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A multi-objective sustainable supply chain network design problem for perishable foods

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Abstract

Increasing demand for food, environmental degradation, postharvest losses, and lack of financial resources, especially in developing countries, encourage manufacturing supply chains to develop integrated decision models for jointly incorporating economic, environmental, and social aspects into the supply chain network design problems. This research aims to develop a novel multi-objective decision support model for designing a sustainable multi-product green supply chain network for perishable food products. The model aims to minimize the total costs and carbon dioxide emissions while maximizing the social impacts simultaneously. Numerical experiments on several test problems indicate that the total cost is mostly impacted by the fixed cost of constructing warehouses and maintenance costs, respectively. The total amount of carbon emissions is more influenced by the amount of carbon produced in warehouses than transportation activities. We also found that the number of jobs created plays a much more critical role on social satisfaction than the amount of traffic generated by the supply chain. Also, the number of jobs created and the amount of carbon gas produced in the warehouses have a direct relationship; therefore, these two factors should be considered together simultaneously in the supply chain network design problem.

Keywords: Food supply chain network design, sustainable supply chain, perishable food, goal programming, facility location, transportation

1- Introduction

A supply chain network design (SCND) problem typically involves several strategic decisions that specify the related supply chain's configuration; while they have long-lasting effects on the tactical and operational decisions. In general, a SCND problem specifies the locations and capacities of required facilities along with some tactical decisions related to purchasing, production and distribution plans if the demand pattern shows a considerable seasonal fluctuation.

Recent evidences suggest that rising global rates of natural resource consumption combined with population growth have put more pressure on the environment (Kannan et al., 2020). With global awareness about the environmental and social impacts of supply chain operations, decision-makers have been forced to consider all these aspects of sustainability, along with several other features (Meneghetti and Monti, 2015).

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In recent years, researchers considered different aspects of sustainability in supply chains as an important issue (Govindan et al., 2020); therefore, recent years have witnessed a growing academic interest in "sustainable food supply chain network design." Sustainability includes three different sectors, which are economic, environmental, and social. In today's literature, being green in the supply chain generally means producing the lowest possible waste and environmental pollution. Of course, different criteria have been set for the greenness of the supply chain (see for instance Hervani et al., 2005). However, those research works that consider carbon dioxide emission in a mathematical model, just consider minimizing the amount of carbon dioxide emissions during the transportation of products in the chain. Although transportation is the main source of carbon dioxide emissions in supply chains; the importance of carbon dioxide emission in warehouse construction and supply chain’s operations should not be neglected. One of the reasons that makes it difficult to consider these sources of carbon emission is the difficulty of measuring the amount of carbon dioxide emissions at these stages. Of course, there are very few studies that seek to identify the amount of carbon dioxide emissions from other operations such as transportation, construction of warehouses and production centers, storage and transportation of products inside each facility (Mogale, Cheikhrouhou and Tiwari, 2020). Jouzdani and Govindan (2021) demonstrated that other than the pollution created during transportation operations, the second-highest carbon dioxide emissions occur during working with products inside the facility.

Nowadays, when it comes to the social impacts of supply chains, most existing researches incorporate the social impact into their mathematical model via the number of jobs created in the supply chain. Researchers such as Nayeri et al. (2020) have considered negative impacts of injuries to workers while working in the chain. In addition, Song and Ko (2016) have proposed a model for solving the " Perishable Food Supply Chain Network Design "problem, while considering vehicles in two conditions with and without refrigerators to maximize customer satisfaction. According to Zhu et al. (2018), modeling a food supply chain considering all aspects of sustainability has happened very infrequently in the literature.

Up to now, no previous study has investigated the combination of product perishability, the effect of transportation on traffic congestion, and using of refrigerator in transportation. Also, few studies have considered the effects of the time value of money when calculating different costs over a multi-period horizon (Meneghetti and Monti, 2015).

Accordingly, this paper accounts for the following issues in its modeling framework that have not been collectively considered in the literature so far: considering (1) carbon dioxide emission from different sources, (2) heterogeneous transportation, (3) multi-period planning horizon in response to fluctuating demand, (4) time value of money, (5) spoilage of products, (6) impacts of using refrigerator in vehicles on spoilage rate and costs and carbon emission, (7) amount of traffic caused by the supply chain on social satisfaction, and (8) uncertainty in several parameters (including the demand of ¬stores and the amount of product available in procurement centers). The developed model seeks to minimize the total cost of a food supply chain, and CO_2 emissions from transportation and operating activities within facilities; and to maximize the desirable social impacts (such as the number of jobs created). Also, by creating several different scenarios, we consider uncertainties in the model, uncertainties on the demand side, suppliers and logistics, the number of transportation vehicle used, the amount of available foodstuff in each warehouse at the end of each period, and the amount of food transported between the warehouses.

The rest of this paper is organized as follows: a review of the literature is presented in the next section. In section 3, we define the problem, then present the assumptions and the developed mathematical model. Section 4 elaborates on the solution approach. In section 5, by presenting several numerical examples, we evaluate the applicability of the proposed model and analyze its different parameters. Finally, section 6 concludes the paper's conclusions and suggestions for expansion in future studies for interested researchers.

2- Literature review

In the following, we review the literature in three complementary streams.

2-1- Perishable food supply chain network design

There are several review papers on SCND problem (e.g., Govindan et al., 2017; Melo et al., 2009). Food chains usually include perishable products, and the quality characteristics of these products make it very difficult to design a supply chain network for perishable food products (Ghezavati et al., 2017). In a recent study, Dutta and Shrivastava (2020) developed a nonlinear mathematical programming model for designing a supply chain network for perishable foodstuff production. They adopted a scenario-based approach to account for uncertainty. In another study (Behzadi et al., 2017), the resilience of a farming supply chain is investigated. The authors developed a model for investigating the perishability of products in a kiwi supply chain aiming at maximizing the profit. They thoroughly investigated the effects of risk administration policy and the perishability of goods on the chain's profit.

Collectively, these studies outline critical role of the perishability of goods that has a significant influence on SCND problem. In this way, we account for the perishability of food products in the design of a food supply chain network.

2-2- Facility location and routing decisions in FSCs

Research works about locating facilities in perishable supply chains has a long history. Among them, Kovačić et al. (2015), investigated the effects of facility location and the duration of shipping on perishable goods. Manouchehri et al. (2020) developed a single-objective mathematical programming model for making routing decisions for perishable goods. They assumed the authoritative parameters and resolved their model using a hybrid meta-heuristic algorithm. As a case study, they studied a chicken supply chain in Iran and obtained the optimum inventory level and temperature in different periods. The model's outcome displayed that the optimized temperature ranges from 4 to 15 °C in different periods. In this work, we jointly make optimal decisions on facility location and routing problems as two major influential factor in the SCND problem.

2-3- Sustainable supply chain network design for perishable food products

In recent years, there has been an increasing amount of researches on sustainability in SCND. Eskandarpour et al.(2015) reviewed sustainable supply chain design articles and Bloemhof and Soysal (2017) provided an overview on sustainable food SCND problem. Evidently, perishable food chains affect the environment and society in different aspects. For example, the storage and transportation of these products with low temperatures require a lot of energy consumption. Bortolini et al. (2016) presented a three-objective mathematical model aiming at minimizing the total costs, delivery time, and carbon emissions for an Italian fruit and vegetable distribution system. The results of their study demonstrate that although the total cost increases up to 2.7%, it can also reduce the carbon effect by 6.6%. Sazvar et al. (2018) presented a multi-objective linear programming model for a designing a sustainable food supply chain network while considering all three aspects of sustainability. The model aimed to minimize costs and greenhouse gas emissions and maximize social health. They found that if the supply chain tended toward organic foods, it would cause social health to be up to four times higher than usual. Similarly, this happens to environmental impacts, which express the importance of organic products. In general, several works are showing that moving towards a more sustainable supply chain can be achieved by a little more cost on the economic side of the supply network (Biuki, Kazemi and Alinezhad, 2020).

In another research, (Allaoui et al., 2018) addressed a sustainable agricultural green food supply chain network design problem resolved via a two-step hybrid approach. Also, Mohammed and Wang (2017a) simultaneously minimized the cost of transportation and delivery time in a meat supply chain. Then, the same authors (Mohammed and Wang, 2017b) expanded their model, considering the environmental impact and distribution time.

Sustainability encourages us to consider the social effect as an outstanding aspect of supply chains. Previous studies in the literature have been poor at considering the social impacts of supply chains. In particular, as discussed in the introduction, traffic congestion should be considered as a substantial social impact of supply chains. Also, considering interest rates in the perishable food supply chain network design problems is scarce. There are some works which investigated using of refrigerators during transportation. Specifically, Jouzdani and Govindan (2021) considered using the refrigerator as a decision variable in their model. However, most of these studies have not considered the different characteristics of food supply chains, such as multi-mode transportation, limited storage capacity, heterogeneous vehicles with limited availability, carbon dioxide emissions, and limited vehicle capacity, collectively in a decision model. Furthermore, past studies in SCND problem have mainly concentrated on two general objective functions, i.e., minimizing the total costs and environmental impacts where the environmental function mostly includes minimizing the carbon dioxide emissions originated from just transportation activities.

In addition, previous studies have generally failed to simultaneously consider several vehicles with different capacities, several products, and several planning periods, which are jointly considered in this research. The literature review conducted by Rashidi et al. (2020) shows that articles dealing with all three aspects of supply chain sustainability are rare. Consequently, the number of studies is much more limited regarding the sustainability of perishable food products.

2-4- Research gap analysis and contributions

The literature shows that a few papers have studied all three aspects of sustainability in supply chains, which are much more limited in the field of perishable food supply chains. To the best of our knowledge, research in perishable SCND that has considered uncertainty in their model is rare. As mentioned earlier, in most previous research, source of carbon emission is limited to the amount of carbon released during transportation activities, (e.g. Colicchia *et al.*, 2016; Musavi and Bozorgi-Amiri, 2017; Kelle *et al.*, 2019). Nevertheless, we considered all three main sources of greenhouse gas emission in the concerned supply chain: during warehouses' construction, transportation, and handling of products in the warehouse (Mogale, Cheikhrouhou and Tiwari, 2020).

Furthermore, to the best of our knowledge, no research has addressed the details of transportation in the food supply chains as much as this study. For example, some of the weaknesses of studies like (Mogale, Cheikhrouhou and Tiwari, 2020; Jouzdani and Govindan, 2021) are that they have not considered the rate of product spoilage during transportation, as well as the impact of using refrigerator on the rate of product spoilage; both of which have been considered in our research. In addition, this research investigates the impact of using refrigerator on the costs and carbon emissions, which has not been investigated before according to the recent literature review by Rashidi *et al.* (2020).

Another case that is very rare in the literature is considering the impact of the traffic generated by the supply chain on social satisfaction. In addition, no research has considered the two factors of traffic and the number of jobs created in the chain simultaneously under the function of social impact (see Jouzdani and Govindan, 2021). Furthermore, in order to be more realistic in the cost dimension, this study considers the interest rate as well.

In this paper, we are going to design a perishable food supply chain network considering all three aspects of sustainability. The supply chain under study is a 3PL network that includes procurement centers, central warehouses, district-level warehouses, and shops. Several types of vehicles, including rail and road modes have been used for transporting the products. Some vehicles can use refrigerator, which affects the rate of product spoilage, carbon dioxide emissions (due to higher fuel use), and, of course, the amount of costs. According to our literature review, we conclude the necessity of doing such research that considers all three aspects of the sustainability in significant details (as discussed above) not only in cost dimension but also in carbon emission and social impact dimensions. The main research contributions of this article are summarized as follows:

1. Locating central warehouses and district-level warehouses while the amount of carbon emission is taken into account
2. Considering the time value of money in cost functions
3. Studying the effect of refrigerator usage on transportation activities and consequently on costs, carbon production, and product corruption.

4. Considering the creation of both permanent and temporary jobs in the chain along with the amount of traffic generated by the transportation system.

3- Problem description

As mentioned in the previous section, researchers have proved that moving towards a more sustainable supply chain means decentralization; which means an increase in costs. So, creating a suitable balance between these two factors is a significantly important issue (Biuki, Kazemi and Alinezhad, 2020). The total costs in this model include the fixed costs of construction of facilities, fixed costs of transportation (e.g., the cost of renting vehicles), variable transportation costs, and inventory costs. Despite of most studies, we also account for those costs resulting from the use of refrigerator and the time value of money in the cost function of our model.

Also, according to a previous study (Mogale, Cheikhrouhou and Tiwari, 2020), the sources of carbon dioxide emissions include two main factors, i.e., CO_2 emission by transportation between facilities and transportation within facilities, which are both affected by using the cooling devices. Consequently, it affects carbon dioxide emissions and the amount of spoilage of products. The last aspect of sustainability is the social impact for which we consider the total number of fixed and temporary jobs, and the amount of traffic caused by transporting products by road.

The overall structure of the supply chain network in our model is shown in figure 1. It is a model designed for a 3PL network; the decision-making sphere starts where the materials are out of the procurement centers and continues until the products are delivered to the shops. It should be noted that the chain is defined only in the forward direction. As shown in figure 1, the rail and road transportation modes can be used between warehouses, with two types of trucks, some of them can use a refrigerator.

The primary purpose of the model is to decide on the place of warehouses and the tactical plan for the movement and storage of products in a multi-period horizon under uncertainty, which should ultimately satisfy all the demands of stores with the lowest cost and at the same time, taking into account environmental considerations and social impacts. Therefore, a multi-objective mathematical model has been developed to simultaneously minimize the total cost and total emissions of carbon dioxide gas and maximize the aforementioned social impacts.

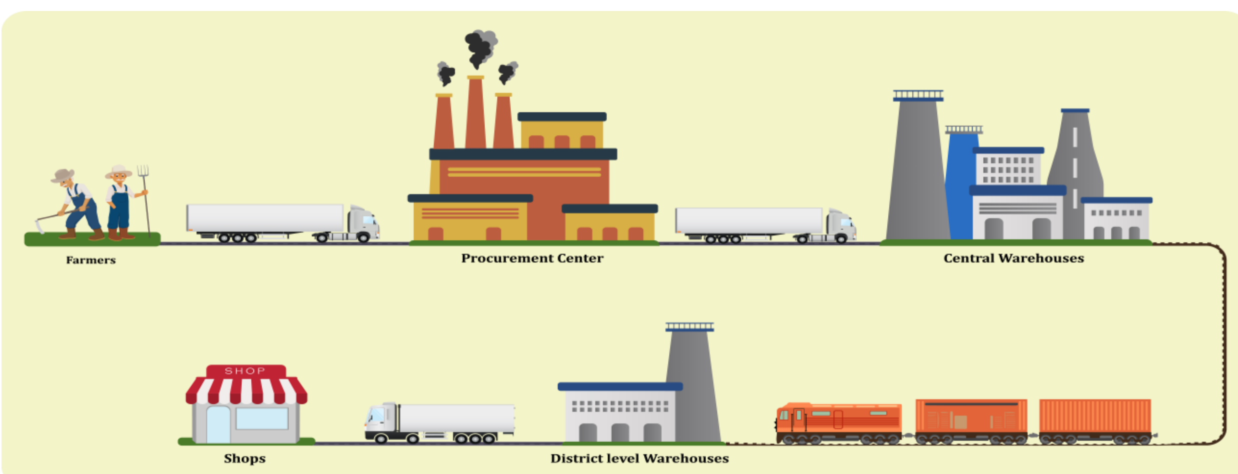

Fig 1. The food supply chain distribution system under study

In this model, the set of vehicles used in each stage, the number of products available in the procurement centers, the amount of final demand of shops, the amount of food available in warehouses at the end of each period, the number of products transferred between warehouses, the use of a refrigerator by each vehicle, the total traffic between facilities and travel time between facilities assuming different traffic flows are inconclusive and are different under each scenario. It should be noted that in order to formulate the spoilage of products, we used the standard method which have been used in the literature (Sazvar et al., 2014).

Several assumptions are considered in the problem formulation:

- Locations of shops and procurement centers are fixed.
- The potential locations of the warehouses are pre-specified.
- Material flow can only be established between two successive echelons of the network.
- The demands of all shops and warehouses along the chain must be fully satisfied (i.e. shortage is not allowed).
- There are three types of vehicles, including two types of trucks and one type of train along the chain, each of which can use the cooling device (refrigerator).
- The maximum number of available vehicles in each scenario is given.
- The maximum vehicle capacity (i.e. full truck load) is used in each transportation.
- The degree of spoilage of products while transportation depends on the type of product and whether or not a refrigerator is used.

Also, the decisions made by the model include:

- the location of warehouses, including central warehouses and district level warehouses
- the number of products transferred between warehouses and the amount of product remaining at the end of each period in each warehouse
- the number of vehicles that should be used in each period
- the usage of cooling devices in the transportation according to the spoilage rate in each case and the amount of cost per unit of the spoiled product, and the amount of carbon dioxide emission.

4- Mathematical model

4-1- Notations

Indices	Description
p	Index of fixed procurement centers, $p=1,2,...,p$
q	Index of candidate locations for central warehouses, $q=1,2,...,Q$
s	Index of candidate locations district level warehouses, $s=1,2,...,S$
f	Index of fixed shops, $f=1,2,...,F$
k	Index of truck types available at procurement centers, $k=1,2,...,K$
l	Index of rake types available at central warehouse, $l=1,2,...,L$
m	Index of truck types available at district level warehouse, $m=1,2,...,M$
t	Index of time periods, $t=1,2,...,T$
n	Index of product types, $n=1,2,...,N$
s'	Index for types of scenarios, $s'=1,2,...,S'$
Parameters	
fc_q	Fixed cost of opening a central warehouse q
fc_s	Fixed cost of opening district-level warehouse s
e_k	Fixed cost of hiring a truck of type k
e_l	Fixed cost of hiring a rake of type l
e_m	Fixed cost of hiring a truck of type m
v_o	Variable transportation cost per unit for each km by road mode with its refrigerator off
v_R	Variable transportation cost per unit for each km by road mode with its refrigerator on

u_o	Variable transportation cost per unit for each km by rail mode with its refrigerator off
u_R	Variable transportation cost per unit for each km by rail mode with its refrigerator on
ic_{qn}	Inventory cost per unit for a product n in central warehouse q for one period
ic_{sn}	Inventory cost per unit for a product n in district level warehouse s for one period
g_{pq}	Distance from facility p to q
g_{qs}	Distance from facility q to s
g_{sf}	Distance from facility s to f
$a^t_{pns'}$	Amount of product n accessible at facility p all along period t under scenario s'
b^t_{qn}	Storage capacity of the central warehouse q
b^t_{sn}	Storage capacity of the district level warehouse s
$d^t_{fns'}$	Demand of shop f for product n all along period t under scenario s'
α^t_{kp}	Maximum number of trucks type k accessible at center p all along period t
α^t_{lq}	Maximum number of rakes type l accessible at warehouse q all along period t
α^t_{ms}	Maximum number of trucks type m accessible at district level warehouse s all along period t
AA^t_{pn}	Maximum quantity type n accessible at a particular procurement center in a given period
Ω_k	Maximum capacity of a truck of type k
Ω_l	Maximum capacity of a rake of type l
Ω_m	Maximum capacity of truck of type m
ω_q	Amount of Carbon dioxide emission during the opening of central warehouse q
ω_s	Amount of Carbon dioxide emission during opening district level warehouse s
ω^{ko}_{pq}	Amount of Carbon dioxide emission for each unit distance for each k type of truck transported from facility p to q with its refrigerator off
ω^{lo}_{qs}	Amount of Carbon dioxide emission for each unit distance for each l type of rake transported from facility q to s with its refrigerator off
ω^{mo}_{sf}	Amount of Carbon dioxide emission per unit distance for each m type of truck transported from facility s to f with its refrigerator off
ω^{kR}_{pq}	Amount of Carbon dioxide emission per unit distance for each k type of truck transported from facility p to q with its refrigerator on
ω^{lR}_{qs}	Amount of Carbon dioxide emission per unit distance for each l type of rake transported from facility q to s with its refrigerator on
ω^{mR}_{sf}	Amount of Carbon dioxide emission per unit distance for each m type of truck transported from district level warehouse s to fair price shop f with its refrigerator on
δ_q	Amount of Carbon dioxide emission while handling each ton of products in central q

δ_s	Amount of Carbon dioxide emission while handling each ton of products in warehouse s
$BigM$	A sufficiently big number
$p_{s'}$	Probability of scenario occurrence s'
w_1	Weight of jobs created
w_2	Weight of Generate traffic
A_q	Number of permanent jobs created in the central warehouse q
A_s	Number of permanent jobs created in the district level warehouse s
B_q	Number of temporary jobs created in the central warehouse q
B_s	Number of temporary jobs created in the district level warehouse s
γ_n	Percentage of inventory required to be destroying product type n at the end of each period
γ_n^{mR}	Percentage of spoilage of products type n in transport by type truck m in case of using refrigerator
γ_n^{mo}	Percentage of spoilage of products type n in transport by type truck m with its refrigerator off
γ_n^{lR}	Percentage of spoilage of products type n in transport by type rake l with its refrigerator on
γ_n^{lo}	Percentage of spoilage of products type n in transport by type rake l with its refrigerator off
γ_n^{kR}	Percentage of spoilage of products type n in transport by type truck k with its refrigerator on
γ_n^{ko}	Percentage of spoilage of products type n in transport by type truck k with its refrigerator off
sv_n	The cost of destroying each product type n per unit
$\varphi_{pqts'}^0$	The basic flow all along period t from facility p to q under scenario s'
$\varphi_{sfts'}^0$	The basic flow all along period t from facility s to f under scenario s'
$\tau_{pqts'}^0$	The travel time assuming free flow from facility p to q all along period t under scenario s'
$\tau_{sfts'}^0$	The travel time assuming free flow from facility s to f all along period t under scenario s'
κ_{pq}	The capacity of the route from facility p to q
κ_{sf}	The capacity of the route from facility s to f
ω_k'	Traffic congestion weight of vehicles of type k
ω_m'	Traffic congestion weight of vehicles of type m
ρ_t	The interest rate in period t

Decision variables	
Binary variables	**Description**
X_q	Equals to 1 if the central warehouse is opened at location q and 0 otherwise
Z_s	Equals to 1 if the district level warehouse is opened at location s and 0 otherwise
$\lambda_{qss'}^{lt}$	Equals to 1 if the truck type l on the route s to f in the time period t under the scenario s' uses the refrigerator
$\lambda_{sfs'}^{mt}$	Equals to 1 if the truck type m on the route s to f in the time period t under the scenario s' uses the refrigerator
$\lambda_{pqs'}^{kt}$	Equals to 1 if the truck type k on the route p to q in the time period t under the scenario s' uses the refrigerator
Continuous variables	
$E_{pqns'}^{t}$	The amount of product n distributed by procurement center p to central warehouse q all along period t under scenario s'
$G_{qsns'}^{t}$	The amount of product n distributed by central warehouse q to district level warehouse s all along period t under scenario s'
$V_{sfns'}^{t}$	The amount of food grain distributed by district level warehouse s to fair price shop f all along period t under scenario s'
$I_{qns'}^{t}$	The amount of product n accessible at central warehouse q at the end of period t under scenario s'
$B_{sns'}^{t}$	The amount of product n accessible at district level warehouse s at the end of period t under scenario s'
$\varphi_{pqts'}$	Total traffic from facility p to q all along period t under scenario s'
$\varphi_{sfts'}$	Total traffic from facility s to f all along period t under scenario s'
$\tau_{pqts'}$	The travel time from facility p to q all along period t under scenario s'
$\tau_{sfts'}$	The travel time assuming free flow from facility s to f all along period t under scenario s'
Integer variables	
$N_{pqs'}^{kt}$	The number of trucks type k traversed from procurement center p to central warehouse q in period t under scenario s'
$N_{qss'}^{lt}$	The number of trucks type l traversed from central warehouse q to district level warehouse s in period t under scenario s'
$N_{sfs'}^{mt}$	The number of trucks type m traversed from district level warehouse s to fair price shop f in period t under scenario s'

4-2- Model formulation

As mentioned earlier, the mathematical model consists three objective functions, each of which consisting of several parts. The first objective function is related to the economic dimension. It aims to minimize the total cost, which includes the fixed cost of constructing warehouses, fixed and variable cost of transportation, and finally, the inventory cost of products stored in warehouses at the end of each period, part of which must be disposed due to spoilage and partly kept for the next period.

Economical Objective = Minimizing Total Cost (TC)

Min Obj (TC) = Fixed cost of facility location + Transportation cost (fixed and variable cost) + Inventory cost

$$\text{Fixed cost of Facility location} = \sum_{q\in Q} fc_q X_q + \sum_{s\in S} fc_s Z_s \tag{1}$$

$$\text{Fixed transportation cost} = \sum_{s'\in S'} p_{s'} \left[\frac{\sum_{t\in T}\sum_{k\in K}\sum_{p\in P}\sum_{q\in Q} e_k N^{kt}_{pqs'} + \sum_{t\in T}\sum_{l\in L}\sum_{q\in Q}\sum_{s\in S} e_l N^{lt}_{qss'} + \sum_{t\in T}\sum_{m\in M}\sum_{s\in S}\sum_{f\in F} e_m N^{mt}_{sfs'}}{\prod_{t\in T}\left(1+\rho_t\right)} \right] \tag{2}$$

$$\text{Variable transportation cost} = \sum_{s'\in S'} p_{s'} \left[\frac{\begin{array}{l} \sum_{t\in T}\sum_{n\in N}\sum_{p\in P}\sum_{q\in Q}\left(1-\lambda^{kt}_{pqs'}\right) v_o g_{pq} E^t_{pqns'} + \sum_{t\in T}\sum_{n\in N}\sum_{p\in P}\sum_{q\in Q} \lambda^{kt}_{pqs'} v_R g_{pq} E^t_{pqns'} \\ + \sum_{t\in T}\sum_{n\in N}\sum_{q\in Q}\sum_{s\in S}\left(1-\lambda^{lt}_{qss'}\right) u_o g_{qs} G^t_{qsns'} + \sum_{t\in T}\sum_{n\in N}\sum_{q\in Q}\sum_{s\in S} \lambda^{lt}_{qss'} u_R g_{qs} G^t_{qsns'} \\ + \sum_{t\in T}\sum_{n\in N}\sum_{s\in S}\sum_{f\in F}\left(1-\lambda^{mt}_{sfs'}\right) v_o g_{sf} V^t_{sfns'} + \sum_{t\in T}\sum_{n\in N}\sum_{s\in S}\sum_{f\in F} \lambda^{mt}_{sfs'} v_R g_{sf} V^t_{sfns'} \end{array}}{\prod_{t\in T}\left(1+\rho_t\right)} \right] \tag{3}$$

$$\text{Inventory cost} = \sum_{s'\in S'} p_{s'} \left[\frac{\sum_{t\in T}\sum_{n\in N}\sum_{q\in Q}\left(\left(1-\gamma_n\right) I^t_{qns'} ic_{qn} + I^t_{qns'} Sv_n \gamma_n\right) + \sum_{t\in T}\sum_{n\in N}\sum_{s\in S}\left(\left(1-\gamma_n\right) B^t_{sns'} ic_{sn} + B^t_{sns'} Sv_n \gamma_n\right)}{\prod_{t\in T}\left(1+\rho_t\right)} \right] \tag{4}$$

The second objective function aims to minimize adverse environmental impacts, and the total amount of destructive effects on the environment, including the amount of carbon dioxide produced during the construction of warehouses, during transportation, and while working inside warehouses.

Environmental impact = Minimizing Total Emission of Carbon dioxide (TE)

Min Obj 2 = Carbon emission rate arising from facility establishment
+ Carbon emission rate arising from transportation
+ Carbon emission rate arising from handling

Carbon emission rate arising from facility establishment $= \sum_{q \in Q} \omega_q X_q + \sum_{s \in S} \omega_s Z_s$ (5)

carbon Emission rate arising from Transportation =

$$\sum_{s' \in S'} p_{s'} \left[\begin{array}{l} \sum_{t \in T} \sum_{k \in K} \sum_{p \in P} \sum_{q \in Q} \left(1 - \lambda_{pqs'}^{kt}\right) \omega_{pq}^{ko} g_{pq} N_{pqs'}^{kt} + \sum_{t \in T} \sum_{k \in K} \sum_{p \in P} \sum_{q \in Q} \lambda_{pqs'}^{kt} \omega_{pq}^{kR} g_{pq} N_{pqs'}^{kt} \\ + \sum_{t \in T} \sum_{l \in L} \sum_{q \in Q} \sum_{s \in S} \left(1 - \lambda_{qss'}^{lt}\right) \omega_{qs}^{lo} g_{qs} N_{qss'}^{lt} + \sum_{t \in T} \sum_{l \in L} \sum_{q \in Q} \sum_{s \in S} \lambda_{qss'}^{lt} \omega_{qs}^{lR} g_{qs} N_{qss'}^{lt} \\ + \sum_{t \in T} \sum_{m \in M} \sum_{s \in S} \sum_{f \in F} \left(1 - \lambda_{sfs'}^{mt}\right) \omega_{sf}^{mo} g_{sf} N_{sfs'}^{mt} + \sum_{t \in T} \sum_{m \in M} \sum_{s \in S} \sum_{f \in F} \lambda_{sfs'}^{mt} \omega_{sf}^{mR} g_{sf} N_{sfs'}^{mt} \end{array} \right] \quad (6)$$

carbon emission rate arising from handling $= \sum_{s' \in S'} p_{s'} \left[\begin{array}{l} \sum_{t \in T} \sum_{n \in N} \left(\sum_{p \in P} \sum_{q \in Q} E_{pqns'}^{t} + \sum_{q \in Q} \sum_{s \in S} G_{qsns'}^{t} \right) \delta_q \\ + \sum_{t \in T} \sum_{n \in N} \left(\sum_{q \in Q} \sum_{s \in S} G_{qsns'}^{t} + \sum_{s \in S} \sum_{f \in F} V_{sfns'}^{t} \right) \delta_s \end{array} \right]$ (7)

The last objective is related to the social dimension (i.e., the total positive effects of decisions on the society). It aims to maximize the number of permanent and temporary jobs created by the supply chain, while minimizing the amount of traffic caused by the road transport fleet.

Social impact = maximizing social impact (SC)

Max Obj 3 = Fixed and temporary jobs created – total traffic congestion impact of the fleet

Fixed and temporary jobs created $= \sum_{s' \in S'} p_{s'} \left[w_1 \left(\begin{array}{l} \sum_{q \in Q} A_q X_q + \sum_{s \in S} A_s'' Z_s \\ + \sum_{t \in T} \sum_{n \in N} \sum_{p \in P} \sum_{q \in Q} B_q E_{pqns'}^{t} \\ + \sum_{t \in T} \sum_{n \in N} \sum_{q \in Q} \sum_{s \in S} B_s' G_{qsns'}^{t} \end{array} \right) \right]$ (8)

total traffic congestion impact of the fleet$= \sum_{s' \in S'} p_{s'} \left[w_2 \left(\sum_{p} \sum_{q} \sum_{t} \varphi_{pqts'} \tau_{pqts'} + \sum_{s} \sum_{f} \sum_{t} \varphi_{sfts'} \tau_{sfts'} \right) \right]$ (9)

The first four limitations are related to estimating the amount of traffic caused by the supply chain transport fleet and its impact on social welfare. Equations (10) and (11) determine the time of movement between the two warehouses according to the amount of traffic created and the capacity of each street for the number of vehicles; equations (12) and (13) indicate the amount of traffic generated by the supply chain transport fleet between the warehouses.

Subject to:

$$\tau_{pqts'} = \tau^0_{pqts'} \times \left[1 + 0.15\left(\frac{\varphi_{pqts'}}{\kappa_{pq}}\right)\right] \qquad ;\forall p, \forall q, \forall t, \forall s' \tag{10}$$

$$\tau_{sfts'} = \tau^0_{sfts'} \times \left[1 + 0.15\left(\frac{\varphi_{sfts'}}{\kappa_{sf}}\right)\right] \qquad ;\forall s, \forall f, \forall t, \forall s' \tag{11}$$

$$\varphi_{pqts'} = \varphi^0_{pqts'} + \sum_k \omega'_k N^{kt}_{pqs'} \qquad ;\forall p, \forall q, \forall t, \forall s' \tag{12}$$

$$\varphi_{sfts'} = \varphi^0_{sfts'} + \sum_m \omega'_m N^{mt}_{sfs'} \qquad ;\forall s, \forall f, \forall t, \forall s' \tag{13}$$

Equation (14) indicates that at least one central warehouse must be constructed along the chain and among the candidate's locations. Equation (15) states that for each type of product; products transferred to central warehouses from each procurement center, cannot exceed the maximum capacity of that procurement center. Equation (16) indicates that there only can be product flows to the constructed central warehouses from each procurement center. Equations (17) and (18) indicate that there is a product flow between consecutive levels if they are both constructed.

$$\sum_{q \in Q} X_q \geq 1 \tag{14}$$

$$\sum_{q \in Q} E^t_{pqns'} \leq AA^t_{pn} \qquad \forall p, \forall t, \forall n, \forall s' \tag{15}$$

$$E^t_{pqns'} \leq bigM X_q \qquad \forall p, \forall q, \forall t, \forall n, \forall s' \tag{16}$$

$$G^t_{qsns'} \leq bigM X_q Z_s \qquad \forall q, \forall s, \forall t, \forall n, \forall s' \tag{17}$$

$$V^t_{sfns'} \leq bigM Z_s \qquad \forall s, \forall f, \forall n, \forall s' \tag{18}$$

Equations (19) and (20) consider the spoilage of products. They indicate that the number of products transferred from each warehouse must be less than the inventory level available in that warehouse. Equation (21) indicates that the demand for shops must be answered, and the shortage is not allowed.

$$\sum_{s \in S}\sum_{l \in L}\left(1-\gamma^{lR}_n\right)\lambda^{lt}_{qss'}G^t_{qsns'} + \sum_{s \in S}\sum_{l \in L}\left(1-\gamma^{lo}_n\right)\left(1-\lambda^{lt}_{qss'}\right)G^t_{qsns'} \leq \left(1-\gamma_n\right)I^t_{qns'} \qquad \forall q, \forall t, \forall n, \forall s' \tag{19}$$

$$\sum_{f \in F}\sum_{m \in M}\left(1-\gamma^{mR}_n\right)\lambda^{mt}_{sfs'}V^t_{sfns'} + \sum_{f \in F}\sum_{m \in M}\left(1-\gamma^{mo}_n\right)\left(1-\lambda^{mt}_{sfs'}\right)V^t_{sfns'} \leq \left(1-\gamma_n\right)B^t_{sns'} \qquad \forall s, \forall t, \forall n, \forall s' \tag{20}$$

$$\sum_{s \in S}\sum_{m \in M}\left(1-\gamma^{mR}_n\right)\lambda^{mt}_{sfs'}V^t_{sfns'} + \sum_{s \in S}\sum_{m \in M}\left(1-\gamma^{mo}_n\right)\left(1-\lambda^{mt}_{sfs'}\right)V^t_{sfns'} = d^t_{fns'} \qquad \forall f, \forall t, \forall n, \forall s' \tag{21}$$

Equations (22) and (23) are related to the maximum capacity of each warehouse. They indicate that the total number of products in each warehouse should always be less than the capacity of that warehouse.

$$I^{(t-1)}_{qns'} + \sum_{p \in P}\sum_{k \in K}\left(1-\gamma^{kR}_n\right)\lambda^{kt}_{pqs'}E^t_{pqns'} + \sum_{p \in P}\sum_{k \in K}\left(1-\gamma^{kR}_n\right)\left(1-\lambda^{kt}_{pqs'}\right)E^t_{pqns'} \leq b^t_{qn} \qquad \forall q, \forall t, \forall n, \forall s' \tag{22}$$

$$B_{sns'}^{(t-1)} + \sum_{q\in Q}\sum_{k\in K}\left(1-\gamma_n^{lR}\right)\lambda_{qss'}^{lt} G_{qsns'}^{t} + \sum_{q\in Q}\sum_{k\in K}\left(1-\gamma_n^{lo}\right)\left(1-\lambda_{qss'}^{lt}\right) G_{qsns'}^{t} \le b_{sn}^{t} \qquad \forall s,\forall \mathrm{t},\forall \mathrm{n},\forall s' \tag{23}$$

Equations (24) and (25) are related to inventory balance considering the corruption of products at the end of each period in each warehouse and at the time of transportation.

$$\left(1-\gamma_n\right) I_{qns'}^{(t-1)} + \sum_{p\in P}\sum_{k\in K}\left(1-\gamma_n^{kR}\right)\lambda_{pqs'}^{kt} E_{pqns'}^{t} + \sum_{p\in P}\sum_{k\in K}\left(1-\gamma_n^{kR}\right)\left(1-\lambda_{pqs'}^{kt}\right) E_{pqns'}^{t} - \sum_{s\in S} G_{qsns'}^{t} = I_{qns'}^{t} \qquad \forall q,\forall \mathrm{t},\forall \mathrm{n},\forall s' \tag{24}$$

$$\left(1-\gamma_n\right) B_{sns'}^{(t-1)} + \sum_{q\in Q}\sum_{l\in L}\left(1-\gamma_n^{lR}\right)\lambda_{qss'}^{lt} G_{qrns'}^{t} + \sum_{q\in Q}\sum_{l\in L}\left(1-\gamma_n^{lo}\right)\left(1-\lambda_{qss'}^{lt}\right) G_{qrns'}^{t} - \sum_{f\in F} V_{sfns'}^{t} = B_{sns'}^{t} \qquad \forall s,\forall \mathrm{t},\forall \mathrm{n},\forall s' \tag{25}$$

Equations (26-28) are related to the capacity of vehicles. Equations (29-31) are related to the maximum number of vehicles available, and in total, these six limits specify the number of trucks that must be used to transport goods between each facility. Finally, the equations (32-34) determine the type of each variable that have been used in the model.

$$\sum_{n\in N} E_{pqns'}^{t} \le \sum_{k\in K} N_{pqs'}^{kt}\Omega_k \qquad \forall \mathrm{p},\forall \mathrm{q},\forall \mathrm{t},\forall \mathrm{s'} \tag{26}$$

$$\sum_{n\in N} G_{qsns'}^{t} \le \sum_{l\in L} N_{qss'}^{lt}\Omega_l \qquad \forall q,\forall s,\forall \mathrm{t},\forall \mathrm{s'} \tag{27}$$

$$\sum_{n\in N} V_{sfns'}^{t} \le \sum_{m\in M} N_{sfs'}^{mt}\Omega_m \qquad \forall s,\forall f,\forall \mathrm{t},\forall \mathrm{s'} \tag{28}$$

$$\sum_{q\in Q} N_{pqs'}^{kt} \le \alpha_{kp}^{t} \qquad \forall \mathrm{p},\forall k,\forall \mathrm{t},\forall \mathrm{s'} \tag{29}$$

$$\sum_{s\in S} N_{qss'}^{lt} \le \alpha_{lq}^{t} \qquad \forall s,\forall l,\forall \mathrm{t},\forall \mathrm{s'} \tag{30}$$

$$\sum_{f\in F} N_{sfs'}^{mt} \le \alpha_{ms}^{t} \qquad \forall s,\forall m,\forall \mathrm{t},\forall \mathrm{s'} \tag{31}$$

$$X_q, Z_s, \lambda_{qss'}^{lt}, \lambda_{sfs'}^{mt}, \lambda_{pqs'}^{kt} \in \{0.1\} \qquad \forall p,\forall \mathrm{q},\forall \mathrm{s},\forall s',\forall f,\forall l,\forall t,\forall m,\forall k \tag{32}$$

$$E_{pqns'}^{t}, G_{qsns'}^{t}, I_{qns'}^{t}, B_{sns'}^{t} \ge 0 \qquad \forall p,\forall q,\forall s,\forall f,\forall t,\forall n,\forall \mathrm{s'} \tag{33}$$

$$N_{pqs'}^{kt}, N_{qss'}^{lt}, N_{sfs'}^{mt} \in \mathbb{Z}^{+} \qquad \forall p,\forall q,\forall s,\forall f,\forall k,\forall l,\forall m,\forall t,\forall s' \tag{34}$$

5- Solution approach

Due to the existence of several objective functions, we need to use an approach to solve the model that can optimize these functions simultaneously. One of these approaches is the goal programming method. Goal programming method was developed several times in articles such as (Lee, 1972;Lee, 1972;Tamiz, Jones and Romero, 1998). Generally, goal programming methods aims to minimize the deviation of the target function from the expected level. In 2007, (Chang, 2007) introduced a new method called multi-choice goal programming (MCGP). He argued that in problems with uncertainty, this method can be used to solve multi-objective models because it allows the decision-maker to set multi-choice aspiration levels for each goal to avoid underestimation of the decisions. The disadvantage of this method is that it consists of multiplying binary numbers; which made the model a nonlinear one; which makes it hard to understand. So in another research (Chang, 2008) proposed new method, namely "Revised Multi-Choice Goal Programming" (revised MCGP), this new model does not include multiplicative terms of binary variables; therefore, besides having the benefits of the previous model, it can easily be solved by common linear programming packages; industrial participants can also work with it smoothly. To solve the presented problem in our paper, we use Revised Multi-Choice Goal Programming, which is expressed as follows (Chang, 2008):

$$Min. \sum_{k=1}^{3} \left[W_k^d \left(d_k^- + d_k^+ \right) + W_k^e \left(e_k^- + e_k^+ \right) \right] \tag{35}$$

Subject to:

$$f_k(x) + d_k^- - d_k^+ = y_k \qquad k=1,2,3 \tag{36}$$

$$y_k + e_k^- - e_k^+ = f_{k,\min} \qquad k=1,2,3 \tag{37}$$

$$f_{k,\min} \le y_k \le f_{k,\max} \qquad k=1,2,3 \tag{38}$$

$$d_k^- . d_k^+ = 0 \qquad k=1,2,3 \tag{39}$$

$$e_k^- . e_k^+ = 0 \qquad k=1,2,3 \tag{40}$$

$$d_k^-, d_k^+, \mathrm{e}_k^-, \mathrm{e}_k^+ \ge 0 \qquad k=1,2,3 \tag{41}$$

$$\sum_{i=1}^{n} X_i = D \tag{42}$$

$$X_i \le V_i \qquad i=1,2,...,n \tag{43}$$

$$X_i \ge 0 \qquad i=1,2,...,n \tag{44}$$

Where $f_{k,\min}$ and $f_{k,\max}$ are range of goals, the decision variable is continuous d_k^+ and d_k^- are the value of positive and negative deviation of $f_k(x)$ from y_k; consequently, y_k defines the aspiration level of $f_k(x)$ as its acceptable/tolerable level. e_k^+ And e_k^- are the value of positive and negative deviations of y_k from $f_{k,\min}$. Finally, W_k^e and W_k^d are respectively the relative importance of the connection (d_k^+, d_k^-) and (e_k^+, e_k^-).

6- Numerical examples and managerial insights

In this section, to clarify the importance of this research and better understand it before the conclusion, we are focusing on the main features of the proposed model with several numerical experiments, where the dimensions of problems including the number of equipment, scenarios, and time intervals are visible in table 1. Then, some of the main parameters by using numeric experiment number 5 in each target function are investigated (details about numerical examples are provided in Appendix). The defined model is a Mixed Integer Quadratically Constrained Program (MIQCP); so, we solved several small and medium sized instances by GAMS version 24.1.2 with the solver BARON.

According to table 1 and figure 2, by increasing the number of candidates locations for central warehouses and district-level warehouses, the number of jobs created by supply chain will increase rapidly. However, this increase will not continue forever. After reaching the optimal number of warehouses, the number of constructed warehouses will remain constant, and as a result, the number of jobs that created will remain constant. Besides, we can see the relationship between the amount of carbon emission due to handling and the number of jobs created by the supply chain; these two have taken almost exactly the same path. So, when we aim to design a sustainable supply chain in all dimensions, we have to consider the number of jobs created and the carbon emission due to handling at the same time in the model. For example, if we just reduce carbon production, in this way, it dramatically reduces the social satisfaction resulting from creating jobs.

Similarly, as shown in table 1 and figure 3, the amount of traffic caused by road transport fleet and carbon emission during transportation have almost the same trend; so, these two factors have to be considered together at the same time too.

Table 1. Numerical experimentations

Experiment number	Procurements	Potential central warehouses	Potential district level warehouses	Shops	Product types	Time period	scenarios
1	1	1	1	2	1	1	2
2	1	1	2	2	1	1	2
3	1	1	2	2	2	2	2
4	2	2	2	4	2	2	2
5	2	2	3	4	2	2	3
6	2	2	6	8	2	2	3
7	2	2	8	10	2	2	3
8	2	6	8	10	2	2	3
9	2	8	8	10	2	2	3
10	3	8	10	10	2	2	3

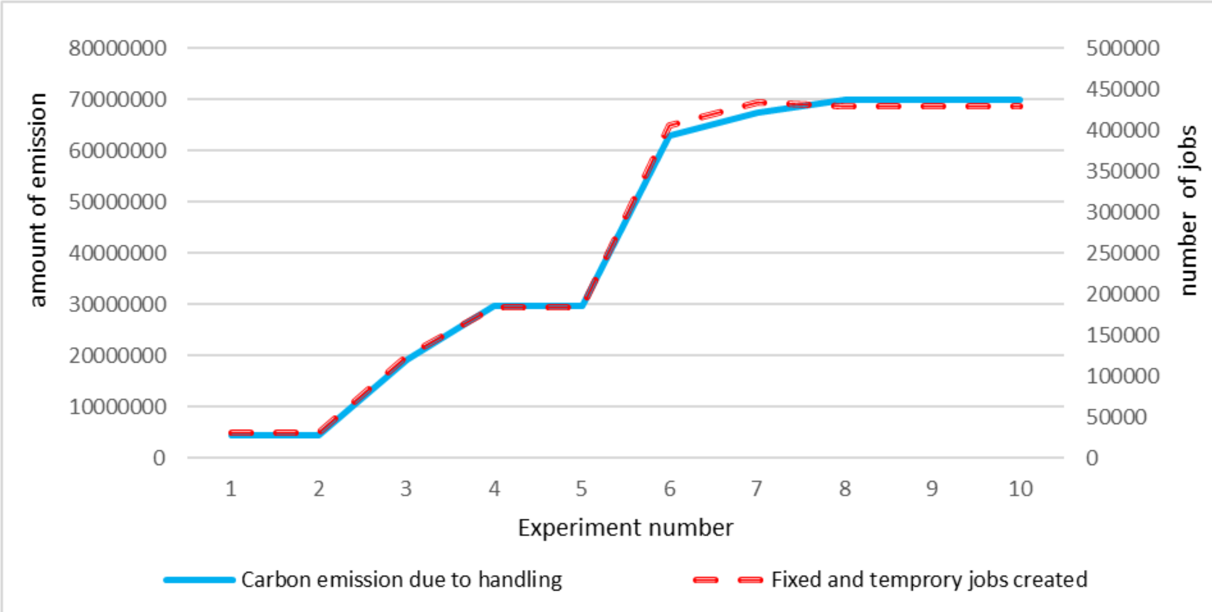

Fig 2. The relationship between carbon emission due to handling, the number of jobs created, and the number of facilities

Fig 3. The relationship between carbon emission due to transportation, total traffic created, and the number of facilities

Solving the numerical example according to experiment number 5 in table 1, shows that the two main parts of costs are the fixed cost of construction of facilities and the variable cost of transportation (table 2); however, according to table 2 and figures 4 and 5, it can be observed that the total costs are the most sensitive to the fixed cost of constructing warehouses. Moreover, it clearly can be seen that increasing the disposal cost of rotten products at the end of each period will directly impact on inventory costs.

Table 2. Results of solving the first objective function

Objective functions	Costs
Economical Objective (Z1)	2.800810E+9
Inventory cost	3924551.700
Fixed cost of facility location	2.700000E+9
Fixed transportation cost	1107438.017
Variable transportation cost	1.524108E+8

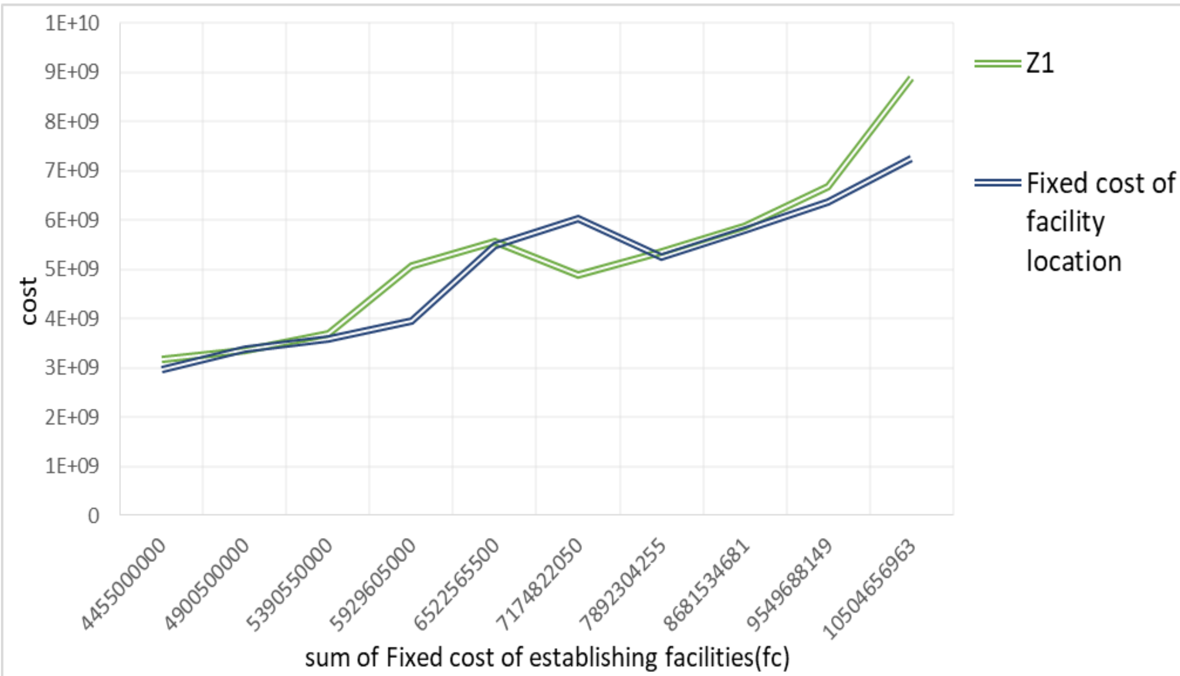

Fig 4. The impact of the fixed cost of establishing (FC) on Z1 and the fixed cost of facility location

According to table 3 in the term of carbon dioxide emissions, as in previous researches, it was proved that the highest amount of pollution is caused during transportation and in the following ranks, there is the amount of carbon dioxide produced during working with products in storage, and finally, the least amount of carbon emission occurs during the construction of facilities. Nevertheless, when it comes to the highest sensitivity to the variables expressed, as seen in figure 5, the amount of the second objective function is mainly influenced by the amount of CO_2 emissions produced during handling in warehouses. By increasing the amount of carbon dioxide emission per ton of each product in each warehouse, the total amount of gas emission and the amount of gas emission during working with products goes through an utterly similar process and increase to the same extent. Also, because the use or non-use of the refrigerator does not considerably affect the amount of pollution emission by vehicles, the main factor in deciding whether to use the refrigerator or not will be the cost of its usage.

Table 3. Results of solving the second objective function

Objective Functions	Carbon emission
Economical Objective (Z2)	3.748028E+7
Carbon emission rate arising from facility establishment	2060000.000
Carbon emission rate arising from transportation	2.613048E+7
Carbon emission rate arising from handling	2.968936E+7

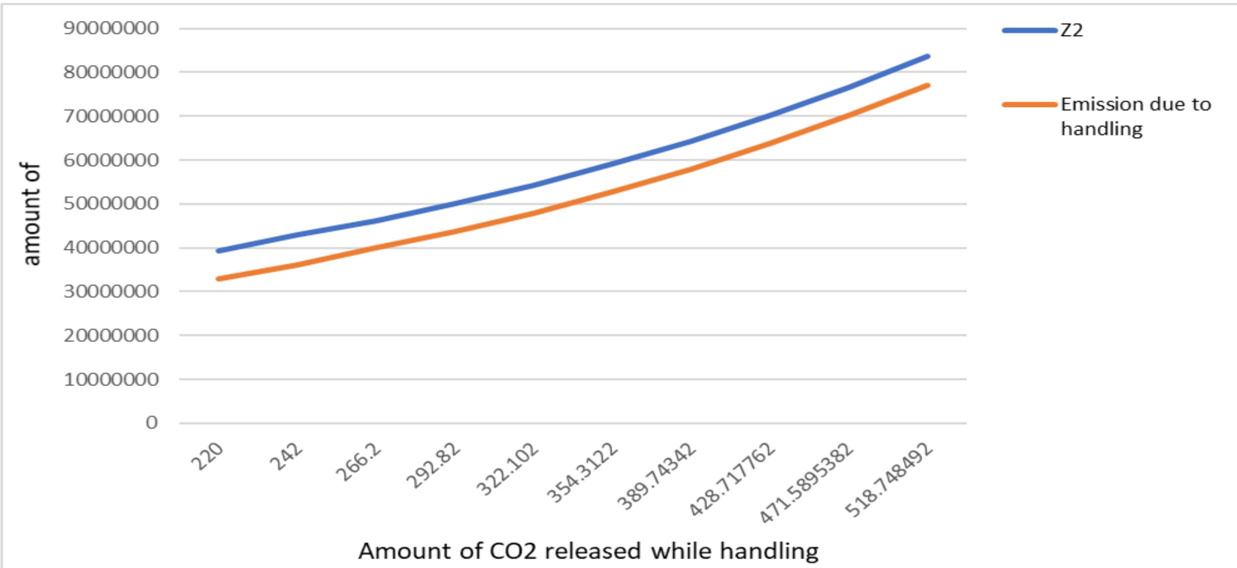

Fig 5. The impact of amount of CO_2 emission while handling ($\delta_s + \delta_q$) on Z2 and emission due to handling

Table 4. Results of solving the third objective function

Objective Functions	Objective Value
Social impact (Z3)	421550.305
Fixed and temporary jobs created	183937.693
total traffic congestion impact of the flee	55596.324

Fig 6. The impact of the capacity of the route ($\kappa_{sf} + \kappa_{pq}$) on Z3 and emission due to handling

Finally, according to table 4 when it comes to social impacts, the role of the number of jobs created is not comparable to the role of traffic creation in social satisfaction. In other words, the number of jobs created has a much more significant impact on social satisfaction and a large amount of the third objective function. Of course, the impact of traffic on social satisfaction is greatly influenced by the weight we assign to, in third function; so, when we consider weights for the functions in the third objective function equal, we will see figure 6, which shows that by increasing the capacity of the streets, traffic decreases and the amount of the third target function (Z3) increases almost as much as the reduction of traffic. Therefore, the first approach to increase social satisfaction should be to create more jobs, but in different societies and in crowded and busy cities, minimizing traffic may also affect social satisfaction.

7- Conclusions and future works

This study aims to discover sustainability in the sustainable perishable food supply chain network design by combining all three sustainability dimensions and presenting a three-objective mathematical model for supporting strategic and tactical decision-making. This study is among the small number of articles in the literature that consider specific aspects and details of the sustainable perishable food supply chain network design, e.g., perishability is considered both during storage and at the time of transportation between warehouses, vehicles (in rail and road mode) can reduce the amount of spoilage in different products by using refrigerators. In the case of using refrigerators due to the increase in CO_2 emission, a balance between efficiency and reduction of environmental impacts is considered; in addition to the environmental dimension, the amount of carbon dioxide produced in warehouses is considered. In the economic dimension, the time value of money is considered, which is very rare in literature. The social dimension considers the fixed and temporary jobs that the chain creates, and the amount of traffic generated by the road transport fleet. Uncertainty in the proposed model is considered by considering different scenarios. Finally, to solve the proposed model, we applied a revised multi-choice goal programming method due to its simplicity of implementation, adding the lowest number of variables to the primary model, relatively appropriate solving time, and flexibility against the level of ideals and decision makers' opinions.

The most prominent findings of this study can be summarized as follow: the amount of traffic caused by road transport fleet and carbon emission during transportation are complimentary. So, by minimizing these two at the same time, we can achieve a better result. The second significant finding was that maximizing the jobs created by the chain is in contrast to minimizing carbon emissions during handling in warehouses. Therefore, decision-makers should consider both sides simultaneously and strike a proper balance between the two goals according to priorities. The research has also shown that the main cost in this type of supply chain is the cost of constructing warehouses and transportation costs; moreover, the total cost shows the highest sensitivity to the cost of constructing warehouses. In addition, the investigation of social impact has shown that the number of jobs created in the chain has a much more significant impact on social satisfaction. Using refrigerator in vehicles does not have a significant role in carbon emission; therefore, the main decisive factor in terms of using refrigerator or not is its cost and the spoilage rate of products.

Finally, several limitations need to be noted regarding the present study that can be focused on, in future researches. Although the current study accounts for data uncertainty, it would be interesting to use fuzzy mathematical programming to consider epistemic uncertainty in input data. Another limitation of this study is that the candidate locations for constructing warehouses were already known, but it is possible to consider determining the candidates' locations in the decision-making model. Another potential area of future research would be to develop a meta-heuristic algorithm to solve the model.

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Appendix A.

In this section, we provide the set of parameters that we have used to solve the presented model in Section 6. Table A1 shows the parameters that are scenario-independent. The results of solving model with these parameters are presented in Section 6 (note that the parameter values that we used in tables A1 and A2 are extracted from several researches in the literature, (e.g. Colicchia *et al.*, 2016; Mogale, Cheikhrouhou and Tiwari, 2020; Jouzdani and Govindan, 2021).

Table A1. Values of scenario-independent parameters.

Parameter	Value	Parameter	Value
fc_{q1}	1000000000	sv_n	$n_1 = 2,\ n_2 = 3$
fc_{q2}	1100000000	γ_n	n_1=0.15, n_2=0.09
fc_{s1}	600000000	ic_{qn}	q_1n_1=2, q_1n_2=3, q_2n_1=2, q_2n_2=3
fc_{s2}	650000000	ic_{sn}	s_1n_1=2, s_1n_2=3, s_2n_1=2, s_2n_2=3, s_3n_1=2, s_3n_2=3
fc_{s3}	700000000		
e_k	400	g_{pq}	$p_1q_1 = 500,\ p_1q_2 = 200,\ p_2q_1 = 400,\ p_2q_2 = 300$
e_l	600	g_{qs}	$q_1s_1 = 100,\ q_1s_2 = 80,\ q_1s_3 = 70$ $q_2s_1 = 90,\ q_2s_2 = 90,\ q_2s_3 = 80$
e_m	300	g_{sf}	$s_1f_1 = 40,\ s_1f_2 = 30,\ s_1f_3 = 50,\ s_1f_4 = 40$ $s_2f_1 = 50,\ s_2f_2 = 40,\ s_2f_3 = 40,\ s_2f_4 = 40$ $s_3f_1 = 20,\ s_3f_2 = 30,\ s_3f_3 = 50,\ s_3f_4 = 40$
Ω_k	500	b_{qn}^t	$t = 1,2:\ q_1n_1 = 40000,\ q_2n_1 = 40000,$ $q_1n_2 = 50000,\ q_2n_2 = 50000$
Ω_l	1000	b_{sn}^t	$t = 1,2:\ s_{1,2,3}n_1 = 35000,\ s_{1,2,3}n_2 = 40000$
Ω_m	300	AA_{pn}^t	$t = 1:\ p_1n_1 = 5000000,\ p_1n_2 = 55000000$ $p_2n_1 = 5000000,\ p_2n_2 = 60000000$ $t = 2:\ p_1n_1 = 55000000,\ p_1n_2 = 50000000$ $p_2n_1 = 55000000,\ p_2n_2 = 55000000$
$\omega_{q=1,2}$	1000000	$\omega_{p=1,2,q=1,2}^{ko}$	50
$\omega_{s=1,2}$	60000	$\omega_{q=1,2,s=1,2,3}^{lo}$	60
$\delta_{q=1,2}$	100	$\omega_{s=1,2,3,f=1,2,3,4}^{mo}$	50
$\delta_{s=1,2}$	100	$\omega_{p=1,2,q=1,2}^{kR}$	60
$A_{q=1,2}$	100	$\omega_{q=1,2,s=1,2,3}^{lR}$	75
$A_{s=1,2}$	50	$\omega_{s=1,2,3,f=1,2,3,4}^{mR}$	60
$B_{q=1,2}$	2	γ_n^{mR}	$n_1 = 0.04,\ n_2 = 0.06$

$B_{s=1,2}$	2	γ_n^{mo}	$n_1 = 0.08,\ \ n_2 = 0.1$
$\alpha_{kp=1,2}^{t=1,2}$	300	γ_n^{lR}	$n_1 = 0.04,\ \ n_2 = 0.06$
$\alpha_{lq=1,2}^{t=1,2}$	200	γ_n^{lo}	$n_1 = 0.06,\ \ n_2 = 0.08$
$\alpha_{ms=1,2,3}^{t=1,2}$	300	γ_n^{kR}	$n_1 = 0.04,\ \ n_2 = 0.06$
$\kappa_{p=1,2,q=1,2}$	25	γ_n^{ko}	$n_1 = 0.08,\ \ n_2 = 0.1$
$\kappa_{s=1,2,3,f=1,2,3,4}$	30	$\rho_{t=1,2}$	0.1
$\omega_k^{'}$	0.3	w_1	0.5
$\omega_m^{'}$	0.15	w_2	0.5

We used random uniform functions to generate scenario-dependent parameters in each scenario; which are presented in table A2.

Table A2. Values of scenario-dependent parameters

Parameter	Scenario1	Scenario2	Scenario3
$a_{pn\acute{s}}^{t} \sim uni\ (60000{,}100000)$	$t = 1:\ \ p_1n_1 = 73717,\ \ p_1n_2 = 96038,$ $p_2n_1 = 66537,\ \ p_2n_2 = 69539$ $t = 2:\ \ p_1n_1 = 76128,\ \ p_1n_2 = 67825,$ $p_2n_1 = 92045,\ \ p_2n_2 = 97738$	$t = 1:\ \ p_1n_1 = 74207,\ \ p_1n_2 = 87444,$ $p_2n_1 = 93844,\ \ p_2n_2 = 72479$ $t = 2:\ \ p_1n_1 = 78806,\ \ p_1n_2 = 64755,$ $p_2n_1 = 78345,\ \ p_2n_2 = 70311$	$t = 1:\ \ p_1n_1 = 94818,\ \ p_1n_2 = 98578,$ $p_2n_1 = 69707,\ \ p_2n_2 = 76446$ $t = 2:\ \ p_1n_1 = 84374,\ \ p_1n_2 = 98018,$ $p_2n_1 = 64124,\ \ p_2n_2 = 82286$
$d_{fn\acute{s}}^{t} \sim uni\ (2000{,}3000)$	$t = 1:\ \ f_1n_1 = 2713,\ \ f_1n_2 = 2736,\ \ f_2n_1 = 2361,\ \ f_2n_2 = 2214,$ $f_3n_1 = 2550,\ \ f_3n_2 = 2932,\ \ f_4n_1 = 2923,\ \ f_4n_2 = 2284$ $t = 2:\ \ f_1n_1 = 2364,\ \ f_1n_2 = 2730,\ \ f_2n_1 = 2370,\ \ f_2n_2 = 2551,$ $f_3n_1 = 2088,\ \ f_3n_2 = 2901,\ \ f_4n_1 = 2597,\ \ f_4n_2 = 2176$	$t = 1:\ \ f_1n_1 = 2509,\ \ f_1n_2 = 2022,\ \ f_2n_1 = 2100,\ \ f_2n_2 = 2020,$ $f_3n_1 = 2327,\ \ f_3n_2 = 2909,\ \ f_4n_1 = 2823,\ \ f_4n_2 = 2782$ $t = 2:\ \ f_1n_1 = 2509,\ \ f_1n_2 = 2022,\ \ f_2n_1 = 2100,\ \ f_2n_2 = 2020,$ $f_3n_1 = 2430,\ \ f_3n_2 = 2633,\ \ f_4n_1 = 2403,\ \ f_4n_2 = 2198$	$t = 1:\ f_1n_1 = 2293,\ f_1n_2 = 2281,\ \ f_2n_1 = 2064,\ \ f_2n_2 = 2634,$ $f_3n_1 = 2382,\ \ f_3n_2 = 2501,\ \ f_4n_1 = 2061,\ \ f_4n_2 = 2253$ $t = 2:\ \ f_1n_1 = 2451,\ f_1n_2 = 2341,\ \ f_2n_1 = 2044,\ \ f_2n_2 = 2966,$ $f_3n_1 = 2196,\ \ f_3n_2 = 2522,\ \ f_4n_1 = 2165,\ f_4n_2 = 2945$
$\varphi_{pqt\acute{s}}^{0} \sim uni\ (8{,}15)$	$t = 1:\ p_1q_1 = 10,\ \ p_1q_2 = 11,$ $p_2q_1 = 14,\ \ p_2q_2 = 13$ $t = 2:\ \ p_1q_1 = 14,\ p_1q_2 = 8,$ $p_2q_1 = 11,\ \ p_2q_2 = 11$	$t = 1:\ p_1q_1 = 11,\ \ p_1q_2 = 12,$ $p_2q_1 = 9,\ \ p_2q_2 = 12$ $t = 2:\ \ p_1q_1 = 9,\ p_1q_2 = 9,$ $p_2q_1 = 11,\ \ p_2q_2 = 12$	$t = 1:\ p_1q_1 = 11,\ \ p_1q_2 = 14,$ $p_2q_1 = 11,\ \ p_2q_2 = 10$ $t = 2:\ \ p_1q_1 = 13,\ p_1q_2 = 10,$ $p_2q_1 = 10,\ \ p_2q_2 = 14$

$\varphi^0_{sft\acute{s}} \sim uni$ (10,15)	$t=1$: $s_1f_1=10$, $s_1f_2=12$, $s_1f_3=11$, $s_1f_4=12$, $s_2f_1=10$, $s_2f_2=10$, $s_2f_3=13$, $s_2f_4=13$, $s_3f_1=14$, $s_3f_2=11$, $s_3f_3=14$, $s_3f_4=12$, $t=2$: $s_1f_1=14$, $s_1f_2=13$, $s_1f_3=13$, $s_1f_4=13$, $s_2f_1=14$, $s_2f_2=11$, $s_2f_3=12$, $s_2f_4=11$, $s_3f_1=14$, $s_3f_2=12$, $s_3f_3=10$, $s_3f_4=13$	$t=1$: $s_1f_1=13$, $s_1f_2=12$, $s_1f_3=14$, $s_1f_4=14$, $s_2f_1=10$, $s_2f_2=13$, $s_2f_3=14$, $s_2f_4=14$, $s_3f_1=10$, $s_3f_2=12$, $s_3f_3=13$, $s_3f_4=10$, $t=2$: $s_1f_1=10$, $s_1f_2=12$, $s_1f_3=14$, $s_1f_4=10$, $s_2f_1=13$, $s_2f_2=11$, $s_2f_3=11$, $s_2f_4=11$, $s_3f_1=14$, $s_3f_2=13$, $s_3f_3=12$, $s_3f_4=12$	$t=1$: $s_1f_1=10$, $s_1f_2=14$, $s_1f_3=12$, $s_1f_4=12$, $s_2f_1=11$, $s_2f_2=12$, $s_2f_3=13$, $s_2f_4=11$, $s_3f_1=13$, $s_3f_2=14$, $s_3f_3=13$, $s_3f_4=10$, $t=2$: $s_1f_1=10$, $s_1f_2=11$, $s_1f_3=14$, $s_1f_4=10$, $s_2f_1=12$, $s_2f_2=12$, $s_2f_3=10$, $s_2f_4=14$, $s_3f_1=11$, $s_3f_2=12$, $s_3f_3=13$, $s_3f_4=10$
$\tau^0_{pqt\acute{s}} \sim uni$ (100,200)	$t=1$: $p_1q_1=181$, $p_1q_2=170$, $p_2q_1=133$, $p_2q_2=184$ t=2: $p_1q_1=139$, $p_1q_2=124$, $p_2q_1=173$, $p_2q_2=176$	$t=1$: $p_1q_1=187$, $p_1q_2=120$, $p_2q_1=172$, $p_2q_2=158$ t=2: $p_1q_1=126$, $p_1q_2=169$, $p_2q_1=166$, $p_2q_2=164$	$t=1$: $p_1q_1=141$, $p_1q_2=184$, $p_2q_1=118$, $p_2q_2=150$ t=2: $p_1q_1=157$, $p_1q_2=125$, $p_2q_1=131$, $p_2q_2=142$
$\tau^0_{sft\acute{s}} \sim uni$ (50,90)	$t=1$: $s_1f_1=83$, $s_1f_2=56$, $s_1f_3=60$, $s_1f_4=62$, $s_2f_1=55$, $s_2f_2=71$, $s_2f_3=85$, $s_2f_4=74$, $s_3f_1=87$, $s_3f_2=56$, $s_3f_3=71$, $s_3f_4=85$, $t=2$: $s_1f_1=64$, $s_1f_2=52$, $s_1f_3=82$, $s_1f_4=85$, $s_2f_1=71$, $s_2f_2=83$, $s_2f_3=79$, $s_2f_4=57$, $s_3f_1=73$, $s_3f_2=52$, $s_3f_3=73$, $s_3f_4=74$	$t=1$: $s_1f_1=79$, $s_1f_2=76$, $s_1f_3=82$, $s_1f_4=59$, $s_2f_1=70$, $s_2f_2=87$, $s_2f_3=79$, $s_2f_4=83$, $s_3f_1=52$, $s_3f_2=57$, $s_3f_3=79$, $s_3f_4=76$, $t=2$: $s_1f_1=55$, $s_1f_2=86$, $s_1f_3=79$, $s_1f_4=81$, $s_2f_1=79$, $s_2f_2=57$, $s_2f_3=78$, $s_2f_4=64$, $s_3f_1=79$, $s_3f_2=61$, $s_3f_3=50$, $s_3f_4=67$	$t=1$: $s_1f_1=82$, $s_1f_2=53$, $s_1f_3=59$, $s_1f_4=51$, $s_2f_1=66$, $s_2f_2=59$, $s_2f_3=56$, $s_2f_4=54$, $s_3f_1=85$, $s_3f_2=77$, $s_3f_3=63$, $s_3f_4=88$, $t=2$: $s_1f_1=74$, $s_1f_2=51$, $s_1f_3=62$, $s_1f_4=71$, $s_2f_1=67$, $s_2f_2=79$, $s_2f_3=75$, $s_2f_4=67$, $s_3f_1=89$, $s_3f_2=70$, $s_3f_3=81$, $s_3f_4=53$