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Robust optimization to design a four-echelon perishable supply chain under stochastic deterioration rate: A case study

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Abstract

The perishable dairy industry has to deal with multiple challenges such as demand forecasting, price fluctuations, lead time, and inflated orders along with difficulties of climatic and traffic conditions, storage areas and shipment in unfavorable circumstances. This research introduces a robust bi-level mathematical model to optimize a multi-echelon Perishable Supply Chain (PSC. To this end, integrated multi-objective Mixed Integer Linear Programming (MILP) models are developed to formulate the problem. stochastic deterioration rate is taken into account as the main factor that determines model performance due to perishability of products. In order to contribute to the literature, mainly by addressing uncertainty and perishability, a solution technique based on robust programming and ε-constrait approach is developed to accommodate suggested bi-level model. This technique can deal with problem uncertainty while also ensuring the robustness of the overall system. Sensitivity analysis is implemented along with three well-known quality indicators to assess the performance of the proposed solution method and quality of obtained solutions. Finally, real case study is provided using the CPLEX solver to showcase the applicability of the proposed methodology and discuss the complexity of the model. Results demonstrate the efficiency of the proposed methodology in finding optimal solutions.

Keywords: Supply chain network design, perishable supply chain, robust optimization, dairy industry

1-Introduction

Supply chains are considered the pillars of the global economy, and each organization is a member of at least one supply chain. All daily activities, such as withdrawing money, eating in a restaurant, and online ordering, are a type of participation in supply chains (Scholten & Fynes, 2017). Many researchers focus on supply chain management for food, pharmaceutical, and blood products. Preparing healthy foods, drugs, blood, and particularly materials with short lifetime and perishable products is one of the concerns of companies involved in chain management. The risks of perishable products appear in each stage of the supply chain, and critical control points, such as materials, manufacturing, and expiry date, should be determined to obtain information. Also, a clear provision of information (such as weather conditions, seasonal materials, perishing at a specific time, and storage conditions) leads to further uncertainty for some supply chain participants and consumers. Regarding the importance of supply chain issues and relevant challenges, such as customer demand variability, delivery time, inventory shortage, and particular conditions of perishable products relative to non-perishable products, supply chain management for perishable products are of greater importance (Darestani & Hemmati, 2019).

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Since the food supply chain is one of the largest and most complex global industrial sectors, it plays an important role in economic growth. Features of food products, such as lifetime, affect three sustainability criteria significantly because perishable food products with a limited lifetime need much attention due to large volume of wastage, detrimental environmental effects, and particular storage and transportation conditions (Sazvar & Sepehri, 2020).

Perishable products have a more complex structure and are subject to more uncertainty and vulnerability (Dagne et al., 2020). Dairy products are perishable products. A large volume of Methane is emitted during the production process of these products, creating a substantial impact on global warming and greenhouse gas emissions (Shafiee et al., 2020). Prior studies have mostly focused on carbon emission, and less attention has been paid to estimating the cost of greenhouse gas emissions, NOx, and HC in a multi-echelon perishable products supply chain in an uncertain environment. Therefore, an environmentally friendly supply chain design for perishable products is necessary considering the expiry date of these products and demand uncertainty. This research investigated all the issues mentioned above by a synthesis approach: (1) Presenting multiple objective programming models for the four-echelon multi-product perishable supply chain network design problem. The Model supports choice about the product flows, modes of transport, inventory volume, the number of raw materials, routes and pollution rate across the supply chain. (2) Providing recommendations for the design and operation of a supply chain of dairy as a perishable product in the case of the Pegah Co. in Iran. The solution of the Model is calculated based on data and regional characteristics such as type of product, cost, mode of transport, and transport infrastructure. (3) Analysis of differentiation in the design of the perishable supply chain network design by modifying the weight of the objective functions in different scenarios, thereby assisting decision-makers in predicting changes in supply network configuration when the priority of the objective functions changes.

The research mainly aims to propose a robust model to design a perishable products supply chain network by considering economic and environmental indicators. The secondary objectives are as follows:

- Incorporating uncertainty parameters such as demand and transportation costs into the proposed model
- Incorporating the effects of deterioration and the lifetime of perishable dairy products into the model

Then, the problem is defined, and its important structural features are described. Based on the assumptions and problem properties, we develop a mixed-integer linear programming model for the problem. Also, a robust optimization-based approach and the GAMS 25 software are used to solve the problem. In the ‘Findings’ section, various numerical trials based on a real case study of the dairy products supply chain are considered to assess the model. In the ‘Conclusion and recommendations’ section, the results and suggested topics for future studies are provided. A general schematic diagram of multi-echelon supply chain problems is presented in figure 1.

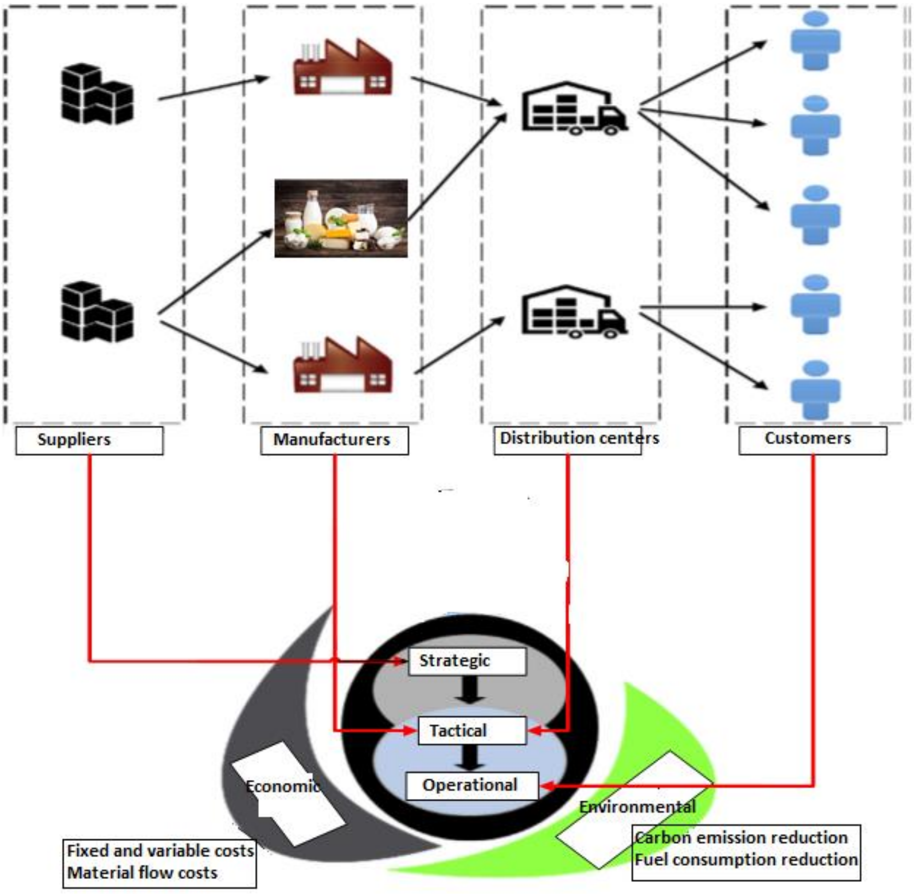


Fig 1. General schematic diagram of the problem

2-Literature review

The supply chain of products and services, especially when it comes to highly perishable products needing high level of services, is usually difficult to handle. In this case, simulation can offer a reliable approach toward studying and evaluating the processes and outcomes of such supply chains, and presenting suitable alternatives that can achieve optimal performance. Spoilage is a common phenomenon. Products may lose their value or quality suddenly or gradually. Fruits, vegetables, flowers, medicines, blood, dairy products, meat and food are prominent examples. Spoilage is the main concern of the supply chain, because the quality or value of most products is reduced over the life span. (Tavakkoli Moghaddam et al., 2019)(Sazvar et al., 2016)

Darestani and Hemmati (2019) designed a bi-objective supply chain network for perishable products by considering uncertainty concerning perishability. They used the queuing theory to decrease lead-time in distribution centers. The two objectives considered were to minimize total network costs and minimize greenhouse gas emissions. Some parameters (such as demand, operating costs, transportation costs, and allowable capacity of distribution centers) were considered uncertain. Also, in this model, an optimization approach was used to control these uncertain parameters. Finally, they used two multi-criteria decision-making methods, i.e., weighted sum and Torabi-Hassini, to solve the bi-objective model. The results indicated that there was a significant difference between the mean of the first objective, the second objective, and the running time. They used TOPSIS to choose the most efficient method and the Torabi-Hoseini to find the most effective solution (Darestani & Hemmati, 2019). Hsu (2019) proposed a mixed-integer multi-period, multi-product model for perishable food product logistics by considering costs, environmental effects, and service levels. The compromise solution provided recommendations concerning locations and transportation flows for both general logistics and the cold chain. In addition, decisions on the location of food products processors, distribution centers, retailers, and related operating units were supported by maximum service level, minimum cost, and minimum emission volume(Hsu, 2019). A case study was used to illustrate the results, and a sensitivity analysis was conducted to compare the effects of environmental and service factors Sazvar and Sepehri (2020) addressed some economic, environmental, and social issues, such as unemployment, job creation for local labor in their hometowns, immigration of unemployed people, and naturalization of nonnatives for retailers. They assessed the group of perishable products from the viewpoint of economic and environmental features and developed a linear multi-objective mathematical model to determine integrated recruitment and replenishment policy for the retailor in line with sustainable development. They provided a numerical analysis using the data from the flower industry. According to the results, economic and social indicators will improve if essential facilities and infrastructures are provided to settle qualified immigrants. It was also found that social welfare would be increased by focusing on strategies such as job creation for local people in retail centers without an increase in the production capacity and by implementing careful policies on immigration and naturalization (Sazvar & Sepehri, 2020).

Shafiee et al. (2021) designed a mathematical model for a three-level multi-product sustainable supply chain in the dairy industry under uncertainty by assuming the first-in-first-out (FIFO) policy of the products. For this purpose, they presented a mixed-integer non-linear programming model to optimize the total costs of the chain while observing environmental and social considerations. They used a robust-heuristic optimization approach and the ε-constraint method to solve the model because of the uncertainty of economic parameters, the capacity of facilities, and demand. The results demonstrated the efficiency and capability of the proposed model in achieving qualified solutions in rational time (Shafiee et al., 2021).

Yadav et al. (2022) designed a food supply chain network to identify challenges of agriculture food supply chain (AFSC), conduct a review of research streams on designing an agro-food supply chain network (AFSCN), and assess different indicators of a performance measurement system for the food supply chain. The results indicated that the main challenges are related to food. On the other hand, technology, digitalization, and effective design of AFSCN[1] can be adapted (Yadav et al., 2022).

Yazdani et al. (2022) proposed a group decision-making model to direct farmers in the Andalusia province of Spain. Farmers, retailers, and supermarkets were assessed using questionnaires. The results indicated that farmers had the lowest resiliency against disruptions, while supermarkets were very flexible (Yazdani et al., 2022).

Tirkolaee and Aydin (2022) introduced a fuzzy two-level decision-making backup system to optimize a sustainable multi-level, multiproduct model for perishable product distribution. They suggested an integrated solution method based on fuzzy weighted goal programming (FWGP) to be adapted to the two-level model. The model could overcome uncertainty while guaranteeing the sustainability of the whole system (Tirkolaee & Aydin, 2022). It should be noted that most of the studies from 2012 to 2022 were reviewed for the current research. However, due to limitations, some studies from 2019 to 2022, as well as the current research, are presented in table 1.

A review of the previous studies shows that many researchers, such as Sazvar and Sepehri (2020), Yadav et al. (2022), Tirkolaee and Aydin (2022), Shafiee et al. (2021), Yavari et al. (2019), Musavi & Bozorgi-Amiri(2017), (Jouzdani & Govindan, 2021) and Govindan et al.(2014), considered economic and environmental aspect in modeling the perishable supply chain. Tirkolaee and Aydin (2022), Sazvar and Sepehri (2020), Dashtizadeh et al. (2020), and Darestani and Hemmati (2019) considered carbon emission index as a popular and valid indicator of environmental effects. Tirkolaee and Aydin (2022), Shafiee et al. (2021), Rahbari et al. (2019), Jonkman (2019), Ma et al.(2019), Savadkoohi et al.(2018), and Shrivastava et al.(2018) incorporated uncertainty of some parameters into the perishable supply chain. Among the studies in this area, only Shafiee et al. (2021) considered the first-in-first-out (FIFO) issue policy in the supply chain. Sazvar and Sepehri (2020), Dashtizadeh et al. (2020), Yavari et al. (2019), and Shafiee et al. (2021) designed a multi-period multi-product supply chain in the studied area. Also, Yadav et al. (2022), Tirkolaee and Aydin (2022), Chernonog (2020), Diabat et al.(2019), Savadkoohi et al.(2018), Eskandari-Khanghahi et al.(2018), Aggarwal (2018) and Grillo et al.(2017) considered fixed lifetime, and Sazvar and Sepehri (2020), Rahbari et al.(2019), Denge et al.(2019), (Bortolini et al., 2018), Ghezavati et al.(2017), Rashidi et al.(2016) and Sazvar et al. (2016) assumed random lifetime in the perishable products supply chain.

[1] Agriculture Food Supply Chain

In the present research, the cases and items that were addressed in previous studies separately are combined, and a new model in the area of multi-product multi-period perishable dairy products supply chains is proposed by considering fixed and random lifetime and issue policy under uncertainty. Since network design has a long-term effect on the performance of the supply chain, and changing the network design in the short term is costly and time-consuming, supply chain network design should be carried out with sufficient care. This research is the first quantitative project in which a centralized multi-echelon multi-product multi-period supply chain is proposed by considering uncertainty in parameters, including demand, price, perishing costs, perishing level, and inventory in four levels in the dairy industry. Since dairy products are used widely in the daily food diet, and their distribution is accompanied by risk (due to the direct effect on society's health), the perishability of dairy products is considered in the proposed model with two indicators, namely fixed and random lifetime. Also, optimal decisions on production, distribution, allocation, cost balance (cost function), and costs of CO_2, CO, HC, and NOx gas emissions (environmental cost function) are included in the proposed model.

Table 1. Summarized literature review

No.	Studies	Levels of supply chain					Product lifetime		Type of perishability		Data	Indicator		Solution method	Model type	Case study
		Retailing	Manufacturing	Supply	Consumption	Others	Random	Fixed	Constraints	Objective function		Economic	Environmental			
1	(Yadav et al., 2022)	*	*	*				*	*		Real	*	*	Benders and Lagrange decomposition algorithm		Dairy
2	(Yazdani et al., 2022)			*							Real				Fuzzy	Agriculture
3	(Tirkolaee & Aydin, 2022)	*	*	*	*			*	*		Hypothetical	*	*	FWGP and LP Metric	Probabilistic	-
4	(Shafiee et al., 2020)	*	*	*				*			Real	*	*	GAMS	Robust	Dairy
5	(Chernonog, 2020)	*	*					*		*	Hypothetical			Two-stage optimization	Fuzzy	
6	(Mohebalizadehgashti et al., 2020)	*	*	*	*			*	*	*	Real	*	*	e-constraint	Fuzzy	Meat
7	(M. A. A. Khan et al., 2020)	*		*				*		*	Hypothetical			Mathematical solution method	Stochastic	
8	(Shafiee et al., 2020)			*			*			*	Real	*	*	Augmented e-constraint	Stochastic	Flower industry
9	(Sahebjamnia et al., 2020)			*			*		*		Hypothetical			MOPSP, NSGA II, and MOICA	Stochastic	Orange
10	(Onggo et al., 2019)	*		*				*		*	Hypothetical			Monte Carlo simulation	MILP	
11	(Diabat et al., 2019)	*		*				*	*		Real			Lagrange relaxation	Stochastic	Hospitals
12	(Yavari & Zaker, 2020)	*	*					*		*	Real	*	*	LP-Metrics	Stochastic	Dairy
13	(Accorsi et al., 2019)	*	*					*	*		Hypothetical			Monte Carlo simulation	MLP	
14	(Bottani et al., 2019)			*				*	*		Real			Ant Colony Optimization	Probabilistic	
15	(Darestani & Hemmati, 2019)	*	*	*	*			*	*		Hypothetical	*	*	Multi-criteria decision-making	Stochastic	
16	(Rahbari et al., 2019)	*	*				*		*		Hypothetical			LP-Metrics	MIP	
17	(Deng et al., 2019)	*	*	*	*	*	*		*					LP-Metrics	Stochastic	Avocado
18	(Yavari & Geraeli, 2019)	*	*	*	*		*		*		Real	*	*	YAG	Stochastic	Dairy industry
19	(Jonkman et al., 2019)		*	*				*		*	Real			CPLEM and e-constraint	MILP	Sugar production
20	(Hsu, 2019)	*	*	*			*		*		Real	*	*	Compromise programming	MILP	Grocery
	This research	*	*	*	*		*	*	*	*	Real	*	*	e-constraint	Robust	Dairy

According to the examined papers, the novelties of this study are discussed as follows:

i. Developing a novel multi-objective, multi-period, multi-level, multi-product MILP model to design a perishable product supply chain (PPSC),
ii. Studying the environmental sustainability in PPSC design problem in order to minimize the deterioration rate as much as possible and besides minimizing the total cost and total environmental pollution,
iii. Enhancing the performance of the solution method using the robustness cost,
iv. Evaluating the performance of the model using well-known metrics, and problem instances,
v. Validating the proposed model and solution methods using a real case study in Tehran/Iran.

3-Describing the mathematical model

Increased economic and environmental concerns have forced companies to have a new attitude toward the effects of supply chain design activities on the environment and economy. Nowadays, a challenging task in the food industry is the distribution of perishable products of high quality in the food supply chain. Therefore, designing an environmentally friendly supply chain for perishable products seems necessary due to the expiry date of these products and demand uncertainty. A product passes different stages in its lifecycle management. Each of these stages has its specific features and requires particular activities in order for the organization to be able to gain the highest profit from lifecycle management. The problem under study aims to determine optimal decisions on production, distribution, allocation, cost balance (cost function), and costs of CO_2, CO, HC, and NOX gas emissions (environmental cost function).

The suppliers are animal husbandry centers sending raw material (milk) required by the factory immediately after the order and dairy production centers producing several perishable products and sending them to distribution centers and retailers to meet final customer demand. There is the possibility of inventory shortage due to a failure in sending materials by suppliers. Also, the inventory of raw materials and products is depleted from the warehouse according to the FIFO policy due to the limited lifetime of perishable products. This research considers economic and environmental aspects in decisions related to allocation, routing, and location problems. Generally, perishable product supply chain network design aims to include economic and environmental indicators.

3-1-Model assumptions

A four-echelon multi-product supply chain with several suppliers, a producer, distribution centers, and a target market is considered. The chain is planned for several periods.

- Economic and environmental indicators are considered.
- The proposed model includes multiple periods.
- Various perishable products are considered to design the supply chain network (multi-product).
- The retailers' demand is assumed to be uncertain.
- A fore-echelon supply chain with several suppliers, a manufacturer, distribution centers, and customers is considered.
- Distribution centers intermediate transferring various perishable products from production centers to customers.
- All facilities have a limited capacity in production-inspection centers.
- A flow exists between two consecutive processes, and there is no link between facilities and other related facilities.
- Both random and fixed product lifetimes are considered.
- Perishable products may deteriorate when being transshipped from production centers to distribution centers and from distribution centers to customers.
- In the case of quality and freshness decline, the products are returned from customers to distribution centers and from distribution centers to manufacturers.
- Several vehicles with different capacities are considered.

3-2-Indices, parameters, and variables

Indices, parameters, and variables used in the model are presented in table 2.

Table 2. Indices, parameters, and variables

Indices	
$\boldsymbol{t}$	Time period t (Six periods are considered.)
p	Set of products ($p = 1,2,\dots,P$)
s	Set of suppliers ($s = 1,2,\dots,S$)
r	Set of retailing centers ($r = 1,2,\dots,R$)
$\boldsymbol{k}$	Set of distribution centers ($k = 1,2,\dots,K$)
$\boldsymbol{m}$	Set of materials ($m = 1,2,\dots,M$)
$\boldsymbol{i},\boldsymbol{j}$	Set of routs ($i = 1,2,\dots,I$)
$\boldsymbol{n}$	Number of products ($n = 1,2,\dots,N$)
$\boldsymbol{z}$	Warehouses ($z = 1,2,\dots,Z$)
$\boldsymbol{f}$	Manufacturers ($f = 1,2,\dots,F$)
v	Vehicle type ($v = 1,2,\dots,V$)
$\boldsymbol{w}$	Weight
$\boldsymbol{y}$	Product lifetime
$\boldsymbol{d}$	Price
Parameters	
$\tilde{\omega}$	Fuel consumption cost
FX_k	Fixed cost of inaugurating distribution center k
HF_{mzft}	Cost of holding material m in warehouse z of manufacturer f in period t
FHK_{pzkt}	Cost of holding material m in warehouse z of distribution center k in period t
HR_{pzrt}	Cost of holding material m in warehouse z of retailing center r in period t
VIp_{zkt}	Variable cost in distribution units
PUR_{pfdt}	Cost of purchasing product p from manufacturer f at price d in period t
PUR_{pkdt}	Cost of purchasing product p from distribution center k at price d in period t
PUR_{psdt}	Cost of purchasing product p from supplier s at price d in period t
FCQ_r	Fixed cost of ordering for retailer r
FCQ_k	Fixed cost of ordering for distribution center k
FCQ_f	Fixed cost of ordering for manufacturer f
$XVTC_{pfk}$	Variable cost of transporting a unit of product p from manufacturer f to distribution center k
$XFTC_{pfk}$	Fixed cost of transporting a unit of product p from manufacturer f to distribution center k
$XVTC_{pkr}$	Variable cost of transporting a unit of product p from distribution center k to retailer r
:$XFTC_{pkr}$	Fixed cost of transporting a unit of product p from distribution center k to retailer r
$XVTC_{msf}$	Variable cost of transporting a unit of material m from supplier s to manufacturer f
$XFTC_{msf}$	Fixed cost of transporting a unit of material m from supplier s to manufacturer f
XVP_p	Variable cost per unit of product p
A	Unit lost sales cost (due to deterioration)
ΠP_r	Unit lost sales cost of product p in retailing center r
ΠP_k	Unit lost sales cost of product p in distribution center k
ΠP_f	Unit lost sales cost of product p in manufacturer f
Θ_P	Deterioration level of inventory of product p
CD_f	Cost of unmet demand of manufacturer f
CD_k	Cost of unmet demand of distribution center k
CD_r	Cost of unmet demand of retailer r
LQC_{pr}	Cost of product p in retailing center r
LQC_{pk}	Cost of waste of product p in distribution center k

Table 2. Continued

Parameters	
ODN	Freshness priority of the product (relative importance of the product)
$T\acute{\varepsilon}$	Tax (surcharge percentage) per unit of carbon emission due to production in manufacturers
$T\beta$	Tax (surcharge percentage) per unit of NOx emission due to transportation (of products or material) with vehicle v
$T\alpha$	Tax (surcharge percentage) per unit of CO2 emission due to transportation (of products or material) with vehicle v
$T\gamma$	Tax (surcharge percentage) per unit of HC emission due to transportation (of products or material) with vehicle v
$T\lambda$	Tax (surcharge percentage) per unit of CO emission due to transportation (of products or material) with vehicle v
ASR	Number of material movements between suppliers and manufacturer
ARP	Number of products movements between manufacturer and distribution centers
ARR	Number of products movements between distribution centers and retailers
ETH	Environmental pollution emission volume of manufacturer
$ET_{\gamma vsf}$	HC emission volume due to transportation by vehicle v per unit of load from supplier s to manufacturer f
$ET_{\lambda vsf}$	CO emission volume due to transportation by vehicle v per unit of load from supplier s to manufacturer f
$ET_{\beta vsf}$	NOx emission volume due to transportation by vehicle v per unit of load from supplier s to manufacturer f
$ET_{\alpha vsf}$	CO2 emission volume due to transportation by vehicle v per unit of load from supplier s to manufacturer f
$ET_{\gamma vfk}$	HC emission volume due to transportation by vehicle v per unit of load from manufacturer f to distribution center k
$ET_{\lambda vfk}$	CO emission volume due to transportation by vehicle v per unit of load from manufacturer f to distribution center k
$ET_{\beta vfk}$	NOx emission volume due to transportation by vehicle v per unit of load from manufacturer f to distribution center k
$ET_{\alpha vfk}$	CO2 emission volume due to transportation by vehicle v per unit of load from manufacturer f to distribution center k
$ET_{\gamma vkr}$	HC emission volume due to transportation by vehicle v per unit of load from distribution center k to retailer r
$ET_{\lambda vkr}$	CO emission volume due to transportation by vehicle v per unit of load from distribution center k to retailer r
$ET_{\beta vkr}$	NOx emission volume due to transportation by vehicle v per unit of load from distribution center k to retailer r
$ET_{\alpha vkr}$	CO2 emission volume due to transportation by vehicle v per unit of load from distribution center k to retailer r
$ET_{\gamma vkf}$	HC emission volume due to transportation by vehicle v per unit of load from distribution center k to manufacturer f
$ET_{\lambda vkf}$	CO emission volume due to transportation by vehicle v per unit of load from distribution center k to manufacturer f
$ET_{\beta vkf}$	NOx emission volume due to transportation by vehicle v per unit of load from distribution center k to manufacturer f
$ET_{\alpha vkf}$	CO2 emission volume due to transportation by vehicle v per unit of load from distribution center k to manufacturer f
$ET_{\acute{\varepsilon}}$	Carbon emission volume due to production in manufacturer
DE_{sf}	Distance from supplier s to manufacturer f
DE_{fk}	Distance from manufacturer f to distribution center k
DE_{kr}	Distance from distribution center k to retailer r
$\boldsymbol{\alpha}'_{n}$	Wastage percentage of product n by the manufacturer
αF	Weighted factor of response to demands
pb	Cost of delay in the delivery of an order
TAB_{P}	Weight of product p
HIp_{f}	Processing time per unit of product p in manufacturer f

Table 2. Continued

Parameters	
CAP_f	Annual production capacity of manufacturer f
CAP_k	Holding capacity of distribution center k
CAP_r	Holding capacity of retailer r
$QDPN_{nr}$	Predicted demand of retailer r for product p
$QDPN_{nk}$	Predicted demand of distribution center k for product p
XV_{vsf}	Capacity of vehicle v to carry material from the supplier s to manufacturer f
XV_{vfk}	Capacity of vehicle v to carry material from manufacturer f to distribution center k
XV_{vkr}	Capacity of vehicle v to carry material from distribution center k to retailer r
MD_{krm}	Average demand of distribution center k and retailer r for product p
RHS_{sf}	Auxiliary variable to calculate the number of movements between supplier s and manufacturer f
RHS_{fk}	Auxiliary variable to calculate the number of movements between manufacturer f and distribution center k
RHS_{kr}	Auxiliary variable to calculate the number of movements between distribution center k and retailer r
$\boldsymbol{\alpha'}$	Material usage factor
M	A large number
CAP_S	Supplying capacity of material m by suppliers
Bj	Percentage of returned products in each level of the supply chain
AR_{sf}	If supplier s is available to supply material m for factory (parameter)
XV_v	Capacity of vehicle v
Decision variables	
$\boldsymbol{\omega}_{Pfkvt}$	Purchased quantity of product p (or gross quantity of the order by the distribution center) from manufacturer f to distribution center k by vehicle v in period t
$\boldsymbol{\omega}_{pkrvt}$	Purchased quantity of product p (or gross quantity of the order by the retailer) from distribution center k to retailer r by vehicle v in period t
$\boldsymbol{\omega}_{msfvt}$	Purchased quantity of material m (or gross quantity of the order by the manufacturer) from supplier s to manufacturer f by vehicle v in period t
SK	1 if distribution center k is opened by a capacity of h, 0 otherwise
QPN_n'	Total produced quantity of products
$\boldsymbol{\xi}_v$	Fuel consumed by vehicle v in a unit distance
$\boldsymbol{\varphi}_{vsft}$	1 if vehicle v travels the distance from supplier s to manufacturer f in period t, 0 otherwise
$\boldsymbol{\varphi}_{vfkt}$	1 if vehicle v travels the distance from manufacturer f to distribution center k in period t, 0 otherwise
θ_{vkrt}	1 if vehicle v travels the distance from distribution center k to retailer r in period t, 0 otherwise
$\mathbf{US_S}$	Number of purchases from supplier s
$\mathbf{US_k}$	Number of purchases from distribution center k
$\mathbf{US_f}$	Number of purchases from manufacturer f
IF_{pzft}	Inventory level of product p in warehouse z of manufacturer f at the beginning of period t=1
IK_{pzkt}	Inventory level of product p in warehouse z of distribution center k at the beginning of period t=1
IR_{pzrt}	Inventory level of product p in warehouse z of retailer r at the beginning of period t=1
ISM	Inventory level of materials in warehouse z of manufacturer f at the beginning of period t=1
λ_{fpt}	Quantity of product p in manufacturer f perished in period t
λ_{kpt}	Quantity of product p in distribution center k perished in period t
λ_{rpt}	Quantity of product p of retailer r perished in period t
QPN_{mtsf}	Quantity of material m sent by supplier s to manufacturer f in period t under scenario s
QPN_{ptfk}	Quantity of product p sent by manufacturer f to distribution center k in period t under scenario s
QPN_{ptkr}	Quantity of product p sent by distribution center k to retailer r in period t under scenario s

Table 2. Continued

Decision variables	
QPN_{ptrk}	Quantity of product p returned from retailer r to distribution center k due to perishing in period t under scenario s
QPN_{ptkf}	Quantity of product p returned from distribution center k to manufacturer f due to perishing in period t under scenario s
WF_r	Quantity of product p returned from distribution center k due to perishing
QD_f	Quantity of unmet demand of manufacturer f
QD_k	Quantity of unmet demand of distribution center k
QD_r	Quantity of unmet demand of retailer r
DQP_f	Demand quantity from manufacturer f
DQP_s	Demand quantity from supplier s
DQP_r	Demand quantity from retailer r
DO_{tn}	Time to send the order
RI	Time to request the order
FRI	Freshness level for delivery requests (distribution centers, manufacturers, and suppliers)
SKO_{ktr}	1 if distribution center k serves retailer r in period t, 0 otherwise
SKO_{kmtf}	1 if distribution center k is allocated to manufacturer for material m in period t, 0 otherwise
PL_{pvt}	Number of pallets required for carrying product p by vehicle v in period t
SI	Time of delivering the order to the customer
BQ_{sf}	Binary variable, used when a material is sent from supplier s to manufacturer f
BQ_{fk}	Binary variable, used when product p is sent from manufacturer f to distribution center k
BQ_{kr}	Binary variable, used when product p is sent from distribution center k to retailer r
ak	1 if distribution supplier s disrupts scenario s, 0 otherwise

The first objective function is formulated in equation (1). The model includes the costs of fuel consumption, unmet demand, holding, transportation, perishability, environmental costs, the costs of establishing distribution centers, and holding costs deducted from the product freshness. The economic goal is to minimize this objective function.

$$\begin{aligned} MinF_1 = \tilde{\omega} & \sum_s \sum_f \sum_k \sum_r \varepsilon_v . \varphi_{vsfkr} DE_{sfkr} \\ & + \sum_s \sum_f \sum_k \sum_r \xi_v . DE_{sfkr} \\ & + \sum_s \sum_f \sum_k PUR_{sfk} . \omega_{sfk} + \sum_f \sum_k \sum_r FCQ_{fkr} . US_{fkr} \\ & + \sum_f \sum_k \sum_r CD_{fkr} . QD_{fkr} \\ & + \sum_f \sum_k \sum_r LQC_{fkr} . \lambda_{fkr} . \pi_{fkr} + [\sum_k \sum_r A . WF_{kr} \\ & + N_{vt} \sum_s \sum_f \sum_k \sum_r [(QPN_{ptsfkr} . XVTC_{sfkr}) + XFTC_{sfkr}] \\ & + [SK . (QPN_{ptfk} . XVTC_{pk}) + XFTC_{pk}] + \sum_s \sum_f \sum_k \omega . T\beta . T\lambda . T\gamma . T\alpha \\ & + ET\varepsilon' . T\varepsilon' QPN' + SK . T\beta . T\gamma . T\lambda . T\alpha . \omega_{pfkv} + FX_k . SK \\ & + \tilde{\omega} . \varphi_v . De . sk . \xi_v + HR_{pzrt} . IR_{pzkt} + IK_{pzkt} + (FHK_{pzkt} + VI_{pzkt}) \\ & + HF_{pzft} . ISM \\ & - \sum_s \sum_f \sum_k FRI . QP\acute{N}_n + \sum_f \sum_k \sum_r ODN . FRI . DQP_{fkr} \end{aligned} \tag{1}$$

The second objective function, formulated by equation (2), evaluates the environmental pollution emission of CO_2, CO, HC, and NO_x, as well as fuel consumption. The environmental goal is to minimize this objective function.

$$MinF_2 = \sum_f \sum_k \sum_r \omega . WF_{kr} . LQC_{fkr} + \sum_\alpha \sum_\beta \sum_\lambda \sum_\gamma ASR . \omega_{psfv} . DE_{sf} . ET_{\alpha\beta\lambda\gamma} + \sum_\alpha \sum_\beta \sum_\lambda \sum_\gamma ARP . \omega_{pfkv} . DE_{fk} . ET_{\alpha\beta\lambda\gamma} + \sum_\alpha \sum_\beta \sum_\lambda \sum_\gamma ARR . \omega_{pkrv} . DE_{kr} . ET_{\alpha\beta\lambda\gamma} \quad (2)$$

The proposed model involves the following constraints.

$$\sum_\alpha \sum_\beta \sum_\lambda \sum_\gamma ET_{vsf} . \omega_{psfv} . BQ_{sf} \leq \sum ET\alpha\beta\lambda\gamma \quad (3)$$
$$\sum_\alpha \sum_\beta \sum_\lambda \sum_\gamma ET_{vfk} . \omega_{pkfv} . BQ_{fk} \leq \sum ET\alpha\beta\lambda\gamma \quad (4)$$
$$\sum_\alpha \sum_\beta \sum_\lambda \sum_\gamma ET_{vkr} . \omega_{pkrv} . BQ_{kr} \leq \sum ET\alpha\beta\lambda\gamma \quad (5)$$
$$\sum_f \sum_k \sum_r XV_{vfk} - 1 \leq \sum_f \sum_k \sum_r XV_{vfk} \leq \sum_f \sum_k \sum_r XV_{vfk} \quad (6)$$
$$\sum SK \leq 1 \quad (7)$$
$$QPN'_n \geq QPN'_n - QPN'_n . \alpha' \quad (8)$$
$$QPN'_n - QPN'_n . \alpha' n \geq \sum_k \sum_r QPN_{pt} - \sum_k \sum_r \theta_p \quad (9)$$
$$HI_{pf} \cdot QPN_{ptfk} \leq \sum_k CAP_k . SK \quad (10)$$
$$HI_{pf} \cdot QPN_{ptfk} \leq \sum_f \sum_k \sum_r CAP_{fkr} \quad (11)$$
$$\sum_f AR_{sf} \leq (1 - a_k^s) CAP_s \quad (12)$$
$$\mathrm{QDPN_{rp}} + \mathrm{QDPN_{kp}} = \left[\left(\omega_{\mathrm{p.st.kvt}} + \omega_{\mathrm{p.k.rv}}\right) - \left(\lambda_{\mathrm{kpt}} + \lambda_{\mathrm{rpt}}\right) . (\mathrm{WF_k} + \mathrm{WF_r})\right] \quad (13)$$
$$\mathrm{IF}_{pzf} + \sum_k \sum_r \omega_{Pfkv} = \sum_k \sum_r QPN_{ptkr} \cdot SKO_{ktr} \quad (14)$$
$$\sum_k \sum_r \omega_{Pv} \leq \sum_k \sum_r CAP_{kr} \cdot SK \quad (15)$$
$$\sum_f \sum_k \sum_r \omega_{pv} \leq \sum_f \sum_k \sum_r XV_v \quad (16)$$
$$\sum_f \sum_k \sum_r DQP_{fkr} \cdot \varphi_v \leq XV_v \cdot VF_{ij} \quad (17)$$
$$SKO_{tr} \leq 1 \quad (18)$$
$$\theta_{vkrt} \leq 1 \quad (19)$$
$$QPN_{ptfk} \cdot SKO_{kmtf} \geq \sum_k MD_{krm} SKO_{tr} \quad (20)$$
$$QPN_{ptfk} \geq \sum_k \omega_{Pkrvt} \quad (21)$$
$$QPN'_n - QPN'_n . \alpha' n \geq \sum_k \sum_r MD_{krm} . \mathrm{SKO_{tr}} \quad (22)$$
$$\sum_k \sum_r MD_{krm} . \mathrm{SKO_{tr}} \leq \mathrm{SK} \cdot \mathrm{CAP_k} \quad (23)$$
$$\mathrm{QPN'_n} = \sum \mathrm{QDPN_{nr}} + \mathrm{QDPN_{nk}} - (\mathrm{QD_f} + \mathrm{QD_k}) \quad (24)$$
$$\mathrm{QPN'_n} \geq \sum_r \mathrm{QDPN_{nr}} - \mathrm{QD_r} \quad (25)$$
$$\sum_s \mathrm{QPN_{ptsf}} \leq \mathrm{CAP_s} \quad (26)$$
$$\frac{\sum_f QPN_{ptsf}}{XV_v} + RHS_{sf} = ASR \quad (27)$$
$$\frac{\sum_k QPN_{ptfk}}{XV_v} + RHS_{fk} = ASP \quad (28)$$
$$\frac{\sum_r QPN_{ptkr}}{XV_v} + RHS_{kr} = ARR \quad (29)$$
$$ASR + RHS_{sf} \geq 0 \quad (30)$$
$$ASp + RHS_{fk} \geq 0 \quad (31)$$
$$ASR + RHS_{kr} \geq 0 \quad (32)$$
$$\sum_f \sum_k \sum_r QPN_{ptsf} = \sum_f \sum_k \sum_r DQP_{Skr} \quad (33)$$
$$\sum_k SK = 1 \quad (34)$$
$$SKO_{ktr} \leq SK \quad (35)$$

$$SKO_{ktr} \leq QPN_{ptkr} \leq SKO_{ktr} \cdot M \quad (36)$$
$$ISM_t = ISM_{t-1} + \sum_f \omega_{pskv} - \sum_f \alpha' \cdot QPN'_n \quad (37)$$
$$IF_{zpzf,t} = (1-\theta_p) IF_{pzf,t-1} + QPN'_n - \sum_f QPN_{ptfk} \quad (38)$$
$$Ik_{pzk} = Ik_{pzk,t-1} + \sum_f \omega_{Pfkvt} - \sum_k QPN_{ptkr} \quad (39)$$
$$\sum_f \sum_k \sum_r DQP_{fkr} - \sum_f \sum_k \sum_r \omega_{Pfkvt} - \sum_f \sum_k \sum_r WF = \sum_f \sum_k \sum_r QD_{fkr} \quad (40)$$
$$\sum_f \sum_k \sum_r \omega_{pv} \leq \sum_f \sum_k \sum_r \varphi_v . \sum_f \sum_k \sum_r XVM_{vm} \quad (41)$$
$$\sum_s \sum_f \sum_k \sum_r Ii^{t.y-1} \leq \sum_s \sum_f \sum_k \sum_r Ii^y \quad (42)$$
$$\sum_f \sum_k \sum_r (XFTC_{fkr} + XFTC_{fkr}).(1 - Ii_r^y) \leq \sum_f \sum_k \sum_r (\mathrm{Ir}_{pzrt} + \omega_{pkrv}) - QPN_{ptkr} + 1 \quad (43)$$
$$QPN_{ptrk} = 0 \quad (44)$$
$$QPN_{ptkf} = 0 \quad (45)$$
$$QPN_{ptkf} + QPN_{ptrk} \leq B_j . \sum_k \sum_r QPN_{pt} \quad (46)$$
$$(\mathrm{SI} \leq \mathrm{RI}) \quad (47)$$
$$Ii_r^y, Ii_f^y, Ii_s^y, \varphi_{vk.r}, \varphi_{vfk}, \varphi_{vsf}, SKO_{ktr}, SKO_{kmtf}\ are\ binary \quad (48)$$
$$\text{Other variables} \geq 0 \quad (49)$$

Equations (3) to (5) represent CO_2, CO, HC, and NOX emissions (developed by this research). In equation (6), the total order of product p transported by vehicle v in period t is divided by the weight of product p (TAB p) to obtain the number of vehicles of type v required to carry product p in period t (Modified article by Szvar & sepehri, 2020). Equation (7) ensures that a distribution center cannot be selected for more than its capacity in a location (Zhalechian et al., 2016). Equations (8) and (9) represent the constraint on flow balance in the manufacturer, distribution center, and retailer (developed by this research). Equations (10) and (11) and (12) show the order in which the capacity constraints of suppliers, manufacturers, and retailers are imposed (developed by this research). According to equation (13), the demand quantity of the distribution center and retailer equals the quantity of product sent to the distribution centers and retailers in each period minus the met demand and quantity of perished products (developed by this research). Equation (14) shows inventory balance in the distribution center k and retailer (Modified articl by Aggarwal, 2018). Equation (15) indicates that the quantity of the products sent to retailers and distribution centers should be according to their capacity (Darestani & Hemmati, 2019).

Equation (16) shows the capacity of each vehicle (Modified articl by Aggarwal, 2018 and Zandkarimkhani et al., 2020). Equation (17) ensures that the capacity of vehicles can be appropriate to carry the demands (Bakhsh & Tawhidi, 2020). Equation (18) shows that each retailer can be supplied only by one distribution center(Modified articl by Tavakkoli Moghaddam et al., 2019). Equation (19) shows that each retailer is visited only once, meaning that the distribution center meets the demand of the retailer in each period at most one visit(Modified articl by Tavakkoli Moghaddam et al., 2019). Equation (20) guarantees that the average demand of distribution centers for all products is met. Equation (21) states that the output of a product from a distribution center should be less than or equal to its input (Modified articl by (Yavari & Geraeli, 2019). Equation (22) expresses that the average customer demand is met (Kalbadi & Barkinejad., 2020). Equation (23) is to specify the capacity constraint of distribution centers and retailers (Kalbadi & Barkinejad., 2020). Equations (24), Komasi & Hashem., 2020) and (25) are the demand balance and average so that the demand of retailer r for product m equals the total quantity sent from distribution centers to the retailer (equations (25) developed by this research). Equation (26) dictates that the quantity purchased from each supplier should not exceed its capacity. Equations (27) to (32) specify the number of movements between suppliers, manufacturers, distribution centers, and retailers to carry products and materials (Komasi & Hashem., 2020). Equations (33), Modified articl by Yavari & Geraeli, 2019) and (34), Zhalechian et al., 2016) state that the demand in each level of the supply chain for each product in each period should be responded to in the same period completely. Equation (35) declares that a distribution center can be assigned to customers if it has already been established (Mahmoudi et al., n.d.). In equation (36), products flow from a distribution center to a customer if the distribution center is assigned to the customer (Mahmoudi et al., n.d.). Equation (37) is the initial inventory balance in the distribution center (Mahmoudi et al., n.d.). Equation (38) shows the quantity of product n in the manufacturer in period t (Modified articl by (Yavari & Geraeli, 2019). Equation (39) is related to the quantity of product n in distribution center k in period t (Darestani & Hemmati, 2019). Equation (40) specifies the unmet demand of retailers, distribution centers, and manufacturers (developed by this research). Equation (41) shows transportation capacity for the flow of products between different centers(Modified articl by Tavakkoli Moghaddam et al., 2019). In equation (42), the auxiliary variable associated with the product with the lifetime of y-1 takes a value of 1 if the value of the auxiliary variable corresponding to the product with the lifetime of y is 1. This means the inventory of a product with a lifetime of y-1 is used to meet the demand whenever the inventory level of the product with a lifetime of y is not adequate to satisfy the demand (Modified articl by Zandkarimkhani et al., 2020). Equation (43) is used to prevent all quantitative variables from being equal to 1 and states that if the available inventory of the product of lifetime y-1 is not used to meet the demand, the positivity of the right-hand side of this constraint causes the auxiliary variable related to the product of lifetime y-1 to be zero (Modified articl by F. J. Khan & Yacoubi., 2016). Equations (44) and (45) dictate that no product is returned from retailers to distribution centers and from distribution centers to manufacturers before the end of the product lifetime (Azami et al., 2017). Equation (46) represents the return of perished products to distribution centers and manufacturers (Modified articl by Darestani & Hemmati, 2019). Equation (47) shows the freshness of products (developed by this research). Equations (48) and (49) characterize binary and nonnegative variables.

3-3-Robust approach

In this research the robustness approach proposed by Aghezzaf (2010) was used, following the method suggested by Mulvey et al. (1995). The objective function is written as follows (Mulvey & Ruszczyński, 1995)(Aghezzaf et al., 2010).

$$minz = \eta . \max(\xi_s - \xi_s^*) + \lambda . \sum_{s \epsilon S} P_s . \xi_s \qquad (50)$$

In the above equation, ξ_s denotes the optimal cost in scenario S, and ξ_s^* stands for the optimal value obtained by the deterministic solution of the model under scenario s. Also, η and λ are parameters determined by the decision-maker. The term $\max(\xi_s - \xi_s^*)$ represents maximum variability, and the expression $\sum_{s \epsilon S} P_s . \xi_s$ indicates the expected cost. A tradeoff can be performed between these terms by considering different values for η and λ by the decision-maker. Increasing the value of η leads to a lower variability and higher expected cost, and vice versa. According to the above discussions, the research process can be presented as follows.

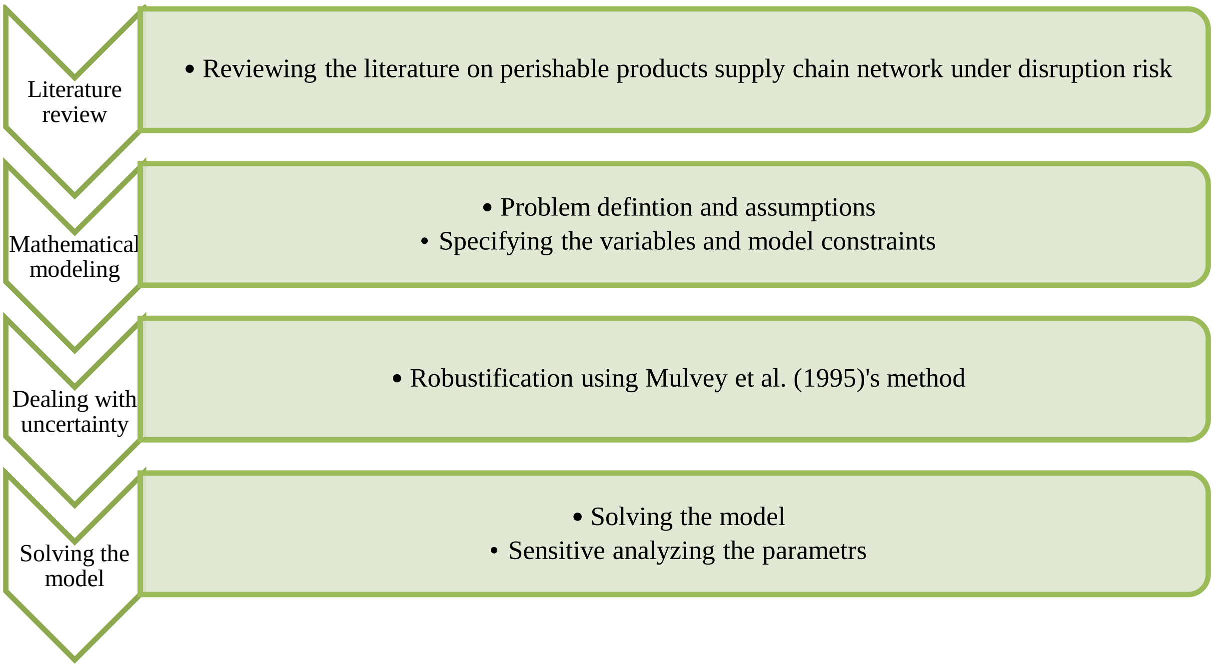


Fig 2. Research process

3-4-Solution method

The model developed in the previous section specifies the studied problem but is not solvable. To solve the problem, we need a comprehensive model by combining time periods. In the robust model of Mulvey et al. (1995), a combination of events that occur from the first period to the last one builds a scenario. The probability of each scenario equals the Cartesian multiplication of events. To formulate the problem, we should introduce new parameters.

$S^t = \Omega^1 \times \Omega^2 \times \ldots . \times \Omega^t$: A set of potential events to period t

s^0: The starting point

$path_{s^t} = \{s^0 . s^1 . \ldots . s^t\}$: A set of paths, subsets of path s^t

$s^t \in S^t = (\omega^0 \times \omega^1 \times \ldots . \times \omega^t)$: A path of events from the starting point to a point in period t

s^T: A path of events from the starting point to a point at the end of period T, which completes a scenario

$P(S^t = s^t) = \prod_{t=1}^{t} p(\Omega^t = \omega^t)$: The probability to which the order of events passes through path s^t

The perishable supply chain network design problem is an NP-Hard problem that cannot be solved by exact solution methods. On the other hand, the model designed in this paper is a multi-objective mixed integer linear programming model. In this model, due to the presence of multiple objective functions, there is no solution optimizing all objectives simultaneously. Thus, decision-makers seek a preferred solution. Accordingly, in multi-objective mathematical programming models, the optimality is replaced by efficiency or Pareto optimality. A Pareto optimal solution is a solution that none of its corresponding objective function values can improve unless by worsening at least one of the other objectives(Aghaei et al., 2011). One of the best approaches to solving multi-objective problems is the ε-constraint method, in which one of the objective functions is optimized while the others are transformed into constraints. In this research, the augmented ε-constraint method proposed by Mavrotas. (2009) is used to deal with the multi-objective nature of the problem. The augmented ε-constraint method has advantages over the simple ε-constraint method because the augmented version reduces the running time by eliminating redundant iterations and not choosing weakly Pareto solutions.

More clearly, in this method, the algorithm quickly exits nested loops that lead to non-feasible solutions(Mavrotas, 2009).

In the solution algorithm of this research, first, each of the two objective functions is considered the main objective function, and optimal solutions are obtained. Now, considering the economic objective function as the main objective function, the best possible solution for this function and the worst solution for the environmental objective function are obtained. Then, the environmental objective function is considered the main objective, and the model is solved to get the best possible solution to this function. Accordingly, the range of the environmental objective function is obtained. Then, the economic objective function is assumed to be the main objective function, and the range of the environmental objective function is divided into g_N points. Then, the problem is solved at least g_N times, and a set of efficient and feasible solutions is obtained. The solution corresponding to the best value of the objective function is chosen as the optimal solution. The following equation represents the general model of the algorithm.

$$\max Q(x) + eps.(s_N/r_N) \tag{51}$$

st:

$x \in S$

$N(x) - s_N = e_N$

where $e_N = lb_N + (i_N + r_N)/g_N$.

In this equation, lb_N is the lower bound of the objective function N, S is the feasible region, g_N is the number of grid points, r_N is the range of the objective function N, eps is an infinitesimal, and i_N is the counter. The e-constrained method has several advantages over the weighting method:

- For linear problems, the weighting method is applied to the original feasible region and results to a corner solution (extreme solution), thus generating only efficient extreme solutions. On the contrary, the ε-constraint method alters the original feasible region and is able to produce non-extreme efficient solutions. As a consequence, with the weighting method we can spend a lot of runs that are redundant in the sense that there can be a lot of combination of weights that result in the same efficient extreme solution. On the other hand, with the ε-constraint we can exploit almost every run to produce a different efficient solution, thus obtaining a richer representation of the efficient set.
- In the weighting method the scaling of the objective functions has strong influence in the obtained results. Therefore, we need to scale the objective functions to a common scale before forming the weighted sum. In the e-constrained method this is not necessary.
- An additional advantage of the ε-constraint method is that we can control the number of the generated efficient solutions by properly adjusting the number of grid points in each one of the objective function ranges. Also, we can obtain exact Pareto solutions by means of this algorithm instead of approximated solutions.

4-Results

The assumptions of the designed model were stated based on the features of the dairy industry. A dairy company with ten distribution centers, eight locations as candidates for establishing the manufacturing center, and five locations as candidates for constructing a warehouse are considered. The CPLEX solver with a time limitation of 3000 seconds is used to solve the model. Table 3 shows the summarized results. All calculations were performed using a PC with a corei7 2.27 GHz processor and internal memory of 4GB.

Table 3. Model solution results

Location and number of distribution center	Freshness level of the product	Total perish rate of the supply chain
Center 1	0.92	0.141
Center 2	0.68	
Center 3	1	
Center 4	0.96	
Center 5	0.47	
Center 6	0.61	
Center 7	0.96	
Center 8	0.84	
Center 9	0.48	
Center 10	1	

As described before, the augmented ε-constraint method is used for this case study. The first stage of this method is to select the main objective function, which is the first one here. The model is solved by applying different values of ε, and the Pareto solutions are presented in the following tables. Then, the first problem in the proposed models is selected, and the Pareto fronts of each model for the first problem are described step by step, including the payoff tables, the values of ε, and Pareto fronts for deterministic and robust state with an uncertainty level of 0.5.

Table 4. The payoffs of deterministic and robust problems

Problem type	Objective functions	Objective nature	Optimal value of the first objective	Optimal value of the second objective
Deterministic problem	First	Minimization	3451641	3354861
	Second	Minimization	1240	1148
Robust problem with uncertainty level of 0.5	First	Minimization	3652584	3569547
	Second	Minimization	1246	1196

In the next step, the range of the secondary objective function (second objective function) is divided into six equal intervals. The results of the breakpoints (the value of ε) for the second objective function, transformed into a constraint, are presented in the following table for deterministic and robust problems.

Table 5. The value of ε obtained for deterministic and robust models

Problem		Breakpoints					
		0	1	2	3	4	5
Deterministic problem	Second	1952	1657	1863	2067	1772	1977
Robust problem with uncertainty level of 0.5	Second	1990	1794	1891	2108	1884	2060

Finally, the problem was solved as a single objective model by substituting the obtained values and using the augmented ε-constraint method. The results for six Pareto efficient points are presented in the table below.

Table 6. Pareto efficient solutions to the model

Pareto solution	Deterministic problem		Robust problem with uncertainty level of 0.5	
	Value of the first objective function	Value of the second objective function	Value of the first objective function	Value of the second objective function
1	1320142	2824	1332547	2884
2	1374216	3022	1596239	3124
3	1486238	3241	1620381	3284
4	1601653	3482	1892362	3472
5	1798274	3621	1770764	3591
6	2054185	3714	2173711	3684

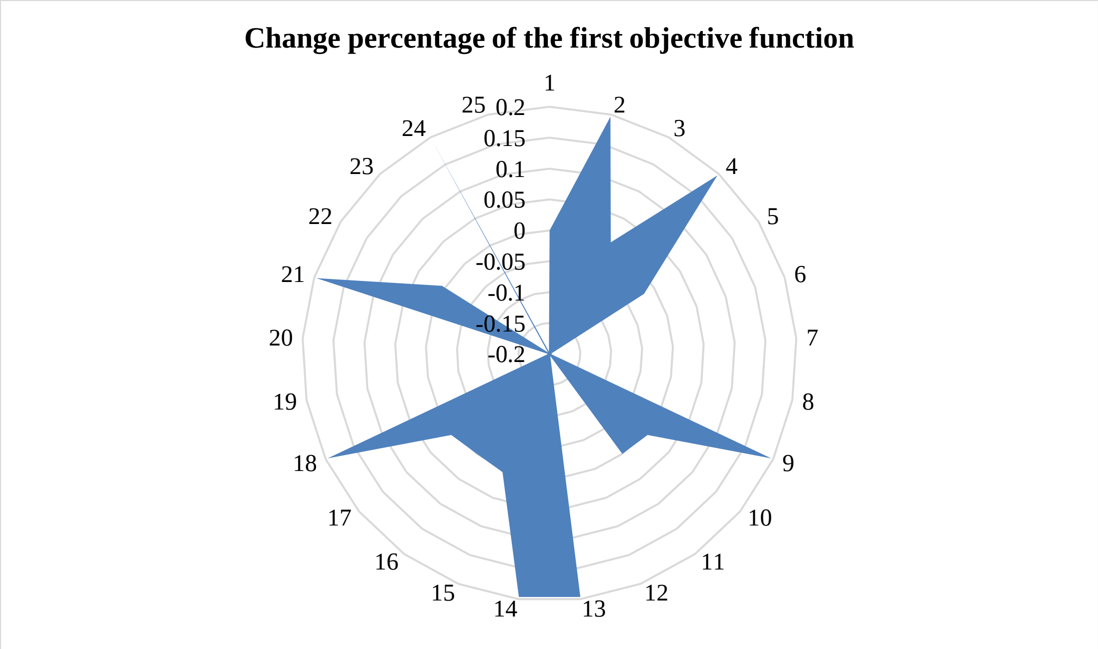
According to the results in the above tables, Pareto fronts in deterministic and robust problems are slightly different, but the equation obtained for objective functions based on the Pareto front is the same and indicates the relationship between the objectives. This relationship between the problem objectives can be attributed to the dependency between the uncertainty parameters used in the two objective functions.

Then, a sensitivity analysis of one of the model parameters, i.e., demand, is conducted. For this purpose, 15 trials are designed in which a change in demand by 20% at five different levels is considered. The results are presented in the following figure and table.

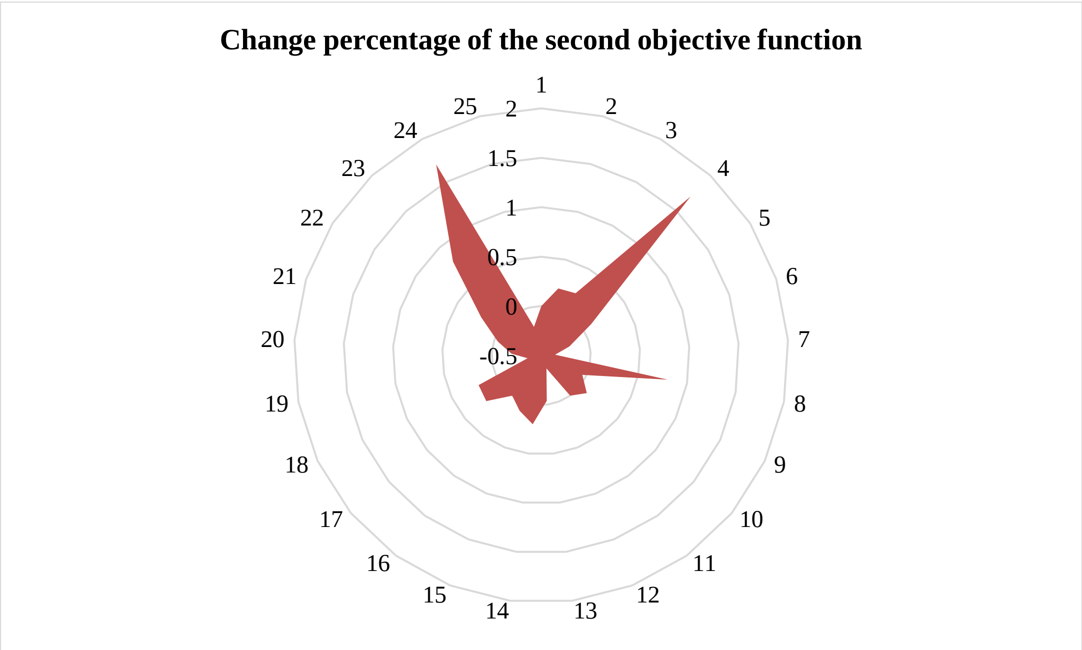
Table 7. Results of demand sensitivity analysis

Trial	Demand	Uncertainty level	Change percentage of the first objective function	Change percentage of the second objective function
1	Unchanged	0.6	0	0
2	Increased	0.7	0.196	0.2
3	Unchanged	1	0.005	0.220
4	Increased	0.8	0.196	1.705
5	Unchanged	0.9	-0.018	0.097
6	Decreased	0.6	-0.196	-0.2
7	Decreased	0.7	-0.196	-0.36
8	Decreased	1	-0.196	0.803
9	Increased	0.8	0.196	-0.04
10	Unchanged	0.9	0.005	0.0976
11	Increased	0.6	0	0
12	Decreased	0.7	-0.196	-0.36
13	Increased	1	0.196	-0.04
14	Increased	0.8	0.196	0.2
15	Decreased	0.9	0.005	0.098

As observed, the change percentage in the objective functions is in line with the changes in input parameters (demand and uncertainty level). For example, consider the demand decrease at the confidence level of 0.7 in row 7. As a result of this trial, a decrease occurs in the first objective function by 19% and the second objective function by 36%.



(a)



(b)

Fig 3. Changes in the objective functions due to demand changes

In this section, the behavior of the objective functions relative to the changes in the product lifetime is assessed. For this purpose, we solve the model for different values of this parameter while fixing other parameters, and the results are assessed. Figure 3 represents the results of the sensitivity analysis of the objective functions relative to the product lifetime. The sensitivity analysis for the product lifetime of 2-5 days shows a 20% and 30% decrease in the value of the first and second objective functions, respectively.

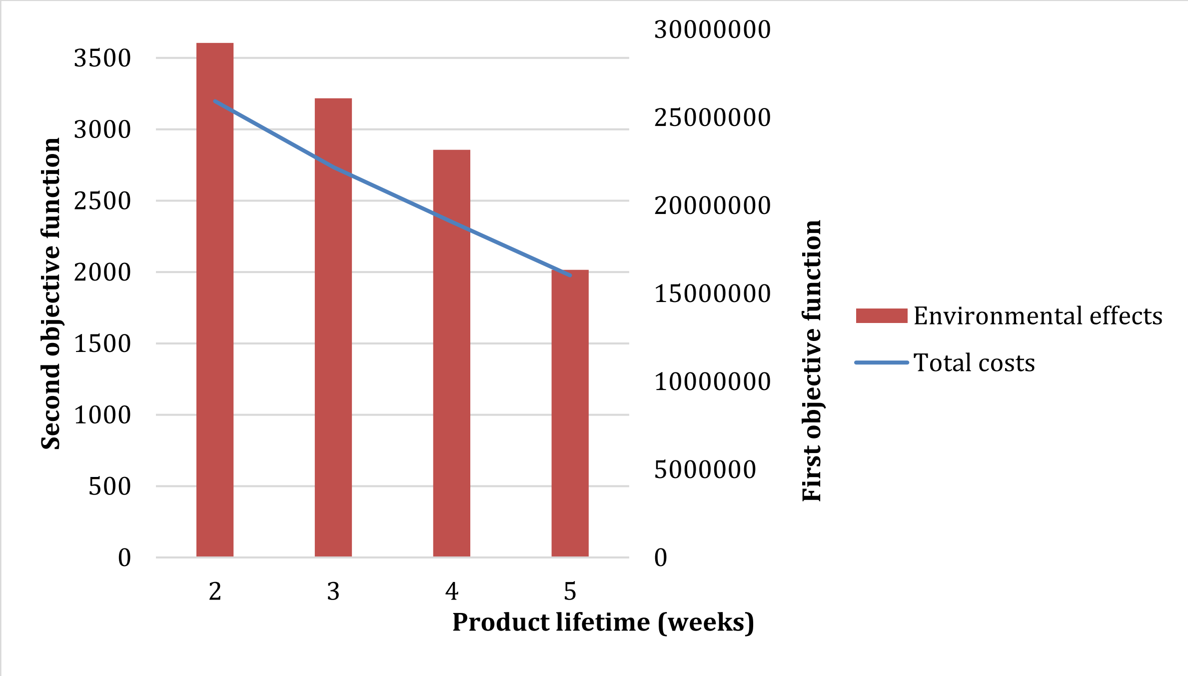


Fig 4. Changes in objective functions versus product lifetime

To assess the efficiency of the scenario path model utilized to deal with uncertainty, we use the relative value of the multi-stage stochastic approach (RVMSA) index. This index calculates the difference percentage of the objective function in the deterministic and stochastic models. The objective function in the deterministic model is calculated by substituting the mathematical expectation for uncertain parameters in the formula. Therefore, we use $E[\phi_m^t(s^T)]$ instead of $\phi_m^t(s^T)$ and $E\left[\mathrm{DP}_{jp}^t(s^T)\right]$ instead of $\mathrm{DP}_{jp}^t(s^T)$ in the objective function.

$$RVMSA = \frac{Q^{STO} - Q^{DET}}{Q^{DET}} = \frac{374584 - 368421}{368421} = 0.017 \tag{52}$$

The results indicate that the use of the stochastic model improves the objective function by 0.017%, and the stochastic model is more efficient compared with the deterministic model.

Also, to assess the validity of the results, we use the extreme condition method. In this method, a very large or very small value is assigned to problem parameters, and the behavior of the model is observed (Sterman, 2000). Accordingly, after solving the model, an unreasonably very large number, 100 times the ordinary transportation cost, is assigned for transportation costs between some manufacturers and retailers. It is observed that the product exchange between these parts of the supply chain is removed. In addition, the total profit of the supply chain network increases due to a decrease in the number of available paths having a reasonable cost. Then, changes are imposed in various parameters to observe the associated effects.

Table 8. Changes in the first and second objective functions

θ_1	θ_3	Satisfaction degree of the first objective	Satisfaction degree of the second objective
0.9	0.1	0.914	0.158
0.7	0.3	0.893	0.438
0.5	0.5	0.636	0.936
0.3	0.7	0.605	0.977
0.1	0.9	0.588	0.990

The comparative results are presented in figure 5 for better visibility.

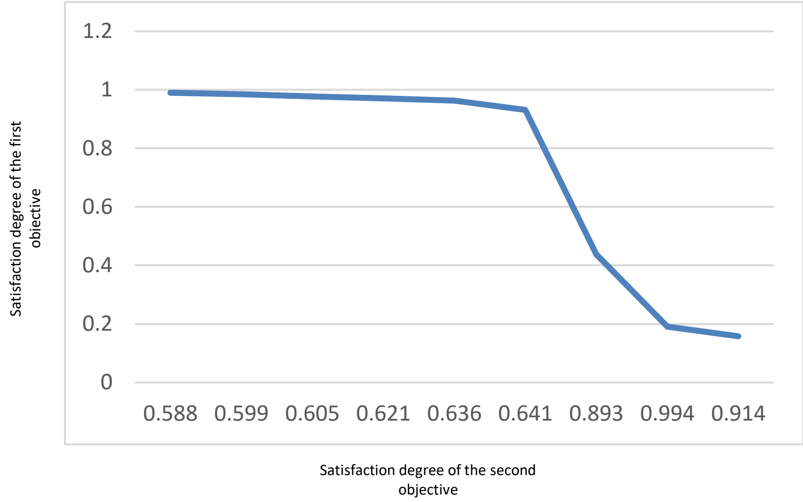


Fig 5. Relative changes in the satisfaction degree of the first and second objective functions

The robustification approach includes two main parts. The first part decreases maximum variability meaning that the maximum variability of solutions is expected to decrease by increasing the coefficient of the first part. To assess this matter, we impose some changes in the coefficient of the second objective function. As this coefficient increases, the ratio of the maximum variability to total changes decreases. Indeed, the expected value increases when this coefficient rises, and the maximum variability is lower. Note that if only the expected value is considered, the risk-aversion of the studied supply chain's managers is ignored. In this approach, managers are enabled to perform a trade-off between the expected value and maximum variability based on their subjectivities.

5-Conclusions

Considering financial challenges faced by Iranian firms, as well as shortages associated with the environmental dimension of development, it is necessary to observe these issues in designing different dimensions of businesses. In the traditional viewpoints, only financial and economic dimensions of problems were taken into account, but in two recent decades, the green concept, i.e., considering environmental issues, was arisen due to new environmental conditions (increasing environmental pollution). One of the most important areas in which environmental issues are relevant besides economic issues is supply chain network design, which has recently received a great deal of attention from researchers. In this regard, dairy supply chains are a notable sector related to perishable products because the materials and products of this chain are greatly perishable with a short lifetime. Therefore, due to the importance and criticality of the issue, this research addressed the supply chain network design for perishable products in the dairy industry. This research proposed a multi-objective mathematical model in which the first objective minimizes total costs and the second one minimizes environmental effects. Due to the uncertain nature of the problem and some parameters, a robust optimization approach was used, and the augmented ε-constraint method was employed to solve the model.

5-1-Managerial implications

The results indicated that the use of robust models could be helpful for managers to decide in uncertain markets to optimize material flow in producing dairy products. Also, product lifetime was found to be an important factor in the supply chain costs. Increasing the product lifetime can reduce the costs of the supply chain, and managers are recommended to make decisions to produce products with a longer life so that economic growth is achieved in this industry besides reducing the environmental pollution. The following recommendations can be presented based on the analysis results.

- The results of the proposed model are useful for the studied firm and affect the objectives. Other food industries also can use this model to optimize their objectives. However, the structure of their supply chain and uncertainty parameters should be similar to those dealt with in this research. Thus, supply chains aiming to assess their economic and environmental performance can adapt the proposed structure and solution method of the present research.
- Considering the uncertainty of some key parameters, the use of robust models helps managers adopt appropriate decisions on financial flows in uncertain markets and optimal material flow in producing flexible products in the dairy supply chain.
- Regarding different product lifetime and the importance of this matter in environmental pollution, production managers of the studied supply chain can make proper decisions to create a production system with the most product durability and the least environmental pollution and help the economic growth in this industry.

5-2-Future directions and limitations

Future research is recommended to pay attention to the risk of environmental factors such as exchange rate and inflation rate on different investments and corresponding impacts on supply chain profitability according to the country's economic conditions. In addition, it is suggested to investigate other methods dealing with uncertainty and compare their results with the approach proposed in this research. Also, other environmental effects can be considered in decision-making. Regarding the risk, researchers can take into account the impact of sanctions on decision-making and, more specifically, on each of the research variables.

The main limitations of the current paper include the following:

- Usually, there is no specific database of transportation costs, so in this study, drivers' assessments were employed to estimate transportation costs,
- The demand amount was just estimated based on the report of the case study experts.

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