\\
&+\varepsilon_2 \sum_{p=1}^{P}\sum_{l=1}^{L}\left((1-\frac{\theta 2}{2})D4_{p,l,(t=1)} + \frac{\theta 2}{2}D3_{p,l,(t=1)} - D3_{p,l,(t=1)}\right)\\
&+\varepsilon_2 \sum_{p=1}^{P}\sum_{l=1}^{L}\left(D2_{p,l,(t=1)} - (1-\frac{\theta 2}{2})D1_{p,l,(t=1)} - \frac{\theta 2}{2}D2_{p,l,(t=1)}\right)\\
&+\varepsilon_3 \sum_{p=1}^{P}\sum_{l=1}^{L}\sum_{t=1}^{T}\left(\sum_{t'=1}^{t}\left((1-\frac{\theta 3}{2})D4_{plt'} + \frac{\theta 3}{2}D3_{plt'} - D3_{plt'}\right)\right)\\
&+\varepsilon_3 \sum_{p=1}^{P}\sum_{l=1}^{L}\sum_{t=1}^{T}\left(\sum_{t'=1}^{t}\left(D2_{plt'} - (1-\frac{\theta 3}{2})D1_{plt'} - \frac{\theta 3}{2}D2_{plt'}\right)\right)
\end{aligned} \tag{34}$$

The environmental objective function and social responsibility objective function are accorded to Eqs. (6), (7).

S.t.
Eqs. (10)-(24), (26)-(29) and

$$E[TCOST] = TA + TB + TC + TD \tag{35}$$

$$\begin{aligned}
&TCOST \sum_{q=1}^{Q}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} G4_q.Dis_{ij}.A_{qijt} \sum_{q=1}^{Q}\sum_{j=1}^{J}\sum_{t=1}^{T} H_{qj}.Ua_{qjt}\ {}_{max}\\
&+\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} O4_j.\lambda c_{ijt} + \sum_{q=1}^{Q}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} M4_{qi}.A_{qijt}\\
&+\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} G4_p.Dis_{jk}.B_{pjkt}\\
&+\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{t=1}^{T} CP_{pj}.\theta_{pjt} + CV4_{pj}.X_{pjt}\\
&+\sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{t=1}^{T} AJ_{pj}.\theta_{pjt}.C^{(op)} + \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} G4_p.Dis_{kl}.C_{pklt}\\
&+\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{t=1}^{T} H_{pk}.Ub_{pkt} + \sum_{j=1}^{J}\sum_{k=1}^{K} O4_k.\lambda b_{jk}\\
&+\sum_{p=1}^{P}\sum_{l=1}^{L}\sum_{t=1}^{T} CB4_{pl}.W_{plt} + \sum_{k=1}^{K}\sum_{l=1}^{L} O4_l.\lambda a_{kl}
\end{aligned} \tag{36}$$

$$W_{plt} \le W_{p,l,t-1} + \left(\frac{\theta 1}{2}D3_{plt} + (1-\frac{\theta 1}{2})D4_{plt}\right) - \sum_{k=1}^{K} C_{pklt}\ \forall p,l,(t\ge 2) \tag{37}$$

$$W_{plt} \geq W_{p,l,t-1} + \left(\frac{\theta 1}{2} D2_{plt} + (1 - \frac{\theta 1}{2}) D1_{plt}\right) - \sum_{k=1}^{K} C_{pklt} \, \forall p, l, (t \geq 2) \quad (38)$$

$$W_{plt} \leq \left(\frac{\theta 2}{2} D3_{plt} + (1 - \frac{\theta 2}{2}) D4_{plt}\right) - \sum_{k=1}^{K} C_{pklt} \, \forall p, l, (t = 1) \quad (39)$$

$$W_{plt} \geq \left(\frac{\theta 2}{2} D2_{plt} + (1 - \frac{\theta 2}{2}) D1_{plt}\right) - \sum_{k=1}^{K} C_{pklt} \, \forall p, l, (t = 1) \quad (40)$$

$$\alpha_{plt} \leq 1 - \frac{W_{plt}}{\sum_{t'=1}^{t} \left(\frac{\theta 3}{2} D3_{plt'} + (1 - \frac{\theta 3}{2}) D4_{plt'}\right)} \forall p, l, t \quad (41)$$

$$\alpha_{plt} \geq 1 - \frac{W_{plt}}{\sum_{t'=1}^{t} \left(\frac{\theta 3}{2} D2_{plt'} + (1 - \frac{\theta 3}{2}) D1_{plt'}\right)} \forall p, l, t \quad (42)$$

$$0.5 \leq \theta 1, \theta 2, \theta 3 \leq 1 \quad (43)$$

4.4 Linearization

The mathematical probabilistic programming model in the current research is non-linear due to the multiplication of two positive variables (α_{plt}) and ($\theta 3$) in the constraints (41) and (42). McCormick method is used to linearize the multiplication of these two positive variables (McCormick, 1976; Moheb-Alizadeh et al., 2021). To better understand this method, imagine two positive variables (x) and (y) multiplied by each other. For linearization, first, a new auxiliary variable is defined and replaces the multiplication of these two decision variables in the problem ($w = x.y$). Then, their upper and lower limits are specified and calculated for each variable (x) and (y). Finally, the following restrictions are added to the problem.

$$\begin{aligned} & x^L \leq x \leq x^P \\ & y^L \leq y \leq y^P \\ & w \geq x^L y + x y^L - x^L y^L \\ & w \geq x^U y + x y^U - x^U y^U \\ & w \leq x^U y + x y^L - x^U y^L \\ & w \leq x y^U + x^L y - x^L y^U \end{aligned} \quad (44)$$

According to the above method, the new variable (ψ_{plt}) is first defined and replaced by multiplying the two decision variables above ($\psi_{plt} = \theta_3 \times \alpha_{plt}$). In the next step, the upper and lower limits of the variables are determined and calculated. Also, the following constraints are added to the model.

$$\theta 3^{(lo)} \leq \theta 3 \leq \theta 3^{(up)} \quad (45)$$

$$\alpha_{plt}^{(lo)} \leq \alpha_{plt} \leq \alpha_{plt}^{(up)} \forall p, l, t \quad (46)$$

$$\psi_{plt} \geq \theta 3^{(lo)} . \alpha_{plt} + \alpha_{plt}^{(lo)} . \theta 3 - \theta 3^{(lo)} . \alpha_{plt}^{(lo)} \forall p, l, t \quad (47)$$

$$\psi_{irt} \geq \theta 3^{(up)} . \alpha_{plt} + \alpha_{plt}^{(up)} . \theta 3 - \theta 3^{(up)} . \alpha_{plt}^{(up)} \forall p, l, t \quad (48)$$

$$\psi_{plt} \leq \theta 3^{(up)} . \alpha_{plt} + \alpha_{plt}^{(lo)} . \theta 3 - \theta 3^{(up)} . \alpha_{plt}^{(lo)} \forall p, l, t \quad (49)$$

$$\psi_{plt} \leq \theta 3^{(lo)} . \alpha_{plt} + \alpha_{plt}^{(up)} . \theta 3 - \theta 3^{(lo)} . \alpha_{plt}^{(up)} \forall p, l, t \quad (50)$$

Also, the linearized and rewritten equation of constraints (41) and (42) is as follows.

$$W_{plt} \leq \frac{\theta 3}{2}\sum_{t'=1}^{t} D3_{plt'} + \sum_{t'=1}^{t} D4_{plt'} - \frac{\theta 3}{2}\sum_{t'=1}^{t} D4_{plt'} - \frac{\theta 3}{2}\left(\sum_{t'=1}^{t} D3_{plt'}\right)\alpha_{plt} - \left(\sum_{t'=1}^{t} D4_{plt'}\right)\alpha_{plt} + \frac{\theta 3}{2}\left(\sum_{t'=1}^{t} D4_{plt'}\right)\alpha_{plt} \forall p, l, t \tag{51}$$

$$W_{plt} \geq \frac{\theta 3}{2}\sum_{t'=1}^{t} D2_{plt'} + \sum_{t'=1}^{t} D1_{plt'} - \frac{\theta 3}{2}\sum_{t'=1}^{t} D1_{plt'} - \frac{\theta 3}{2}\left(\sum_{t'=1}^{t} D2_{plt'}\right)\alpha_{plt} - \left(\sum_{t'=1}^{t} D1_{irt'}\right)\alpha_{plt} + \frac{\theta 3}{2}\left(\sum_{t'=1}^{t} D1_{plt'}\right)\alpha_{plt} \forall p, l, t \tag{52}$$

4.5 Fuzzy goal programming (FGP) method

Many real-world programming problems usually have more than one primary objective other than cost minimization or profit maximization, as goals such as reducing environmental pollution, increasing customer satisfaction, and increasing quality. In most cases, the intended goals may be incompatible and conflict. Even if the goals of the problem are in the same direction but have different measurement units and heterogeneity, the algebraic sum of these goals is in the form of a single objective function. Not possible for this reason, it is necessary to use a suitable method to deal with the multi-objective nature of the model and to include all the objectives in decision-making. One of these methods is the FGP approach. In this method, each of the ideal goals is defined, and the goal of the model is to minimize the sum of negative and positive deviations of each goal from the defined ideals. The objective function of this approach seeks to minimize unfavorable or undesirable deviations from ideals. In cost-type ideals, more deviations of the researcher (positive), and in profit-type ideals, lower deviations of the researcher (negative) should be minimized. FGP is one of the multi-criteria decision-making methods used to solve real problems. This model is based on two concepts of goal programming and fuzzy programming. In 2008, Yaghoobi and Tamiz presented their proposed FGP approach. The changes in their model included making a series of improvements in the weighted goal programming model and combining this model with the fuzzy programming technique, which led to the presentation of a new FGP model. Yaghoobi and Tamiz's method seeks to minimize the maximum deviations of each objective function. This method can consider different weights for positive and negative deviations (Hocine et al., 2020; Selim & Ozkarahan, 2008; YAGHOOBI et al., 2008). Yaghoobi and Tamiz's FGP model is as follows.

$$\begin{aligned}
&Min \sum_{i=1}^{i_o} w_i \frac{d_i^+}{\Delta_i^R} + \sum_{i=i_o+1}^{j_o} w_i \frac{d_i^-}{\Delta_i^L} + \sum_{i=j_o+1}^{k} w_i \left(\frac{d_i^-}{\Delta_i^L} + \frac{d_i^+}{\Delta_i^R}\right) \\
&s.t. \\
&(AX)_i - d_i^+ \leq b_i i = 1, \dots, i_o \\
&\mu_i + \frac{d_i^+}{\Delta_i^R} = 1 i = 1, \dots, i_o \\
&(AX)_i + d_i^- \geq b_i i = i_o + 1, \dots, j_o \\
&\mu_i + \frac{d_i^-}{\Delta_i^L} = 1 i = i_o + 1, \dots, j_o \\
&(AX)_i + d_i^- - d_i^+ = b_i i = j_o + 1, \dots, k_o \\
&\mu_i + \frac{d_i^-}{\Delta_i^L} + \frac{d_i^+}{\Delta_i^R} = 1 i = j_o + 1, \dots, k_o \\
&(AX)_i - d_i^+ \leq b_i^u i = k_o + 1, \dots, k \\
&(AX)_i + d_i^- \leq b_i^l i = k_o + 1, \dots, k \\
&\mu_i, d_i^-, d_i^+ \geq 0
\end{aligned} \tag{53}$$

In the above model, the index (i) indicates the fuzzy objectives of the decision, each of which can be expressed by a piecewise linear membership function. The set $(1,\dots,i_o)$ corresponds to problems with an objective minimization function. The set $(i_o+1,\dots,j_o)$ corresponds to problems with an objective maximization function. The set $(j_o,\dots,k_o)$ corresponds to problems with a triangular membership function. The set $(k_o,\dots,K)$ corresponds to problems with a trapezoidal membership function. The parameter (w_i) shows the weight or importance of negative or positive deviations of each goal. (d_i^-) and (d_i^+) are negative and positive deviations from the goal. $(\mu_i\ )$ is a model decision variable that determines the degree of the membership function for the fuzzy objective (i). (X) is the vector of decision variables. (Δ_i^L) and (Δ_i^R) are the maximum acceptable tolerance range for the minimization and maximization objective functions, respectively. (b_i^u) and (b_i^l) define the upper and lower bounds of the general satisfaction interval for the trapezoidal membership function. The FGP model of the current research is formulated according to the Yaghoobi and Tamiz method in the following equations.

$$MinFGP\colon wf_1\frac{df_1^+}{\Delta_1^R}+wf_2\frac{df_2^+}{\Delta_2^R}+wf_3\frac{df_3^-}{\Delta_3^L} \tag{54}$$

S.t.
Eqs. (10)-(24), (26)-(29), (34)-(40), (43), (51), (52) and

$$MTCOST-df_1^+\le Bf_1 \tag{55}$$

$$TCO2-df_2^+\le Bf_2 \tag{56}$$

$$TSOCIAL+df_3^-\ge Bf_3 \tag{57}$$

$$uf_1+\frac{df_1^+}{\Delta_1^R}=1 \tag{58}$$

$$uf_2+\frac{df_2^+}{\Delta_2^R}=1 \tag{59}$$

$$uf_3+\frac{df_3^-}{\Delta_3^L}=1 \tag{60}$$

$$df_1^+,df_2^+,df_3^-,uf_1,uf_2,uf_3\ge 0 \tag{61}$$

5. Case study

The proposed green supply chain network model was implemented in an industrial unit in the real world to check the validity and reliability of the mathematical model and the reasonableness of the answers. This section aims to conduct a case study to check the practical effectiveness of the proposed model. This section uses the proposed model in an actual case study in the north of Iran and Mazandaran province. The industrial unit selected for this research produces various products, including ventilation equipment, heating products, and industrial fans. With the investigations, their industrial ventilators were selected as the manufactured product group for this case study from among the various products produced in this industrial unit. The mechanism of the supply chain, production, and supply of these products in this company is that at the beginning of this chain, raw materials and parts are purchased from different suppliers and stored in the factory's warehouse. Then the primary materials and parts are placed in the final production process depending on their needs. After the production process is finished, the final products produced are sent to the distribution centers. Distribution centers also distribute products among retailers depending on their demands and needs. This supply chain consists of 5 suppliers of parts, three manufacturing centers, three distribution centers, and five selected retail centers. The region investigated in this research is Mazandaran province, which according to the defined supply chain, are retail centers located in the cities of Behshahr, Sari, Amol, Chalus, and Tonekabon. The number of facilities available for the case study is given in Table 2. Also, an overview of the geographical location is shown in Figure 4.

Table 2. Size of the case study

suppliers	manufacturers	distribution center	retailer center	periods	products	parts
5	3	3	5	3	3	5

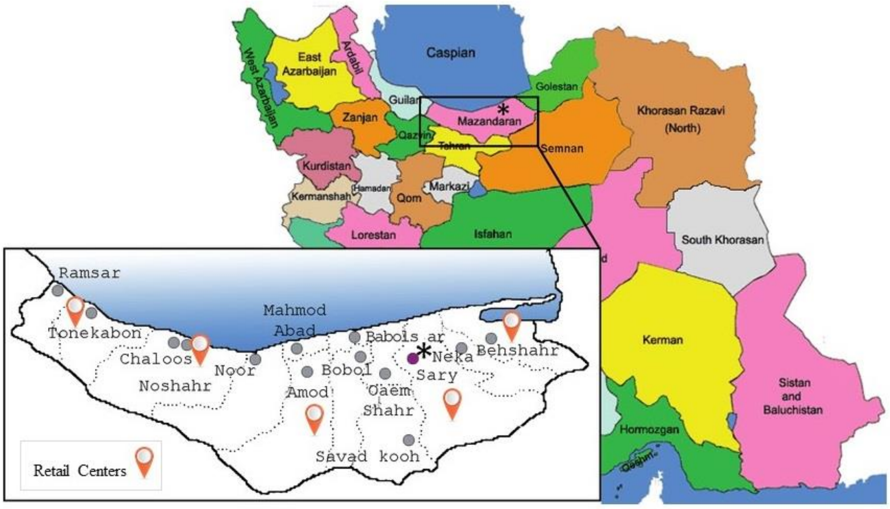

Figure 4. The geographical location of the case study

5.1. Input data

Since the parameters of product demand, ordering cost, purchase cost, transportation cost, production cost, and shortage cost constantly change, it is difficult to calculate them accurately. Therefore, these parameters are considered non-deterministic and represented as trapezoidal fuzzy numbers in mathematical models. A 20% deviation and increased costs are considered for cost parameters. Also, the demand parameter of retailers for different products is a 20% deviation from the estimated amount. If retail demand is estimated at 100, this value will equal the trapezoidal fuzzy number (90, 95, 105, 110). Other non-deterministic parameters are converted into trapezoidal fuzzy numbers in the same way.
The information required to solve the suggested model is supplied in this section. The demand of retailer centers for different products in different periods is displayed in Appendix A's Table A1. Shipping capacity between distributors and retailers is shown in Table A2. Shipping capacity between suppliers and manufacturers is shown in Table A3. Shipping capacity between manufacturers and distributors is shown in Table A4. The holding capacity of parts in the manufacturing center is shown in Table A5. The holding capacity of products in the distribution center is shown in Table A6. The amount of Energy consumed to produce and process each product in manufacturing and distribution centers is shown in Table A7 and A8. Table A9 also displays the remaining problem-related parameters.

5.2. Results

The computation results are shown in this section. The proposed model is coded and solved with the data from the case study. The results are described below. It should be emphasized that GAMS 24.1.2 software in i3, 2.67 GHz, 8 GB RAM PC is used to solve the given model. The first step in using the FGP method is determining the goal's values and the objective functions' tolerance range. This is accomplished by using a payoff table. After solving, Table 3 shows the answers obtained for the goal and the tolerance range for each objective function. The information and results of solving the problem with the FGP method are shown in Table 4.

Table 3. The value of goal and tolerance rang for each objective function.

Economical objective		Environmental objective		Social objective	
Bf_1	Δf_1^R	Bf_2	Δ_2^R	Bf_3	Δ_3^L
47157200000	51591100000	22700730	1961490	345.040	107.464

Table 4. Results and output from solving the FGP model.

Symbol	Value
$MTCOST$	60110300000
$TCO2$	22700730
$TSOCIAL$	295.129
FGP	0.222
df_1^+	12953100000
df_2^+	0
df_3^-	49.911
uf_1	0.776
uf_2	1
uf_3	0.536
$CO_2^{Emissions}$	51.593

The value of the decision variables can be seen after solving the mathematical model and the information obtained from its output. In the rest of this section and in the form of tables, the optimal values obtained for these decision variables of the problem are shown. Table A10 shows the optimal amount produced of each product in manufacturing centers and each period. According to the definition of the problem and the stated assumptions, in each period, the supply chain network is optional to satisfy the demands fully. Part or all of the order can be transferred to the following periods as backorders. Of course, at the end of the last period, all requests for products and all backorders must be answered. According to these assumptions, a service level is defined for retail stores, according to which the model seeks to maximize the response to the need for products and obtain more satisfaction.

For this reason, Table A11 shows the shortage amount in each retail store for each product and period. Table A12 also shows the desired service level in retail centers for products in different periods. One of the valuable pieces of information obtained from solving the model is determining the optimal quantity of materials and products transported between facilities in the supply chain network. Optimal quantity of products sent from production centers to distributors. The ideal number of finished goods should be shipped from production facilities to distributors, as shown in Table A13. Table A14 also shows the optimal quantity of products sent from distribution centers to retail stores.

5.3. Sensitivity analyses and discussion

Sensitivity analysis on parameters is one of the practical techniques to evaluate the trend of model results according to the changes in determining parameters. Sensitivity analysis has been utilized in this part to assess the effectiveness of modeling and look at how changes in model parameters affect the outcome.

5.3.1. Weight coefficient (η) analysis in the RPP approach.

The weight coefficient of the objective function, or parameter (η), in the RPP model's economic objective function establishes the weight or dominance of the second term relative to other terms in the objective function. This weighting factor minimizes the difference and distance between the predicted value and the objective function's maximum value. Usually, the value of this coefficient is considered between 0.3 and 0.8. For this purpose, to determine the optimal value of this coefficient, the objective function values of the stable probability model have been calculated for different eta values from 0.1 to 0.8. Table 5 shows the obtained values for the objective functions for various weight coefficient values (η).

Table 5. Value of economic objective in various weight coefficients ($\boldsymbol{\eta}$)

row	η	value (Iranian Rial)
1	0.1	61902400000
2	0.2	61972100000
3	0.3	60110300000
4	0.4	63668200000
5	0.5	62950500000
6	0.6	63120700000
7	0.7	63264500000
8	0.8	63389600000

Looking at the table above and its results, it is clear that the value of 0.3 is the best value for this coefficient. The objective function's change trend for various values may be seen in Figure 5. The numbers in the graph were shown with the exponential factor ($\times10^9$).

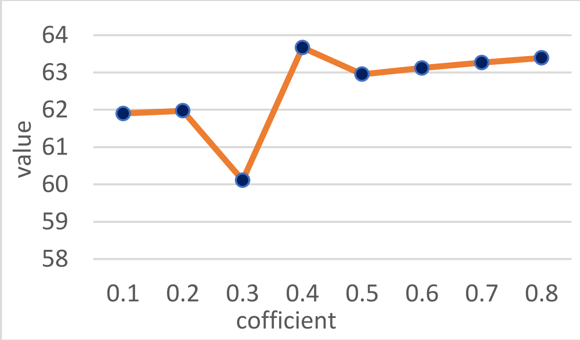

Figure 5. Economic objective function's trend.

5.3.2. Penalty coefficients analysis in RPP approach.

The penalty coefficient (ε) justifies the viability of the problem's mathematical model and risk aversion. Considering a large amount of penalty makes the feasibility of the problem model to be maximized. However, this issue imposes many costs on the model. So, by reducing the amount of epsilon and accepting a small amount of risk, the cost of the whole chain can be reduced to an acceptable amount. In the robust possibility approach, the value of this penalty coefficient is usually considered equal to the cost of deficiency. Table 6 shows the changes in the robust possibility model's economic objective function concerning the increase of this penalty coefficient. This table shows that the objective function's value rises and worsens when the penalty factor increases. Also, in Figure 6, the change economic objective function's trend can be seen concerning the increase of the penalty coefficients (ε).

Table 6. Value of economic objective in various penalty coefficients (ε)

row	$(\varepsilon_1, \varepsilon_2, \varepsilon_3)$	Value (Iranian Rial)
1	150000	60110300000
2	250000	64725800000
3	350000	65099900000
4	450000	65356700000

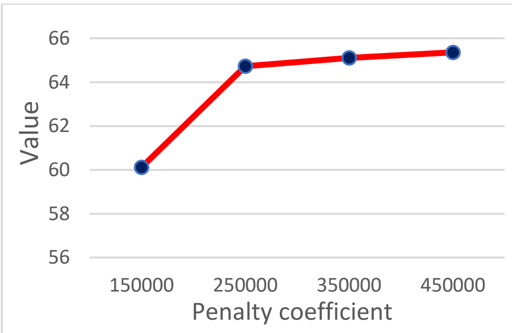

Figure 6. Impact of changes in coefficient (ε) on the economic objective function.

5.3.3. analysis of the weighting factor of objective functions in the FGP model

This section examined how the problem's goal functions changed when the weight coefficients changed. Each objective function was multiplied by a coefficient; the value of this coefficient shows the degree of importance of that objective function. By changing each objective's weight, the objective function's importance can be increased or decreased compared to the rest of the objectives of the problem. Also, the sum of all weight coefficients must be equal to one. The values for the objective functions after the model was solved using various weight coefficient modes are shown in Table 7.

Table 7. The impact of changes in weight coefficient on the objective functions.

row	(wf_1, wf_2, wf_3)	Economical objective Value (Iranian Rial)	Environmental objective Value (Iranian Rial)	Social objective
1	(0.2/0.6/0.2)	62841900000	22701120	295.129
2	(0.6/0.2/0.2)	65584900000	22975250	312.000
3	(0.7/0.2/0.1)	60110300000	22700730	295.125
4	(0.3/0.2/0.5)	84898800000	23504990	332.686
5	(0.33/0.33/0.33)	64759800000	22978120	312.036

Determining the best value for the coefficient of objective functions depends on the problem type and the model's goals. Managers, decision-makers, or model designers usually do this. According to the results obtained from the table above, it is clear that in mode 3, all the objective functions are relatively good compared to the rest of the modes.

5.3. Managerial insights

Some important managerial insights are provided to improve the green supply chain performance in this section: One of the aspects that this paper focuses on is the service level issue. Today, customer satisfaction is paramount. In any highly competitive environment, inventory and service levels are always a concern for any inventory management system and a significant competitive factor. Poor service levels can lead to lost customers and sales, while excess inventory, on the other hand, leads to unnecessary costs due to carrying large amounts of inventory. With the help of the conducted investigations, it has been determined that the factor of the quantity of produced product in the manufacturing center plays a vital role in determining the service level in retail centers, the optimal value of which is shown in Table A10. Also, the correct estimate of the minimum service level in retailer centers can prevent additional costs.This paper tells us that adding uncertainty to the supply chain model makes it more robust and better able to handle market changes. Moreover, it helps the supply chain do better in the market and against competitors. Many parameters and variables frequently fluctuate in the real world, making decision-making and planning difficult. This paper uses an RPP approach against uncertainty in a proposed green supply chain. The robust approach can be a powerful management tool in a supply chain network. Computational results show that using the RPP approach led to the minimization of the total cost, the minimization of carbon emissions, and the maximization of the social aspect. Therefore, using this model in similar supply chains can be a suitable tool for managers and decision makers to solve supply chain issues and problems and enables the decision maker to make more correct decisions.Also, considering environmental issues improves the production process and supply chain efficiency. This can encourage customers to buy environmentally friendly products.

6. Conclusions

maybe talking about social and environmental components in the supply chain was considered unusual in the past decades and was only considered as imposing an excess cost on companies and organizations; But currently, introducing social and environmental components in supply chains and considering them along with other costs has become a requirement in all supply chain networks globally. This research's green supply chain network design problem is modeled as a mix-integer mathematical programming model with three objective functions. The proposed model has a "green" supply chain with multiple products, levels, and periods. This group comprises suppliers, producers, sellers, and stores. This paper proposes a new model for designing an optimal green supply chain network by considering uncertain parameters. We use fuzzy numbers as the parameters to make it more like the real world, where things are uncertain. The model wants to save money by making the best choices for the supply chain. It also wants to reduce pollution and be responsible to society. We care about the environment when we make things by trying to make less CO2. This research is different from others because it combines being responsible to society, ensuring we do not release too much pollution, and reducing costs more efficiently through a supply chain. The obtained results show that the proposed model has the potential to be used in the real world, considering all the mentioned aspects. As part of the results and findings, it can be mentioned that in the optimal case, how much of the products should be produced by which of the factories? What volume of materials and goods is moved between which of the centers? Which of the centers are connected? Also, the amount of carbon dioxide released from the entire network is determined. Applying this model in supply chains can be a suitable tool for managers and decision-makers to solve supply chain issues and problems.
The following presents the topics and fields of development and expansion of the green supply chain. Future research can focus on aspects like model building and solution method improvement. The following are some ideas for development:

- We are expanding the model levels in the reverse direction and combining the proposed model with reverse logistics concepts.
- Include the shortage in the form of lost sales in the problem.
- Use other carbon policies (carbon cap-and-trade, cap, trade) and compare their results with each other.
- They are comparing their results with other solution approaches, such as the epsilon constraint method and LP metric.

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Appendix: Input data and results

Table A1

Numerical values of retailers' demand

	retailer	period 1	period 2	period 3
product 1	1	450	460	400
	2	480	300	350
	3	320	420	280
	4	420	300	270
	5	310	520	350
product 2	1	280	340	360
	2	360	450	450
	3	300	370	310
	4	540	480	430
	5	370	300	250
product 3	1	250	280	320
	2	410	300	430
	3	420	500	290
	4	380	410	450
	5	290	500	330

Table A2

Shipping capacity between distributors and retailers

	retailer	distributor 1	distributor 2	distributor 3
product 1	1	1850	1850	1850
	2	1850	1850	1850
	3	1850	1850	1850
	4	1850	1850	1850
	5	1850	1850	1850
product 2	1	2350	2350	2350
	2	2350	2350	2350
	3	2350	2350	2350
	4	2350	2350	2350
	5	2350	2350	2350
product 3	1	2630	2630	2630
	2	2630	2630	2630
	3	2630	2630	2630
	4	2630	2630	2630
	5	2630	2630	2630

Table A3

Shipping capacity between suppliers and manufacturers

	supplier	manufacturer 1	manufacturer 2	manufacturer 3		supplier	manufacturer 1	manufacturer 2	manufacturer 3
Part 1	1	2300	2300	2300	part 4	1	2150	2150	2150
	2	2300	2300	2300		2	2150	2150	2150
	3	2300	2300	2300		3	2150	2150	2150
	4	2300	2300	2300		4	2150	2150	2150
	5	2300	2300	2300		5	2150	2150	2150
Part 2	1	1800	1800	1800	part 5	1	2800	2800	2800
	2	1800	1800	1800		2	2800	2800	2800
	3	1800	1800	1800		3	2800	2800	2800

	4	1800	1800	1800
	5	1800	1800	1800
part 3	1	2500	2500	2500
	2	2500	2500	1800
	3	2500	2500	2500
	4	2500	2500	2500
	5	250	2500	2500

4	2800	2800	2800
5	2800	2800	2800

Table A4
Shipping capacity between manufacturer and DC

	manufacturer	distributor		
		1	2	3
product 1	1	1850	1850	1850
	2	1850	1850	1850
	3	1850	1850	1850
product 2	1	2350	2350	2350
	2	2350	2350	2350
	3	2350	2350	2350
product 3	1	2630	2630	2630
	2	2630	2630	2630
	3	2630	2630	2630

Table A5
Holding capacity of parts in the manufacturing center

	part	period		
		1	2	3
Manufacturer 1	1	460	580	480
	2	350	470	350
	3	530	650	530
	4	430	560	430
	5	560	680	560
Manufacturer 2	1	530	620	530
	2	380	520	380
	3	560	560	560
	4	450	570	450
	5	575	650	575
Manufacturer 3	1	450	540	450
	2	346	436	364
	3	540	630	540
	4	456	566	456
	5	580	650	580

Table A6
Holding capacity of parts in the distribution center

		distributor		
		1	2	3
product	1	520	710	520
	2	340	650	340
	3	460	580	460

Table A7
Energy consumed in manufacturing center

		manufacturer		
		۱	۲	۳
product	۱	3.33	3.12	3.45
	۲	2.75	3.35	2.92
	۳	3.5	3.46	3.35

Table A8

Energy consumed in distribution center

		distributor		
		1	2	3
product	1	1.23	1.34	1.52
	2	1.13	1.10	1.3
	3	1.17	1.21	1.14

Table A9

Parameters of the problem

Parameter	Value
$\mu^{(P)}$	0.0007
$\mu^{(R)}$	0.000145
TDL	0.123
$\phi^{(job)}$	0.85
$\phi^{(wste)}$	0.15

Table A10

Quantity of produced of product in the manufacturing center

		period		
product	manufacturer	1	2	3
1	1	0	0	0
	2	1850	1850	1443
	3	0	0	0
2	1	0	1550	1550
	2	0	0	0
	3	1825	0	0
3	1	0	0	0
	2	0	0	0
	3	1309	1973	1800

Table A12

Service level in retail centers

product	Retailer	period 1	period 2	period 3
1	1	0.7	1	1
	2	1	1	1
	3	1	1	1
	4	1	0.718	1
	5	1	0.7	1
2	1	1	0.7	1
	2	1	0.884	1
	3	1	1	1
	4	0.7	0.7	1
	5	1	1	1
3	1	0.702	1	1
	2	0.7	1	1
	3	0.7	1	1
	4	0.7	0.7	1
	5	0.702	0.7	1

Table A11

Quantity of backorder in retail center

product	Retailer	period 1	period 2	period 3
1	1	146	0	0
	2	0	0	0
	3	0	0	0
	4	0	185	0
	5	0	270	0
2	1	0	202	0
	2	0	86	0
	3	0	0	0
	4	176	267	0
	5	0	0	0
3	1	81	0	0
	2	133	0	0
	3	137	0	0
	4	123	257	0
	5	94	257	0

Table A13

Shipments of goods from manufacturing facilities to distribution locations

product	manufacturer	Period 1			Period 2			Period 3			period
		1	2	2	1	2	3	1	2	3	DC
1	1	0	0	0	0	0	0	0	0	0	
	2	1850	0	0	1850	0	0	1443	0	0	
	3	0	0	0	0	0	0	0	0	0	
2	1	0	0	0	0	1550	0	0	1550	0	
	2	0	0	0	0	0	0	0	0	0	
	3	0	1825	0	0	0	0	0	0	0	
3	1	0	0	0	0	0	0	0	0	0	
	2	0	0	0	0	0	0	0	0	0	
	3	0	0	1309	0	0	1973	0	0	1800	

Table A14

Shipments of goods from distribution facilities to retailer locations

product	Retailer	Period 1			Period 2			Period 3			period
		1	2	3	1	2	3	1	2	3	DC
1	1	265	0	0	566	0	0	365	0	0	
	2	438	0	0	274	0	0	320	0	0	
	3	292	0	0	348	0	0	256	0	0	
	4	384	0	0	89	0	0	432	0	0	
	5	283	0	0	205	0	0	590	0	0	
2	1	0	256	0	0	109	0	0	531	0	
	2	0	329	0	0	325	0	0	497	0	
	3	0	274	0	0	338	0	0	283	0	
	4	0	317	0	0	165	0	0	660	0	
	5	0	338	0	0	274	0	0	229	0	
3	1	0	0	148	0	0	337	0	0	292	
	2	0	0	242	0	0	407	0	0	393	
	3	0	0	247	0	0	595	0	0	265	
	4	0	0	224	0	0	241	0	0	668	
	5	0	0	171	0	0	294	0	0	559	