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A novel location-inventory-routing problem in a two-stage red meat supply chain with logistic decisions: evidence from an emerging economy

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Abstract

Purpose – This study focuses on a specific method of meat production that involves carcass purchase and meat production by packing facilities with a novel two-stage model that simultaneously considers location-routing and inventory-production operating decisions. The considered problem aims to reduce variable and fixed transportation and production costs, inventory holding cost and the cost of opening cold storage facilities.

Design/methodology/approach – The proposed model encompasses a two-stage model consisting of a single-echelon and a three-echelon many-to-many network with deterministic demand. The proposed model is a mixed-integer linear programming (MILP) model which was tested with the general algebraic modelling system (GAMS) software for a real-world case study in Iran. A sensitivity analysis was performed to examine the effect of retailers' holding capacity and supply capacity at carcass suppliers.

Findings – In this research, the number of products transferred at each level, the number of products held, the quantity of red meat produced, the required cold storage facilities and the required vehicles were optimally specified. The outcomes indicated a two percent (2%) decrease in cost per kg of red meat. Eventually, the outcomes of the first and second sensitivity analysis indicated that reduced retailers' holding capacity and supply capacity at carcass suppliers leads to higher total costs.

Originality/value – This research proposes a novel multi-period location-inventory-routing problem for the red meat supply chain in an emerging economy with a heterogeneous vehicle fleet and logistics decisions.

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The proposed model is presented in two stages and four-echelon including carcass suppliers, packing facilities, cold storage facilities and retailers.
Keywords Two-stage supply chain, Location-inventory-routing problem, Transportation and logistic decisions, Mixed-integer linear programming
Paper type Research paper

1. Introduction

Agricultural and livestock products are the most important sources of protein, and inadequate consumption of these products is likely to cause serious health problems (Adesogan *et al.*, 2020). One of the reasons for inadequate protein intake is the high cost of these products, which could limit people's access (van Huis and Oonincx, 2017; Hajiagha *et al.*, 2018). Red meat is a key source of animal protein (Bergeron *et al.*, 2019). Based on the *World Statistics Portal for Market Data*, red meat consumption in Iran as an emerging economy is 20–40 kg per person. Further, it has been discussed that this source of protein consumption is decreasing due to the increasing rate of retailers' prices for final consumers. Figure 1 illustrates trends in red meat production and consumption in Iran (ur Rahman and ur Rahman, 2020). As shown, red meat consumption has decreased, while red meat production has increased over time. In Iran, the rising prices of raw materials and economic sanctions have led to a dramatic increase in the price of red meat, a 2–3 fold increase in the price per kg of red meat in 2019 compared to 2016. As a result, the consumption rate of red meat (as the most important source of protein in Iran) has decreased significantly. In this regard, this research sets to design and optimise the red meat supply chain to reduce costs as a strategy to reduce the final price of the product.

In a theoretical context, the supply chain of any product consists of three parts, i.e. upstream, midstream and downstream. Improving the performance of each of these parts improves the performance of the entire chain, consequently reducing the total costs and final product prices. Upstream operations involve the procurement of raw materials for the product of interest. Midstream and downstream operations involve the production and distribution of the product. Supply chain management (SCM) aims to coordinate all parts of the supply chain to improve processes, minimise costs and increase productivity (Mahdiraji *et al.*, 2019a, b, 2020). To keep the price of red meat to a minimum, its supply chain must be

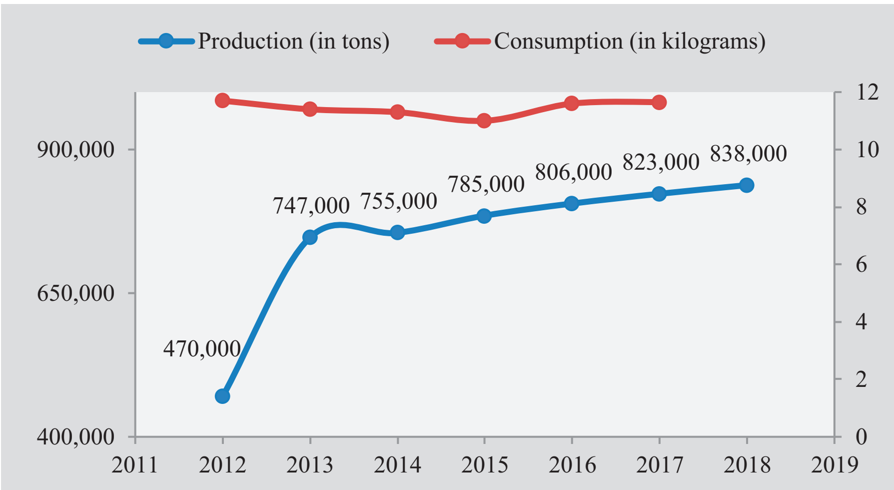

Figure 1.
Meat production and consumption in Iran

examined and optimised. Figure 2 illustrates the studied red meat supply chain in Iran. In addition to the elements shown in this figure, the supply chain may include several opened cold storage facilities (distribution centres) for a more efficient red meat distribution system. Buying livestock and slaughtering them is not economical for some companies (Frisk *et al.*, 2018); thus, these companies buy carcasses, pack them and ultimately sell them to the final consumer. Moreover, the purpose of this study is to design a red meat supply chain in two stages, four-echelon, and multi-period models, in which the operational decisions of location, production, inventory and routing are considered simultaneous, and products are transported using a fleet of heterogeneous vehicles. Furthermore, the red meat supply chain starts from the carcass supply level and after performing the relevant operations, the packed meat is transferred to the retailers at the last level. To the best of our knowledge, this combination and problem have not been investigated previously based on the available literature.

There are various parameters in SCM; for instance, single-period or multi-period, single-product or multi-product, homogeneous or heterogeneous vehicle fleet, and single or multi-echelon supply chain network can all be taken into account (Mosca *et al.*, 2019). Furthermore, for each echelon, networks can be shaped as one-to-one, one-to-many, many-to-one, or many-to-many (Coelho *et al.*, 2014). Different characteristics can also be added to the model, including time window (Wang *et al.*, 2016), risk management (Heidari *et al.*, 2018), transshipment (Rahbari *et al.*, 2018) and perishability (Mirzaei and Seifi, 2015). Furthermore, issues such as the location of facilities, routing of vehicles and inventory can be examined for each supply chain (Biuki *et al.*, 2020). According to the mentioned points, the type of product has a great impact on the design and analysis of the supply chain network (Yavari and Geraeili, 2019). Over time, researchers have turned to supply chain design for a particular product, while in the past a supply chain was designed for a specific product category. Rice is an example of a product whose supply chain network has been studied (Cheraghalipour *et al.*, 2019). Recent articles have shown that all echelons of the supply chain should be considered for better decision-making; nonetheless, as the number of echelons of the chain increases, it makes the model more complex (Tirkolaee *et al.*, 2020). As a result, modelling approaches have moved towards staging based on product type, vehicle type, or different strategic decisions (Heidari *et al.*, 2019). Due to differences in some characteristics of the agricultural supply chain, such as the type of product transported during the supply chain or the type of vehicles used to transport products, it is necessary to model the problem in several stages to achieve appropriate results. Since the product transported in the red meat supply chain consists of two different types, a two-stage model has been scheduled. In the first stage, the carcass is prepared and distributed among the packing facilities, and then the red meat production operation is performed. In the second stage, the packed meat will be distributed among retailers, which cold storage facilities will be also used if needed.

In the present research, the supply chain spans from carcass purchase to the delivery of packed meat to retailers. The proposed model is a multi-period, single-product model for the red meat supply chain with a heterogeneous vehicle fleet. Moreover, the designed network consists of four echelons, including carcass suppliers, packing facilities, cold storage facilities

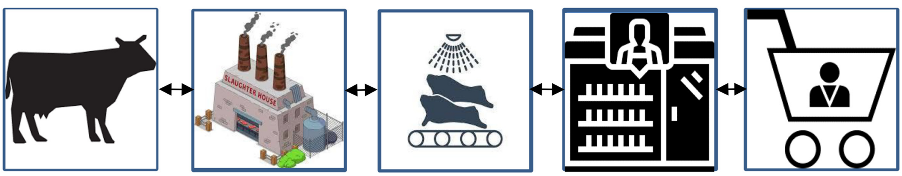

Figure 2.
Red meat supply chain

and retailers. The proposed model is presented in two stages; the first stage includes carcass suppliers and packing facilities, and the second stage includes packing facilities, cold storage facilities and retailers. After solving the model in both stages, the number of products transferred at each level, the number of products held in storage nodes, the quantity of red meat produced, the cold storage facilities that are opened, and the required vehicles are specified. Additionally, a sensitivity analysis is performed on the holding capacity of retailers and supply capacity at carcass suppliers, and changes in the solutions are examined. The originality of this paper can be summarised as follows:

(1) Designing a two-stage, four-echelon red meat supply chain from carcass suppliers to retailers by simultaneously considering location-routing and inventory-production operating decisions;

(2) Providing two mixed-integer linear programming (MILP) models for red meat supply chain (a single-echelon and a three-echelon problem for the first and second stage respectively) in which a heterogeneous vehicle fleet is considered;

(3) Solving a real instance using information from a meat supplier in Iran and comparing the outcomes of solving the model with real information;

(4) Analysing the effect of retailers' holding capacity and supply capacity at carcass suppliers on the outcomes obtained from solving the proposed model with different scenarios.

The remainder of this paper is structured as follows. Section 2 provides a review of the literature on the design of various supply chain networks, including food supply chains. The proposed models for the red meat supply chain network are presented in Section 3. In Section 4, these models are applied to a real case scenario in Iran. In Section 5, sensitivity analysis and discussion are conducted. Finally, Section 6 provides the conclusion and future research directions derived from the research.

2. Literature review

Recently, network design for agricultural and livestock products has received increasing attention from researchers. This has led to an increase in the efficiency of these supply chains and a reduction in the cost of these products (Rahbari *et al.*, 2020). This section provides a review of the literature. Studies on network design for agricultural and livestock products can be divided into qualitative and quantitative categories. Qualitative studies have mainly focused on issues such as improving supply chain quality, product tracking methods and systems, factors influencing the price of products, lead time (due to perishability of the products), etc. (Moons *et al.*, 2019). On the other hand, quantitative studies have focused on the design of the supply chain network for the product of interest and the variables related to SCM, including reducing supply chain costs, increasing supply chain profits, reducing lead time and reducing product shortages (Govindan *et al.*, 2017). In the following sub-sections, relevant studies are categorised and reviewed in detail.

2.1 Supply chain network design and management

Although SCM has received considerable attention since the early 1980s, it is not particularly well understood and there is still the opportunity for improvements and future research (Li and Liu, 2019). Geoffrion and Graves (1974) were amongst the first investigators in the study of supply chain design. They employed Benders' decomposition approach to determine the optimal number and location of distribution centres (DCS) to be established. Pirkul and Jayaraman (1996) proposed a multi-product MIP model for a three-echelon, capacitated plant and a warehouse location problem that aimed to minimise operating warehouses and the annual fixed costs of establishing as well as total transportation and distribution costs. Lagrangian relaxation was applied to the model as an effective approach for solving large-scale problems. Miranda and Garrido (2004) developed a simultaneous model that incorporates economic order quantity and safety stock decisions into a facility location problem with three echelons, including a plant, warehouses and retailers. This was a real case of frozen food distribution, and they solved the problem through Lagrangian relaxation. Miranda and Garrido (2009) developed a mathematical programming model based on Lagrangian relaxation to determine optimal ordering size, client assignment and warehouse locations for a location-distribution-inventory problem. Demand was stochastic and normally distributed. Furthermore, the objective function minimised transportation costs, ordering and inventory costs, safety stock costs and fixed and variable warehouse costs. Yao *et al.* (2010) proposed a mixed-integer programming model for a location-allocation-inventory problem. In their proposed model, customers can be served directly by a warehouse or a plant. Moreover, there was a constraint on the production capacity of plants; however, no capacity constraint was considered for warehouses. Pishvaee and Rabbani (2011) studied the network design for a supply chain consisting of plants, DCs and customers. The model incorporates decisions about the optimal number and location of plants and DCs as well as the quantity of product flow between facilities. They considered both direct and indirect shipments to customers. The objective was to minimise opening costs, transportation costs and costs associated with unused products in plants and DCs. Mousavi and Tavakkoli-Moghaddam (2013) developed a two-stage mixed-integer programming model for a location-routing problem. As a novel approach, they considered cross-docking centre location and vehicle routing scheduling simultaneously. Their proposed algorithm was based on hybrid simulated annealing and tabu search. SCM and related decisions have been investigated to reduce costs by various researchers (Tsao *et al.*, 2012). However, some articles have focused on CO_2 emissions to model their problems (Al Shamsi *et al.*, 2014). Mirzaei and Seifi (2015) developed a mathematical model for an inventory-routing problem that considers lost sales for perishable goods. They used an algorithm based on simulated annealing and tabu search to solve the problem on a large scale. The objective function minimised the total cost of transportation, lost sales and holding inventories. In the related articles on SCM, the scholars considered the location-inventory-routing problems, and most of them concentrated on the design of supply chain networks and algorithms (Tavakkoli-Moghaddam and Raziei, 2016).

More recent studies on supply chain network design have been investigated. For instance, Zhao and Ke (2017) developed a bi-objective location-inventory-routing problem for hazardous material management. This study incorporates risk into the model, and the objective function minimises total cost and risk. Hiassat *et al.* (2017) studied a location-inventory-routing problem for perishable products. They considered a homogeneous fleet of vehicles and used a genetic algorithm to solve the model on a large scale. The problem was formulated as a many-to-many network, and the objective function considered warehouse fixed location cost, routing cost and inventory holding cost. Rafie-Majd *et al.* (2018) addressed a multi-objective location-inventory-routing problem for a three-echelon supply chain of perishable products. Demand was stochastic, and the model was a multi-period, multi-product and heterogeneous fleet composition with an integer nonlinear programming structure that was solved by Lagrangian relaxation. Rahbari *et al.* (2018) developed a multi-period, multi-product and green inventory-routing problem that sought to minimise both costs and CO_2 emissions. A key innovation in their research was to consider transshipment costs. Their proposed model was a mixed-integer linear program solved on a small scale. Supply chain network design and location-inventory-routing problems have been considered to reduce costs by several researchers (Koç, 2019). In this regard, some articles focused on an exact method to solve their problems (Zheng *et al.*, 2019). The application of the two-echelon vehicle routing problem in last-mile delivery with drone delivery has been also investigated recently (Kitjacharoenchai *et al.*, 2020; Martins *et al.*, 2021).

2.2 Supply chain network design for agricultural products

In the related articles on agricultural products, scholars have investigated supply chain network design, with most of them concentrating on the nature of agricultural products (Boudahri *et al.*, 2011; Mahmoudi *et al.*, 2019). Govindan *et al.* (2014) studied a two-echelon LRP for a perishable food supply chain with time windows. Their proposed model was multi-period and considered a heterogeneous vehicle fleet. Finally, a metaheuristic algorithm was employed to solve the model. Javanmard *et al.* (2014) solved a multi-product distribution problem with cross-docking. A time window constraint was considered for each delivery and pickup. Their objective function minimised inventory holding costs and transportation costs. González-Araya *et al.* (2015) proposed an optimisation model for apple harvest planning. Their objective function sought to minimise costs related to workforce, goods and fruit loss due to poor quality. Linnemann *et al.* (2015) used the multi-criteria decision-making (MCDM) approach to design a supply chain of protein foods. The results of solving the model indicated that their design resulted in optimal values for different variables. Wang *et al.* (2016) proposed a multi-objective vehicle routing problem with time windows for a food supply chain. The first objective function minimised fixed costs, transportation costs, penalty costs and damaged costs. The second objective function of their proposed model maximised the average freshness of products. Finally, the model was solved using a two-stage heuristic algorithm based on the Pareto variable neighbourhood search and genetic algorithm. Agricultural products and supply chain network design have been considered to reduce costs by various researchers (Orjuela-Castro *et al.*, 2017; Mahdiraji *et al.*, 2019a, b). In this regard, some articles have focused on a particular agricultural product to model their problems (Gholamian and Taghanzadeh, 2017). The application of supply chain network design models in distributing wheat considering sustainability indicators has also been recently investigated (Motavalli-Taher *et al.*, 2020; Nayeri *et al.*, 2020). The sustainable network design of the supply chains due to the importance of economic, social and environmental pillars in agricultural products has been recently considered via multi-objective optimisation models (Fakhrzad and Goodarzian, 2021).

2.3 Red meat supply chain network design

To develop the holding and logistic condition of the red meat supply chain and minimise costs, the well-designed integrated network for supply chain components is amongst the most important researches. Schütz *et al.* (2009) designed a supply chain network for red meat with probabilistic conditions. Their proposed model was formulated in two stages. The first stage involved strategic location decisions while the second stage involved operating decisions. The model was solved through a real case in Norway. Soysal *et al.* (2014) designed and solved a beef supply chain with environmental considerations. Their proposed model was a multi-objective linear programming model aimed to minimise inventory and transportation costs while minimising CO_2 emissions from transportation operations. Mohammed and Wang (2017a) used a multi-objective probabilistic programming approach to design a meat supply chain network. Their objective functions minimised total transportation cost, the number of vehicles and delivery time. Mohammed and Wang (2017b) developed a fuzzy multi-objective model for a green meat supply chain. Their proposed model aimed to minimise the environmental impact of the supply chain and was solved using MCDM. Neves-Moreira *et al.* (2019) developed a multi-product production-routing problem with delivery time windows and heterogeneous vehicles. Their objective function minimised routing cost as well as inventory holding cost for the supplier and retailers. Their model was tested on a European meat store chain. Sustainable and resilient supply networks in the meat industry in Iran have been recently designed and optimised via a multi-objective model (Gholami Zanjani *et al.*, 2021). Beyond these mentioned developments, the main studies are presented in Table 1.

According to the studies conducted in the field of the agricultural supply chain, especially the red meat supply chain, it is possible to identify gaps in this field. For instance, from a supply chain design and management perspective, Jafarian *et al.* (2019) proposed a multi-period, multi-product inventory-routing problem with a heterogeneous vehicle fleet, by considering the likelihood of vehicle failure via a metaheuristic algorithm. Moreover, Anderluh *et al.* (2019) proposed a model for a two-echelon vehicle routing problem by considering time uncertainty thru a two-stage GRASP with path relinking. However, in this research, in addition to investigating vehicle routing and inventory problems, operational decisions in production, inventory and location are also addressed. Furthermore, from a supply chain design and agricultural perspective, Saragih *et al.* (2019) proposed a location-inventory-routing problem for a three-echelon food supply chain consisting of a single supplier, multiple depots and multiple retailers. They considered a probabilistic and normally distributed retailer demand to minimise fixed warehouse installation costs, transportation costs and inventory holding costs via a mixed-integer nonlinear program and was solved using a heuristic algorithm. In their study, the single-period time horizon was considered; however, in this research, the multi-period time horizon is considered. Moreover, Cheraghalipour *et al.* (2019) designed and solved a bi-stage model for a rice supply chain consisting of producers, DCs, rice factories and customers. The objective functions for both levels sought to minimise the supply chain costs, including fixed DC, production, inventory holding and transportation costs. In their research, the operational decision related to the vehicle routing problem was not considered; however, in our proposed approach, it has been investigated as a key issue. Eventually, from the red meat supply chain perspective, Rahbari *et al.* (2020) proposed a multi-period location-inventory-routing problem model with heterogeneous vehicles using the general algebraic modelling language (GAMS). In their research, a single-stage model containing the livestock suppliers to retailers was presented; however, in the current research, a two-stage model containing the carcass suppliers to retailers is proposed. Moreover, Mohebalizadehgashti *et al.* (2020) proposed a multi-objective green supply chain for meat via a multi-period, multi-product and multi-level model for a homogeneous vehicle fleet. However, in this article, a heterogeneous vehicle fleet is considered.

By and large, the supply of raw materials of this supply chain is one of the issues that should be considered in the design of a red meat supply chain. In other words, livestock supply is not always at the first level of the red meat supply chain; hence, organisations may decide to prepare the carcass first according to various issues and then perform the meatpacking and distribution operations. As a result, this is one of the most important questions and issues that this research addresses. According to previous studies, consideration of the supply chain of agricultural products in several stages makes the problem closer to the real world, and more accurate results are obtained. Also, this will be even more important when the product shipped is different along the supply chain. In the red meat supply chain, the transported product is different in the network. In this regard, this research addresses this issue. Moreover, in the present research, supply chain design is assumed in a two-stage, four-echelon model by simultaneously considering location-routing and inventory-production operating decisions. Furthermore, the fleet of vehicles used in this study is considered heterogeneous. Compared to previous researches, this combination and problem have not been investigated. Furthermore, solving real instances using information from a meat supplier in Iran and comparing the outcomes of solving the model with real information could demonstrate the applicability of the proposed model. Finally, to achieve better results, a series of sensitivity analyses are performed on different parameters of the problem, and the reliability of the problem was tested in different scenarios.

Table 1. Overview of previous researches

Scholar	Year	Modeling stages Single	Multi	Objectives I	II	III	Industry (supply chain)	Main attribute/solving approach
Soysal *et al.*	2014	*		Inventory and transportation costs (TC)	CO_2 emissions	Transportation operations	Beef	PIAP/εconstraint method
Al Shamsi *et al.*	2014	*		TC	Inventory cost	CO_2 emissions	Perishable goods	IRP/GAMS
Javanmard *et al.*	2014	*		Inventory holding cost	TC		Food	SCM/A heuristic procedure and imperialist competitive algorithm
González-Araya *et al.*	2015	*		Costs related to workforce	Fruit loss	Costs related to goods	Apple	SCM/CPLEX
Mirzaei and Seifi	2015	*		TC	Costs of lost sales	Costs of holding inventories	Perishable goods	IRP/Simulated annealing and tabu search
TavakkoliMoghaddam and Raziei	2016	*		Total supply chain costs (TSCC)	Shortage of products		Any products	LIRP/GAMS
Wang *et al.*	2016	*		TSCC	The average freshness of products		Food	VRP/Twophase heuristic algorithm
Mohammed and Wang	2017a	*		TSCC	Number of vehicles	Delivery time	Meat	LRP/LINGO
Mohammed and Wang	2017b	*		TSCC	Environmental impact	Distribution time and delivery rate	Meat	FLRP/LINGO
OrjuelaCastro *et al.*	2017	*		Facility location			Perishable fruits	LAP/GAMS
Gholamian and Taghanzadeh	2017	*		TSCC			Wheat	PLIP/GAMS
Zhao and Ke	2017	*		TSCC	Risk		Hazardous products	LIRP/CPLEX
Hiassat *et al.*	2017	*		Warehouse fixed location cost	Routing cost	Inventory holding cost	Perishable products	LIRP/Genetic algorithm

(*continued*)

Table 1.

Scholar	Year	Modeling stages Single	Multi	Objectives I	II	III	Industry (supply chain)	Main attribute/solving approach
Rafie-Majd *et al.*	2018	*		TSCC			Perishable products	LIRP/Lagrangian relaxation
Rahbari *et al.*	2018	*		TSCC	CO_2 emissions		Any products	IRP/ Simulated annealing
Zheng *et al.*	2019	*		TSCC			Passenger car	LIRP/Generalized benders decomposition
Koç	2019	*		Total costs of depots	Costs of drivers	Costs of fuel	Any products	LRP/Adaptive large neighbourhood search
Jafarian *et al.*	2019	*		Routing cost	Inventory holding cost		Any products	IRP/Metaheuristic algorithm
Anderluh *et al.*	2019		*	Routing cost			Perishable products	VRP/two-stage GRASP
Saragih *et al.*	2019	*		Fixed warehouse installation costs	TC	Inventory holding cost	Food	LIRP/ Simulated annealing
Neves-Moreira *et al.*	2019	*		Routing cost	Inventory holding cost		Meat	PRP/Metaheuristic algorithm
Cheraghalipour *et al.*	2019		*	TSCC			Rice	PLIP/Genetic algorithms and particle swarm optimisation
Rahbari *et al.*	2020	*		TSCC			Red meat	PLIRP/GAMS
Mohebalizadehgashti *et al.*	2020	*		TSCC	CO_2 emissions	Factory utilisation	Meat	LAP/augmented εconstraint method
Current Research	2021		*	Fixed and variable transportation costs	Inventory holding and production costs	Costs of opening cold storage facilities	Red meat	Production Location Inventory Routing Problem/GAMS

3. Modelling

In this section, the problem is stated and presented, and the case red meat network is described. Moreover, the assumptions and the two-stage model are formulated in this section. The schematic algorithm of the method used is represented in Figure 3.

Figure 4 illustrates the schematic diagram of the presented model for a red meat supply chain network. As shown in this diagram, the considered supply chain consists of two stages. In the first stage with a single echelon, the carcass is transported from the supplier to the packing facilities. In the second stage with three echelons, products are transported either directly from packing facilities to retailers or from packing facilities to cold storage facilities and then to retailers.

The proposed model is a multi-period and single-product MILP model with a heterogeneous vehicle fleet. The objective of the first stage of the model is to determine the quantity of packed meat produced and held in each period, the amount of carcass transported to packing facilities, and the best vehicles and routes for transportation. The objective of the second stage is to determine the quantity of packed meat transported in each route, the amount of meat held at each node, whether cold storage facilities are opened in the supply chain, and the best vehicles and routes for transportation.

Notations used in this research are described as follows.

3.1 Sets

$c = \{1, 2, \ldots, C\}$	Set of carcass suppliers
$p = \{1, 2, \ldots, P\}$	Set of packing facilities
$s = \{1, 2, \ldots, S\}$	Set of cold storage facilities
$m = \{1, 2, \ldots, M\}$	Set of retailers
$\omega = c \cup p \cup s \cup m$	Set of all nodes
$vc = \{1, 2, \ldots, VC\}$	Set of vehicle types at 1st echelon
$vp = \{1, 2, \ldots, VP\}$	Set of vehicle types at 2nd echelon
$vs = \{1, 2, \ldots, VS\}$	Set of vehicle types at 3rd echelon
$vm = \{1, 2, \ldots, VM\}$	Set of vehicle types at 4th echelon
$t = \{1, 2, \ldots, T\}$	Set of periods

3.2 Parameters

de_{kt}	The demand for node k for red meat in period t ($k \in m$)
ho_{jt}	Inventory holding cost for node j in period t ($j \in p \cup s \cup m$)
vpc_{it}	Variable production cost at packing facility type i for produce red meat in period t ($i \in p$)
fpc_i	Fixed production cost at packing facility type i for produce red meat ($i \in p$)
sc_{it}	Supply cost at carcass supplier type i for supply carcass in period t ($i \in c$)
afc_j	Annual fixed cost for opening cold storage facility type j ($j \in s$)
$disa_{ij}$	The distance among nodes i and j ($i, j \in p \cup s$)
$disb_{jk}$	The distance among nodes j and k ($j, k \in s \cup m$)
$disc_{ik}$	The distance among nodes i and k ($i, k \in p \cup m$)
$disd_{ij}$	The distance among nodes i and j ($i, j \in c \cup p$)
$caps_j$	Holding capacity of cold storage facility type j for holding red meat ($j \in s$)
$capf_i$	Holding capacity of packing facility type i for holding red meat ($i \in p$)
$capr_k$	Holding capacity of retailer type k for holding red meat ($k \in m$)

(*continued*)

thf_{it}	Maximum production capacity at packing facility type i in period t $(i \in p)$
thc_{it}	Maximum supply capacity at carcass supplier type i in period t $(i \in c)$
cva_{vp}	The storage capacity of vehicle type vp
cvb_{vs}	The storage capacity of vehicle type vs
cvc_{vc}	The storage capacity of vehicle type vc
cvd_{vm}	The storage capacity of vehicle type vm
vta_{vp}	Variable transport cost for vehicle type vp per unit distance
vtb_{vs}	Variable transport cost for vehicle type vs per unit distance
vtc_{vc}	Variable transport cost for vehicle type vc per unit distance
vtd_{vm}	Variable transport cost for vehicle type vm per unit distance
fta_{vp}	Fixed transport cost for vehicle type vp per trip
ftb_{vs}	Fixed transport cost for vehicle type vs per trip
ftc_{vc}	Fixed transport cost for vehicle type vc per trip
ftd_{vm}	Fixed transport cost for vehicle type vm per trip
nva_{vpt}	The number of vehicle type vp existing in period t
nvb_{vst}	The number of vehicle type vs existing in period t
nvc_{vct}	The number of vehicle type vc existing in period t
nvd_{vmt}	The number of vehicle type vm existing in period t
tn	The number of all available nodes
β	A coefficient converting the meat to carcass unit
I_{i0}	Initial inventory level of red meat in node i $(i \in p \cup m)$

3.3 Decision variables

ZS_j	1, if cold storage facility type j opened, 0, else $(j \in s)$
UA_{vpt}	1, if vehicle type vp is used in period t, 0, else
UB_{vst}	1, if vehicle type vs is used in period t, 0, else
UC_{vct}	1, if vehicle type vc is used in period t, 0, else
UD_{vmt}	1, if vehicle type vm is used in period t, 0, else
OP_{it}	1, if packing facility type i produces in period t, 0, else $(i \in p)$
XA_{ijvpt}	1, if arc (i,j) is visited by vehicle type vp in period t, 0, else $(i,j \in p \cup s)$
XB_{ikvct}	1, if arc (i,k) is visited by vehicle type vc in period t, 0, else $(i, k \in c \cup p)$
YA_{jkvst}	1, if arc (j,k) is visited by vehicle type vs in period t, 0, else ()
YB_{ikvmt}	1, if arc (i,k) is visited by vehicle type vm in period t, 0, else $(i, k \in p \cup m)$
XP_{it}	The quantity of red meat that facility type i produced in period t $(i \in p)$
QA_{ijvpt}	The quantity of red meat transferred among node i and j by the vehicle type vp in period t $(i,j \in p \cup s)$
QB_{ikvct}	The quantity of red meat transferred among node i and k by the vehicle type vc in period t $(i, k \in c \cup p)$
GA_{jkvst}	The quantity of red meat transferred among node j and k by the vehicle type vs in period t $(j, k \in s \cup m)$
GB_{ikvmt}	The quantity of red meat transferred among node i and k by the vehicle type vm in period t $(i, k \in p \cup m)$
I_{jt}	The inventory level at node j for red meat in period t $(j \in p \cup s \cup m)$
EA_{jt}	An auxiliary variable used for sub-tour elimination for cold storage facility type j in period t $(j \in s)$
EB_{kt}	An auxiliary variable used for sub-tour elimination for retailer type k at 3rd echelon in period t $(k \in m)$
EC_{it}	An auxiliary variable used for sub-tour elimination for packing facility type i in period t $(\mathrm{i} \in p)$
ED_{kt}	An auxiliary variable used for sub-tour elimination for retailer type k at 4th echelon in period t $(k \in m)$

3.4 Model stage 1

There are multiple carcass suppliers and multiple packing facilities, and retailers' demand is deterministic and variable in different periods. Carcass suppliers have a limited supply capacity in each period (Leksakul and Apiromchaiyakul, 2019). Besides, meat production by packing facilities deals with two types of costs, i.e. variable cost of red meat production and fixed cost of meat production processes. Furthermore, packing facilities have limited production throughput (Teigiserova *et al.*, 2019). Note that, packing facilities can store meat, and each warehouse has a

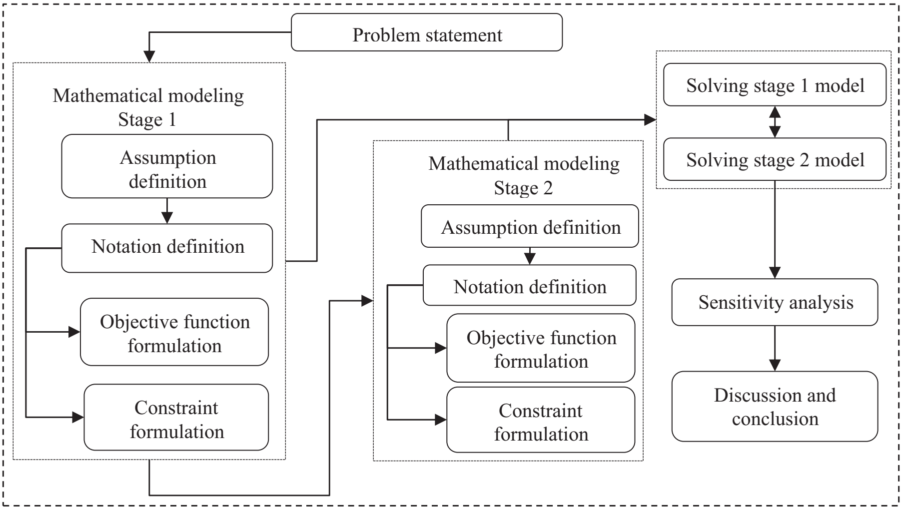

Figure 3.
The algorithmic scheme of the study

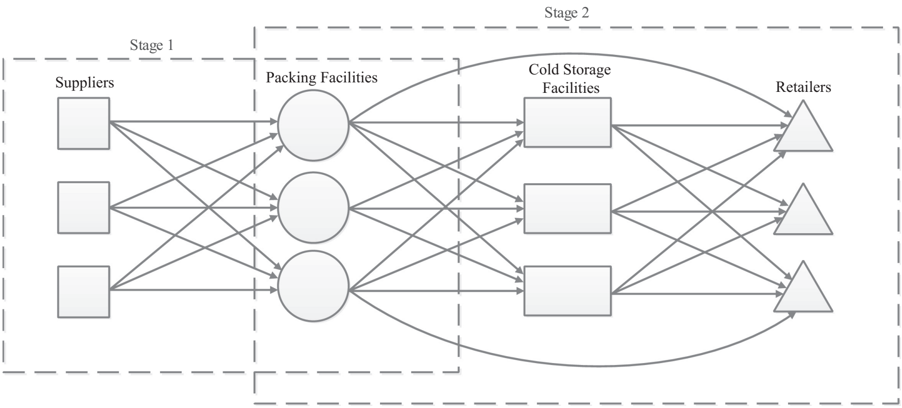

Figure 4.
Red meat supply chain network of this research

specific capacity for holding products and incurs inventory holding costs. In this model, each echelon uses a different fleet, and the number of vehicles is limited. Moreover, vehicles have different and limited capacities. Vehicles start their trip from carcass suppliers and return after delivering carcasses. Besides, variable transportation costs per trip and fixed vehicle costs are considered. The objective function (1) minimises the total supply chain costs, including the cost of carcass purchase from suppliers, variable and fixed production cost at packing facilities, inventory holding cost at packing facilities, variable transportation cost and fixed vehicle cost.

$$\min z = \left\{ \begin{array}{l} \sum_{i=1}^{C} \sum_{j=1}^{P} \sum_{vc=1}^{VC} \sum_{t=1}^{T} QB_{ijvct} sc_{it} + \sum_{i=1}^{P} \sum_{t=1}^{T} vpc_{it} XP_{it} + \sum_{i=1}^{P} \sum_{t=1}^{T} fpc_{i} OP_{it} \\ + \sum_{j=1}^{P} \sum_{t=1}^{T} ho_{jt} I_{jt} + \sum_{i=1}^{C+P} \sum_{k=1|i \neq k}^{C+P} \sum_{vc=1}^{VC} \sum_{t=1}^{T} vtc_{vc} disd_{ik} XB_{ikvct} + \sum_{vc=1}^{VC} \sum_{t=1}^{T} ftc_{vc} UC_{vct} \end{array} \right. \tag{1}$$

The constraints of the first stage are represented below. Constraint (2) is the inventory balance constraint for packing facilities.

$$I_{it} = I_{i(t-1)} + XP_{it} - \left(\sum_{j=1}^{S} \sum_{vp=1}^{VP} QA_{ijvpt} + \sum_{k=1}^{M} \sum_{vm=1}^{VM} GB_{ikvmt} \right) \quad \forall i \in p, t \tag{2}$$

Constraint (3) sets the amount of carcass needed based on the meat conversion factor.

$$\beta XP_{it} + \sum_{k=1|k \neq i}^{P} \sum_{vc=1}^{VC} QB_{ikvct} = \sum_{j=1|j \neq i}^{C+P} \sum_{vc=1}^{VC} QB_{jivct} \quad \forall i \in p, t \tag{3}$$

The capacity constraints are formulated in Eqs. (4) to (7). Constraint (4) ensures that meat production by packing facilities does not exceed their maximum throughput. Constraint (5) ensures that products held in the warehouses of packing facilities do not exceed the maximum allowable capacity. Constraint (6) denotes that the amount of carcass shipped by the supplier does not exceed the associated supply capacity. Constraint (7) indicates that, at each echelon, the total volume of products loaded on the vehicle does not exceed its maximum capacity.

$$XP_{it} \leq thf_{it} OP_{it} \quad \forall i \in p, t \tag{4}$$

$$I_{it} \leq capf_i \quad \forall i \in p, t \tag{5}$$

$$\sum_{j=1}^{P} \sum_{vc=1}^{VC} QB_{ijvct} \leq thc_{it} \quad \forall i \in c, t \tag{6}$$

$$QB_{ikvct} \leq cvc_{vc} XB_{ikvct} \quad \forall i \text{ and } k \in c \cup p, vc, t, i \neq k \tag{7}$$

The next set of constraints are related to transportation. Constraint (8) clarifies that if a vehicle is used for transportation, it must start its trip from the source node. Constraint (9) ensures that the number of vehicles used at each echelon does not exceed availability limits. Constraint (10) is related to node assignment at each echelon, convincing that a vehicle entering a node should leave the same node. Constraint (11) precludes the formation of sub-tours among nodes.

$$\sum_{j=1}^{C} \sum_{k=1}^{P} XB_{jkvct} = UC_{vct} \quad \forall vc, t \tag{8}$$

$$\sum_{i=1}^{C} \sum_{k=1}^{P} XB_{ikvct} \leq nvc_{vct} \quad \forall vc, t \tag{9}$$

$$\sum_{j=1|j \neq k}^{C+P} XB_{jkvct} = \sum_{j=1|j \neq k}^{C+P} XB_{kjvct} \quad \forall k \in c \cup p, vc, t \tag{10}$$

$$EC_{it} - EC_{jt} \geq 1 - tn \left(1 - \sum_{vc=1}^{VC} XB_{jivct} \right) \quad \forall i, j \in p, t, i \neq j \tag{11}$$

Constraint (12) certifies that the quantity of products transported by a vehicle is greater at the start of the trip than along the route.

$$\sum_{i=1}^{C}\sum_{k=1}^{P} QB_{ikvct} \geq \sum_{k=1}^{P}\sum_{j=1|k\neq j}^{P} QB_{kjvct} \quad \forall vc, t \tag{12}$$

The last set of constraints is related to the decision variables. Constraint (13) is related to decision variables for the first stage of the model.

$$\begin{array}{c} OP_{it}, XB_{ikvct}, UC_{vst} \in \{0,1\} \\ QB_{jkvct}, I_{jt}, EC_{it}, XP_{it} \geq 0 \end{array} \quad \forall i \text{ and } j \text{ and } k \in c \cup p, vc, t \tag{13}$$

3.5 Model stage 2

Model stage 2 consists of multiple packing facilities, multiple cold storage facilities and multiple retailers. The demand is deterministic and alternates in different periods. Packing facilities deliver meat to retailers either directly or indirectly through cold storage facilities. Besides, cold storage facilities and retailers can store meat, and warehouses at each node have a specific capacity for holding products and incur inventory holding costs. Note that, in this model, each echelon uses a different fleet, and the number of vehicles is limited. Also, vehicles have different and limited capacities. Vehicles start their trip from packing facilities and return to the initial node after delivering products. In this routing, variable transportation costs per trip and fixed vehicle costs are considered. The second stage objective function (14) is to minimise the total supply chain costs, including inventory holding costs at nodes, cold storage facility opening cost (if needed) and variable transportation cost, as well as fixed vehicle cost at each echelon.

$$\min z = \begin{cases} \sum_{j=1}^{S+M}\sum_{t=1}^{T} ho_{jt}I_{jt} + \sum_{j=1}^{S} afc_j ZS_j + \sum_{i=1}^{P+S}\sum_{j=1|i\neq j}^{P+S}\sum_{vp=1}^{VP}\sum_{t=1}^{T} vta_{vp}disa_{ij}XA_{ijvpt} \\ +\sum_{vp=1}^{VP}\sum_{t=1}^{T} fta_{vp}UA_{vpt} + \sum_{j=1}^{S+M}\sum_{k=1|j\neq k}^{S+M}\sum_{vs=1}^{VS}\sum_{t=1}^{T} vtb_{vs}disb_{jk}YA_{jkvst} + \sum_{vs=1}^{VS}\sum_{t=1}^{T} ftb_{vs}UB_{vst} \\ +\sum_{i=1}^{P+M}\sum_{k=1|i\neq k}^{P+M}\sum_{vm=1}^{VM}\sum_{t=1}^{T} vtd_{vm}disc_{ik}YB_{ikvmt} + \sum_{vm=1}^{VM}\sum_{t=1}^{T} ftd_{vm}UD_{vmt} \end{cases} \tag{14}$$

The first set of constraints in the second stage is related to inventory balance. Constraints (15) and (16) are related to inventory balance at cold storage facilities and retailers, respectively.

$$I_{jt} = I_{j(t-1)} + \sum_{i=1|i\neq j}^{P+S}\sum_{vp=1}^{VP} QA_{ijvpt} - \sum_{i=1|i\neq j}^{S}\sum_{v=1}^{VP} QA_{jivpt} - \sum_{k=1}^{M}\sum_{vs=1}^{VS} GA_{jkvst} \quad \forall j \in s, t \tag{15}$$

$$\begin{aligned} I_{kt} = I_{k(t-1)} &+ \sum_{j=1|j\neq k}^{S+M}\sum_{vs=1}^{VS} GA_{jkvst} - \sum_{j=1|j\neq k}^{M}\sum_{vs=1}^{VS} GA_{kjvst} + \sum_{i=1|i\neq k}^{P+M}\sum_{vm=1}^{VM} GB_{ikvmt} \\ &- \sum_{i=1|i\neq k}^{M}\sum_{vm=1}^{VM} GB_{kivmt} - de_{kt} \quad \forall k \in m, t \end{aligned} \tag{16}$$

The second set of the second stage constraints are related to the capacity. Constraint (17) determines that if a cold storage facility is opened, the amount of meat in the warehouse of the cold storage facility does not exceed the maximum allowable capacity. Constraint (18) indicates that the quantity of products held in retailer warehouses does not exceed their holding capacity. Constraints (19) to (21) ensure that, at any echelon, the total volume of products loaded on a vehicle does not exceed its capacity.

$$I_{jt} \leq caps_j ZS_j \quad \forall j \in s, t \tag{17}$$

$$I_{kt} \leq capr_k \quad \forall k \in m, t \tag{18}$$

$$QA_{ijvpt} \leq cva_{vp} XA_{ijvpt} \quad \forall i \text{ and } j \in p \cup s, vp, t, i \neq j \tag{19}$$

$$GA_{jkvst} \leq cvb_{vs} YA_{jkvst} \quad \forall j \text{ and } k \in s \cup m, vs, t, j \neq k \tag{20}$$

$$GB_{ikvmt} \leq cvd_{vm} YB_{ikvmt} \quad \forall i \text{ and } k \in p \cup m, vm, t, i \neq k \tag{21}$$

The vehicle-related constraints are added next. Constraints (22) to (24) ensure that if a vehicle is used, it should start its trip from the source node. Constraints (25) to (27) ensure that the number of vehicles used at each echelon does not exceed availability limits.

$$\sum_{i=1}^{P} \sum_{j=1}^{S} XA_{ijvpt} = UA_{vpt} \quad \forall vp, t \tag{22}$$

$$\sum_{j=1}^{S} \sum_{k=1}^{M} YA_{jkvst} = UB_{vst} \quad \forall vs, t \tag{23}$$

$$\sum_{i=1}^{P} \sum_{k=1}^{M} YB_{ikvmt} = UD_{vmt} \quad \forall vm, t \tag{24}$$

$$\sum_{i=1}^{P} \sum_{j=1}^{S} XA_{ijvpt} \leq nva_{vpt} \quad \forall vp, t \tag{25}$$

$$\sum_{j=1}^{S} \sum_{k=1}^{M} YA_{jkvst} \leq nvb_{vst} \quad \forall vs, t \tag{26}$$

$$\sum_{i=1}^{P} \sum_{k=1}^{M} YB_{ikvmt} \leq nvd_{vmt} \quad \forall vm, t \tag{27}$$

Constraints (28) to (30) are related to node assignment at each echelon, ensuring that a vehicle entering a node should leave the same node.

$$\sum_{i=1|i \neq j}^{P+S} XA_{ijvpt} = \sum_{i=1|i \neq j}^{P+S} XA_{jivpt} \quad \forall j \in p \cup s, vp, t \tag{28}$$

$$\sum_{j=1|j \neq k}^{S+M} YA_{jkvst} = \sum_{j=1|j \neq k}^{S+M} YA_{kjvst} \quad \forall k \in s \cup m, vs, t \tag{29}$$

$$\sum_{i=1|i \neq k}^{P+M} YB_{ikvmt} = \sum_{i=1|i \neq k}^{P+M} YB_{kivmt} \quad \forall k \in p \cup m, vm, t \tag{30}$$

Constraints (31) to (33) preclude the formation of sub-tours among nodes.

$$EA_{it} - EA_{jt} \geq 1 - tn\left(1 - \sum_{vp=1}^{VP} XA_{jivpt}\right) \quad \forall i, j \in s, t, i \neq j \tag{31}$$

$$EB_{it} - EB_{jt} \geq 1 - tn\left(1 - \sum_{vs=1}^{VS} YA_{jivst}\right) \quad \forall i, j \in m, t, i \neq j \tag{32}$$

$$ED_{it} - ED_{jt} \geq 1 - tn\left(1 - \sum_{vm=1}^{VM} YB_{jivmt}\right) \quad \forall i, j \in m, t, i \neq j \tag{33}$$

Constraints (34) to (36) ensure that the quantity of products transported by a vehicle at each echelon is greater at the start of the trip than along the route.

$$\sum_{i=1}^{P} \sum_{j=1}^{S} QA_{ijvpt} \geq \sum_{j=1}^{S} \sum_{k=1|j \neq k}^{S} QA_{jkvpt} \quad \forall vp, t \tag{34}$$

$$\sum_{j=1}^{S} \sum_{k=1}^{M} GA_{jkvst} \geq \sum_{k=1}^{M} \sum_{i=1|k \neq i}^{M} GA_{kivst} \quad \forall vs, t \tag{35}$$

$$\sum_{i=1}^{P} \sum_{k=1}^{M} GB_{ikvmt} \geq \sum_{k=1}^{M} \sum_{j=1|k \neq j}^{M} GB_{kjvmt} \quad \forall vm, t \tag{36}$$

The next two constraints are due to the balance of products entered and sent from cold storage facilities. Constraint (37) ensures that the quantity of products transported from cold storage facilities does not exceed its capacity. Constraint (38) convinces that the quantity of products transported from packing facilities to cold storage facilities is equal to the quantity transported from cold storage facilities to retailers. Constraint (39) ensures that the quantity of products produced by packing facilities plus the products held in the warehouses of packing facilities is more than or equal to the number of products transported from packing facilities to cold storage facilities, plus the number of products transported from packing facilities to retailers.

$$\sum_{k=1}^{M} \sum_{vs=1}^{VS} GA_{jkvst} \leq caps_j ZS_j \quad \forall j \in s, t \tag{37}$$

$$\sum_{i=1}^{P} \sum_{j=1}^{S} \sum_{vp=1}^{VP} \sum_{t=1}^{T} QA_{ijvpt} = \sum_{j=1}^{S} \sum_{k=1}^{M} \sum_{vs=1}^{VS} \sum_{t=1}^{T} GA_{jkvst} \tag{38}$$

$$XP_{it} + I_{i(t-1)} \geq \sum_{j=1}^{S} \sum_{vp=1}^{VP} QA_{ijvpt} + \sum_{k=1}^{M} \sum_{vm=1}^{VM} GB_{ikvmt} \quad \forall i \in p, t \tag{39}$$

The last set of constraints, i.e. constraint (40) is related to decision variables for the second stage of the model.

$$\begin{array}{ll} XA_{ijvpt}, YA_{jkvst}, YB_{ikvmt}, UA_{vpt}, UB_{vst}, UD_{vmt}, ZS_j \in \{0,1\} & \forall vp, vs, vm, t, \\ QA_{ijvpt}, GA_{jkvst}, GB_{ikvmt}, I_{jt}, EA_{it}, EB_{it}, ED_{it} \geq 0 & i \text{ and } j \text{ and } k \in p \cup s \cup m \end{array} \tag{40}$$

4. Case study and results

In this section, the two-stage model for the designed red meat supply chain is applied to a numerical instance. After solving the model, the outcomes are evaluated, and the best strategy for the company is determined. This instance includes 63 nodes, 42 retailers, 12 cold storage facilities, four packing facilities and five carcass suppliers. Retailers are the major stores across Iran with significant demand for red meat. The 12 cold storage facilities were randomly selected. In addition to the main meatpacking facility of the company, the rest of the packing facilities were randomly selected from different parts of the country. The five carcass suppliers were also randomly selected based on their reputation. Seven periods were considered, and the length of each period is one month. Two types of vehicles were considered at every echelon, 20-ton (v_1), and 10-ton (v_2) vehicles. However, only for the routes among cold storage facilities and retailers (within Tehran), four types of vehicles were considered, 20-ton (v_1), 10-ton (v_2), 5-ton (v_3) and 2-ton (v_4) vehicles. A key point regarding red meat transportation in Iran is that according to veterinary organisation limitations, it is not feasible to transfer red meat by a vehicle between two provinces or two different retailers. Table 2 presents the retailers' demand and holding capacity information in each period. The data are in tons. Moreover, the costs of carcass supply are calculated using information from the *State Livestock Affairs Company* and are \$21,515, \$20,909, \$19,697, \$19,091 and \$18,788, respectively. There are no constraints on carcass supply by suppliers.

The required tonnage of the carcass is determined by multiplying the production quantity of the packing facility by the meat conversion factor. This factor (β) is considered to be 1.25 based on the opinion of the company's experts. For example, 10 tons of packed meat requires 12.5 tons of carcasses. Note that, the variable transportation cost per ton for each vehicles type is \$0.063, \$0.068, \$0.072 and \$0.077; the fixed transportation cost for each vehicles type is \$518, \$382, \$305 and \$195; eventually, the storage capacity of vehicles in each echelon is 20, 10, 5 and 2 (Tons), respectively. The fixed and variable transportation costs are obtained based on the rates set by *Iran Road Maintenance and Transportation Organisation*. The number of available vehicles is considered unlimited since vehicle rental companies can provide the company with an unlimited number of vehicles. Information about meatpacking costs is provided in Table 3. This information is based on the analyses made by the company's experts and middle-level managers.

The initial inventory level is considered zero at all nodes. Inventory holding costs and loading/unloading costs of cold storage facilities in 2018 were \$18 and \$4, respectively; according to the *Consumer and Producer Protection Organisation of Iran*. The holding capacity of cold storage facilities is considered to be 20,000 tons. The distance among nodes is calculated in kilometres (Tables 4–7).

The proposed models are solved using GAMS software (version 24.1.2) on a personal computer (Intel(R) Core (TM) 2.40 GHz). Solving both stages of the model indicates that the required carcass is only purchased from the fifth supplier (c_5). Moreover, meatpacking facilities 1 and 2 (p_1, p_2) affiliated with the company are used for red meat production. The outcomes indicate that there is no need for opening cold storage facilities, and that red meat is directly shipped from packing facilities to retailers. Additionally, the warehouses of retailers and packing facilities are used for holding inventory. Meatpacking facilities operate only during the first six periods. Table 8 illustrates the quantity of meat transported between different echelons. The outcomes indicate that no product is transported in the seventh period since the demanded meat has been supplied to retailers during the prior periods, and there is no need to produce meat in packing facilities during the seventh period.

The vehicle employed at each echelon has the following characteristics/parameters:

Table 2. The demand for retailers and holding capacity

Retailer	Holding capacity	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7	Retailer	Holding capacity	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7
m_1	15	15	15	15	15	15	15	5	m_{22}	15	15	10					
m_2	10	10	10	10	10	10			m_{23}	20	20	20	20	20			
m_3	22	22	21	20	20	20	20		m_{24}	20	20	20	17	10			
m_4	15	15	10	10	10				m_{25}	10	10	10	7				
m_5	13	13	13	10	10				m_{26}	20	20	10					
m_6	15	15	10	10	10	10			m_{27}	36	36	30	30	30			
m_7	15	15	15	15	15	15	10		m_{28}	13	12	13					
m_8	10	10	10	10	10	10			m_{29}	10	10	10					
m_9	10	10	10	10	10	10			m_{30}	22	22	20	20				
m_{10}	15	15	10						m_{31}	11	11	10	10				
m_{11}	10	10	5						m_{32}	20	20	20	20	12			
m_{12}	15	15	15	10	10	10	10	10	m_{33}	10	10	5					
m_{13}	50	50	35	32	28				m_{34}	15	15	10					
m_{14}	10	10	10						m_{35}	20	20	20	20	10			
m_{15}	10	10	10	10	6				m_{36}	20	20	15	10				
m_{16}	15	15	10	10					m_{37}	25	25	20	10				
m_{17}	10	10	10	10	10				m_{38}	10	10	10					
m_{18}	20	20	11						m_{39}	15	15						
m_{19}	10	10	10	10					m_{40}	20	20	10	10				
m_{20}	15	15	10	10	10				m_{41}	20	20	12					
m_{21}	10	10	10						m_{42}	15	15	13					

(1) For the carcass suppliers to packing facilities node, vehicle v_1 should be used 60, 24, 20, 18, 4 and 2 times, respectively, for periods one to six;

(2) For the packing facilities to retailers node, vehicle v_1 should be used 50, 18, 13, 12, 3 and 2 times, respectively, for periods one to six;

(3) For the packing facilities to retailers node, vehicle v_2 should be used 4, 6, 7 and 5 times, respectively, for periods one to four.

The outcomes indicate that the first vehicle type (20 tons) is used more frequently than the second vehicle type (10 tons). The quantity of inventory held by meatpacking facilities and retailers is provided in Table 9. The data indicates that only the quantity of meat required by these facilities is stored in their warehouses.

The total cost for this instance is \$50,385,721 obtained by GAMS in 2,664 s. The total transportation cost for all echelons, including variable and fixed costs, is \$358,918. Meat production and inventory holding cost, which includes the fixed and variable cost of meat production in packing facilities in the first stage is \$2,328,924. Finally, the cost of carcass purchase in the first stage is \$47,697,879. Based on the calculated retailer demand that is 2,031 tons, the cost per kg of meat is \$24.8. Reports gathered from the experts at the studied company indicate that the cost per kg of meat for the proposed instance was \$25.3, while the cost obtained by solving the proposed model was \$24.8, indicating an improvement of about \$0.5.

5. Discussion and implication

For this section, sensitivity analysis has been considered to assess any changes in the system, and it recommends more practical insights for the managers.

5.1 Sensitivity analysis: retailers' holding capacity

According to the case study, the retailers' holding capacity is considered to be limited and equal to their maximum demand during the studied periods. Based on reports from previous years, it may not be possible to fully utilise this capacity in certain periods. Here, the effect on the solution of the model is examined. The worst-case scenario is considered, and the response of the model is observed. The assumption is that retailers have zero capacity for holding products, and every product received is delivered to the customers. Solving both stages of the model indicates that, similar to the original scenario, the required carcass is only purchased from the fifth supplier (c_5). Moreover, meatpacking facilities 1 and 2 (p_1, p_2) affiliated with the company are used for red meat production. Even in this scenario, there is no need for opening cold storage facilities, and red meat is directly transported from packing facilities to retailers. An important observation in this scenario is that only the warehouses of packing facilities are used to hold inventory, and these facilities operate in all seven periods. Table 10 illustrates the quantity amount of meat transported among echelons in scenario 2.

Table 3. Meatpacking facility specifications of the problem

Packing facility	Inventory holding cost (\$)	Warehouse capacity	Maximum production capacity	Fixed production cost (\$)	Variable production cost (\$)
p_1	9	4,000	900	475	611
p_2	9	100	300	455	727
p_3	14	100	600	909	909
p_4	14	500	900	818	818

Table 4. Trip distances among packing facilities and cold storage facilities (KM)

Node	p_1	p_2	p_3	p_4	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}
p_1	0	632	2,322	1,796	1,811	1,797	1,790	1,422	1,589	631	1,987	1,953	1,844	1,240	690	1,488
p_2	651	0	2,008	1,482	1,496	1,481	1,476	1,226	979	2	1,509	1,640	1,609	1,073	754	1,172
p_3	2,306	1,991	0	612	560	571	612	1,188	1,488	1,991	790	485	923	1,387	1,781	898
p_4	1,790	1,475	617	0	49	45	22	746	879	1,477	193	164	794	956	1,265	458
s_1	1,804	1,489	582	45	0	20	62	724	939	1,489	230	130	785	922	1,279	433
s_2	1,792	1,477	569	42	20	0	50	712	927	1,477	232	145	773	910	1,267	421
s_3	1,789	1,474	630	20	60	53	0	754	876	1,474	206	178	791	944	1,264	455
s_4	1,399	1,217	1,200	747	762	747	740	0	1,365	1,217	938	799	451	200	760	349
s_5	1,616	976	1,498	886	927	939	884	1,315	0	976	769	1,045	1,609	1,394	1,409	1,138
s_6	651	2	2,008	1,482	1,498	1,483	1,476	1,227	981	0	1,511	1,640	1,610	1,077	754	1,174
s_7	1,978	1,504	784	189	226	228	202	934	794	1,504	0	332	980	1,142	1,452	644
s_8	1,939	1,624	474	153	122	149	172	788	1,030	1,596	331	0	849	986	1,385	497
s_9	1,765	1,620	931	792	786	771	785	449	1,600	1,620	983	812	0	566	1,158	565
s_{10}	1,215	1,070	1,394	941	957	942	935	201	1,396	1,069	1,132	993	567	0	576	523
s_{11}	676	747	1,799	1,247	1,289	1,274	1,267	748	1,421	747	1,465	1,431	1,154	566	0	965
s_{12}	1,480	1,165	906	454	435	420	447	347	1,120	1,165	645	506	557	536	955	0

As the results indicate, products are shipped in every period, whereas in the prior scenario (scenario 1), no product is produced/transported in the seventh period. In other words, transportation has increased in this scenario compared to the previous one. Vehicle usage at each echelon for this scenario is as follows:

(1) For the carcass suppliers to packing facilities' node, vehicle v_1 should be used 43, 35, 24, 16, 6, 3 and 1 times, respectively, for periods one to seven.

(2) For the packing facilities to retailers' node, vehicle v_1 should be used 35, 20, 12, 8, 3 and 2 times, respectively, for periods one to six.

(3) For the packing facilities to retailers' node, vehicle v_2 should be used 13, 25, 17, 14, 5, 2 and 2 times, respectively, for periods one to seven.

Compared to scenario number 1, the second vehicle type (10 tons) is used more frequently in the route among packing facilities and retailers. The quantity of inventory held in packing facilities is 5 tons for period two in the first node and 2,11,11 and 7 tons for the second node, respectively, in period one to four. These data indicate higher levels of inventory holding in the warehouses of packing facilities compared to scenario number 1.

In the second scenario, the total cost is $50,402,240 obtained by GAMS in 21 s. Solution time has decreased significantly compared to the prior scenario, which is due to no inventory holding strategy followed by retailers. Transportation cost at different echelons is $372,106, which includes both variable and fixed costs. Meat production and inventory holding cost, which includes the fixed and variable cost of meat production in packing facilities in the first stage, is $2,332,255. Finally, the cost of carcass purchase in the first stage is $47,697,879. Comparing these outcomes with the original scenario indicates an increase in total costs by $16,519. This increase is due to the higher levels of inventory held in the warehouses of packing facilities as well as the increase in transportation cost.

5.2 Sensitivity analysis: supply capacity at carcass suppliers

In this section, a sensitivity analysis is performed on the supply capacity of carcass suppliers which has been considered infinite in the real case study. However, according to previous reports, some suppliers may face a limited carcass supply in some periods; thus, it is necessary to investigate the impact of this issue on the results of the case study. In this part, the least possible case stated in the reports, which is equal to 300 tons per month, is considered as the maximum supply capacity at carcass suppliers. After solving the problem in two stages, it is observed that all the values obtained in the second stage are the same as the first scenario. Nonetheless, the values obtained in the first stage have been affected. The main point of this scenario is the purchase of the required carcass from suppliers 2 to 5

Node	c_1	c_2	c_3	c_4	c_5	p_1	p_2	p_3	p_4
c_1	0					1,806	1,584	606	15
c_2		0				1,506	1,192	880	438
c_3			0			1,569	952	1,500	890
c_4				0		5	635	2,311	1,794
c_5					0	628	4	1,993	1,482
p_1	1,800	1,502	1,565	4	628	0	632	2,322	1,796
p_2	1,492	1,187	938	635	3	651	0	2,008	1,482
p_3	603	889	1,489	2,326	2,007	2,306	1,991	0	612
p_4	12	437	878	1,800	1,476	1,790	1,475	617	0

Table 5. Trip distances among carcass suppliers and packing facilities (KM)

Table 6. Trip distances among cold storage facilities and retailers (KM)

Node	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}	s_{11}	s_{12}
m_1	44	47	32	758	880	1,487	190	156	803	957	1,274	467
m_2	59	57	31	762	874	1,492	190	177	809	962	1,280	473
m_3	37	42	36	758	893	1,487	199	147	801	957	1,288	452
m_4	53	58	37	766	881	1,492	188	160	818	966	1,284	473
m_5	33	40	34	755	891	1,485	205	146	799	955	1,273	466
m_6	47	45	19	750	876	1,479	191	164	796	949	1,267	460
m_7	59	55	32	762	877	1,491	186	168	809	961	1,280	472
m_8	44	50	35	760	892	1,489	194	153	806	959	1,277	470
m_9	63	63	43	773	888	1,502	183	163	819	972	1,290	483
m_{10}	42	46	40	755	887	1,485	192	152	802	950	1,273	466
m_{11}	93	91	44	727	852	1,456	230	210	775	926	1,244	437
m_{12}	24	41	75	762	932	1,526	233	111	807	996	1,314	455
m_{13}	934	939	890	1,292	30	952	813	1,051	1,615	1,371	1,395	1,141
m_{14}	768	773	725	1,239	241	1,111	517	886	1,450	1,364	1,486	1,007
m_{15}	1,146	1,131	1,124	1,008	522	458	1,052	1,287	1,387	1,086	1,047	862
m_{16}	318	320	295	1,026	679	1,432	80	424	1,073	1,225	1,388	737
m_{17}	162	147	140	575	955	1,364	338	257	658	774	1,153	285
m_{18}	125	142	176	781	1,033	1,584	335	8	842	979	1,372	490
m_{19}	312	329	363	920	1,220	1,724	522	190	823	1,119	1,512	630
m_{20}	304	321	354	950	1,211	1,753	288	182	924	1,148	1,541	659
m_{21}	451	455	428	1,089	547	1,307	213	557	1,242	1,214	1,397	803
m_{22}	259	264	215	892	662	1,371	231	376	940	1,091	1,230	602
m_{23}	744	761	794	1,352	1,652	2,155	953	622	1,005	1,550	1,943	1,061
m_{24}	599	589	649	1,207	1,507	2,010	808	477	1,120	1,405	1,798	916
m_{25}	649	634	665	878	1,543	1,814	854	596	434	995	1,534	658
m_{26}	567	558	618	1,175	1,475	1,978	558	445	1,089	1,374	1,767	885
m_{27}	430	416	435	321	1,139	1,184	641	502	531	501	925	37
m_{28}	1,049	1,034	1,027	295	1,666	1,360	1,224	1,086	475	305	744	635
m_{29}	519	504	531	268	1,335	1,280	728	590	487	457	968	131
m_{30}	799	783	798	430	1,612	1,602	995	824	22	548	1,106	547
m_{31}	1,486	1,472	1,465	1,216	969	9	1,500	1,628	1,599	1,064	722	1,163
m_{32}	940	925	918	182	1,379	1,076	1,116	976	547	22	580	507
m_{33}	764	748	742	6	1,317	1,217	939	801	446	195	753	350
m_{34}	471	455	486	1,009	1,364	1,812	675	417	598	1,216	1,600	718
m_{35}	478	463	494	786	892	1,779	683	425	473	959	1,277	587
m_{36}	998	982	976	727	938	519	1,173	1,139	1,110	574	496	673
m_{37}	468	453	467	611	1,281	1,565	664	493	316	860	1,285	409
m_{38}	267	252	267	561	1,081	1,490	464	338	525	785	1,279	302
m_{39}	564	581	614	1,172	1,471	1,975	773	442	938	1,370	1,763	881
m_{40}	1,286	1,270	1,264	768	1,417	726	1,461	1,427	1,168	585	2	961
m_{41}	301	286	317	731	1,195	1,643	506	248	568	1,038	1,431	549
m_{42}	625	610	603	386	931	870	801	767	768	464	658	301

(c_2, c_3, c_4, c_5). Table 11 illustrates the amounts of meat transferred between nodes in the third scenario.

The transportation of products in the second stage is similar to that of the first scenario. However, in the first stage, it is observed that the cost of transportation has increased due to the increase in the number of carcass suppliers. After comparing the results with Scenario 1, it is obvious that the same number and types of vehicles have been used. Only in the sixth period in the first stage, a 10-ton vehicle has been employed. Moreover, the amount of inventory held in the packing facility warehouse has decreased compared to Scenario 1, and only in the second period, an amount of 4 tons is stored in the first packing facility warehouse.

Table 7.
Trip distances among packing facilities and retailers (KM)

Node	p_1	p_2	p_3	p_4	Node	p_1	p_2	p_3	p_4
m_1	1,802	1,487	608	13	m_{22}	1,757	1,371	829	217
m_2	1,806	1,492	629	18	m_{23}	2,470	2,155	188	775
m_3	1,802	1,489	600	30	m_{24}	2,325	2,010	121	630
m_4	1,810	1,496	613	22	m_{25}	2,129	1,814	621	663
m_5	1,799	1,485	598	15	m_{26}	2,293	1,978	328	599
m_6	1,794	1,479	616	6	m_{27}	1,499	1,184	894	441
m_7	1,806	1,491	620	18	m_{28}	1,403	1,360	1,397	1,033
m_8	1,804	1,489	606	16	m_{29}	1,595	1,280	990	537
m_9	1,817	1,502	616	29	m_{30}	1,747	1,602	943	804
m_{10}	1,799	1,485	604	12	m_{31}	651	9	1,997	1,471
m_{11}	1,771	1,456	663	55	m_{32}	1,221	1,076	1,377	930
m_{12}	1,841	1,526	563	56	m_{33}	1,394	1,217	1,201	748
m_{13}	1,592	952	1,504	892	m_{34}	2,127	1,812	326	484
m_{14}	1,751	1,111	1,338	727	m_{35}	1,804	1,489	461	492
m_{15}	1,098	458	1,656	1,130	m_{36}	834	519	1,508	982
m_{16}	1,915	1,432	874	279	m_{37}	1,880	1,565	628	473
m_{17}	1,679	1,352	658	147	m_{38}	1,805	1,490	612	273
m_{18}	1,899	1,584	462	157	m_{39}	2,290	1,975	18	595
m_{19}	2,038	1,724	276	344	m_{40}	655	724	1,795	1,270
m_{20}	2,068	1,753	472	335	m_{41}	1,958	1,643	444	315
m_{21}	1,923	1,307	1,011	416	m_{42}	1,185	870	1,135	609

In the third scenario, the total cost is $51,493,366, which was obtained by GAMS in 2,823 s. Solution time increased compared to Scenario 1, which was due to the reduction of the capacity of carcass suppliers and supply from different suppliers. The transportation cost at different echelons is $385,460, which includes both variable and fixed costs. Meat production and inventory holding cost, which includes the fixed and variable cost of meat production in packing facilities in the first stage, is $2,328,815. Eventually, the cost of carcass purchase in the first stage is $48,779,091. Comparing these outcomes with the original scenario indicates an increase in total costs by $1,107,645. This increase is due to the supply of carcasses at higher prices from different suppliers. This increase is also due to the increase in the cost of transporting products. Figure 5 illustrates a comparison between the outcomes of solving the three scenarios for more clarification.

5.3 Managerial insights

Theoretically, the problem presented in this research is a multi-period MILP considering a heterogeneous vehicle fleet and vehicle routing problem. One of the main contributions considered in this problem is the two-stage model consisting of a single-echelon in the first and a three-echelon in the second stage of the model. The first stage includes several carcass suppliers and several packing facilities where after purchasing the carcass, production operations related to red meatpacking are performed. The second stage includes several packing facilities, several cold storage facilities and several retailers where after determining the required cold storage facilities, the product is transferred to retailers.

In *practical* terms, the results presented in Section 4 specify the optimal network structure of a meat production and distribution network. Considering the importance of this product in the nutrition of the population in the emerging economy of Iran and the social and economic impacts of poor performance for these networks, the results can be used as a basis for structuring, producing and optimally distributing similar products. The various parameters of the problem play a crucial role in operational decisions. Increasing and decreasing the parameters can change the supply chain members decisions so that they have a direct impact

Node		Vehicle	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7	Node		Vehicle	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7
c_5	p_1	v_1	817.5	98.75	20					p_2	m_5	v_1		20					
c_5	p_2	v_1	375	375	375	357.5	80	40		p_2	m_6	v_1				20			
p_1	m_1	v_1	15							p_2	m_7	v_2			10				
p_1	m_2	v_1	20							p_2	m_7	v_1				20	20		
p_1	m_3	v_1	40							p_2	m_8	v_2			10				
p_1	m_4	v_1	15							p_2	m_8	v_1	20			20			
p_1	m_5	v_1	16							p_2	m_9	v_2			10				
p_1	m_6	v_1	15	20						p_2	m_9	v_1				20			
p_1	m_7	v_1	15	20						p_2	m_{10}	v_2		5					
p_1	m_9	v_1	20							p_2	m_{11}	v_1	15						
p_1	m_{10}	v_1	20							p_2	m_{12}	v_1		20		20		20	
p_1	m_{12}	v_1	20							p_2	m_{13}	v_2		5					
p_1	m_{17}	v_1	20							p_2	m_{13}	v_1	60	20	40	20			
p_1	m_{18}	v_1	31							p_2	m_{14}	v_1	20						
p_1	m_{19}	v_1	20							p_2	m_{15}	v_1	20		16				
p_1	m_{20}	v_1	20							p_2	m_{16}	v_1	15	20					
p_1	m_{25}	v_1	20							p_2	m_{17}	v_1			20				
p_1	m_{27}	v_1	36							p_2	m_{19}	v_2			10				
p_1	m_{28}	v_2	5							p_2	m_{20}	v_2		5					
p_1	m_{28}	v_1	20							p_2	m_{20}	v_1			20				
p_1	m_{29}	v_1	20							p_2	m_{21}	v_1	20						
p_1	m_{30}	v_2	2							p_2	m_{22}	v_2		5					
p_1	m_{30}	v_1	40							p_2	m_{22}	v_1	20						
p_1	m_{32}	v_1	20	20	20					p_2	m_{23}	v_1	20	20	20	20			
p_1	m_{33}	v_1	15							p_2	m_{24}	v_2				10			
p_1	m_{34}	v_1	20							p_2	m_{24}	v_1	20	20	17				
p_1	m_{36}	v_1	20	15						p_2	m_{25}	v_2			7				
p_1	m_{37}	v_1	35							p_2	m_{26}	v_2		10					
p_1	m_{38}	v_1	20							p_2	m_{26}	v_1	20						
p_1	m_{39}	v_1	15							p_2	m_{27}	v_2				10			
p_1	m_{40}	v_1	40							p_2	m_{27}	v_1		40	20	20			

(*continued*)

Table 8.
Transferred red meat among nodes

Table 8.

Node		Vehicle	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7	Node		Vehicle	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7
p_1	m_{41}	v_1	20							p_2	m_{30}	v_1			20				
p_1	m_{42}	v_1	19							p_2	m_{31}	v_1	16	15					
p_2	m_1	v_1		20	20	20		20		p_2	m_{32}	v_1				12			
p_2	m_2	v_2			10					p_2	m_{34}	v_2	5						
p_2	m_2	v_1				20				p_2	m_{35}	v_2				10			
p_2	m_3	v_2		3						p_2	m_{35}	v_1	20	20	20				
p_2	m_3	v_1			20	20	40			p_2	m_{36}	v_2			10				
p_2	m_4	v_2				10				p_2	m_{37}	v_1		20					
p_2	m_4	v_1		20						p_2	m_{41}	v_1		12					
p_2	m_5	v_2				10				p_2	m_{42}	v_2	9						

	Period								Period						
Node	t_1	t_2	t_3	t_4	t_5	t_6	t_7	Node	t_1	t_2	t_3	t_4	t_5	t_6	t_7
p_1		4						m_{21}	10						
p_2				4	8			m_{22}	5						
m_1		5	10	15		5		m_{23}							
m_2	10			10				m_{24}							
m_3	18				20			m_{25}	10						
m_4		10						m_{26}							
m_5	3	10						m_{27}		10					
m_6		10		10				m_{28}	13						
m_7		5		5	10			m_{29}	10						
m_8	10			10				m_{30}	20						
m_9	10			10				m_{31}	5	10					
m_{10}	5							m_{32}							
m_{11}	5							m_{33}	5						
m_{12}	5	10		10		10		m_{34}	10						
m_{13}	10		8					m_{35}							
m_{14}	10							m_{36}							
m_{15}	10		6					m_{37}	10	10					
m_{16}		10						m_{38}	10						
m_{17}	10		10					m_{39}							
m_{18}	11							m_{40}	20	10					
m_{19}	10							m_{41}							
m_{20}	5		10					m_{42}	13						

Table 9. The inventory level in nodes

on determining the final price of a product. Furthermore, decisions made by the red meat supply chain members have both direct and indirect impacts on other issues, such as environmental problems that must be addressed by all members of the supply chain and government agencies. The following illustrates the *managerial implications* derived from this research, which can help to design the supply chain networks of red meat for similar real circumstances.

(1) In some red meat supply chain networks, livestock is not purchased directly, i.e. carcasses are purchased, converted to red meat and delivered to customers. Hence, to achieve the best economic outcomes, different scenarios in the supply chain network should be investigated and examined. Moreover, given the outcomes from solving the proposed model, it is clear that some real-world problems such as vehicle routing problems are not addressed accurately.

(2) The capacity set by retailers for holding products plays a significant role in strategic decision-making within the supply chain and could lead to significant changes in the cost per kg of product. Thus, in case an integrated supply chain is considered and information continuously flows between its different echelons, the price of red meat can be minimised significantly.

(3) Another important issue to consider in the red meat supply chain is the carcass supply capacity provided by suppliers. This amount varies at different times of the year, and producers must plan carefully to supply the red meat consumed by customers to avoid carcass shortages. This is important in an emergency when the demand for red meat increases. It is also possible to rent the cold storage facilities to reduce transportation costs and maintain the quality of the final product to store the red meat needed for a subsequent time and distribute it to retailers at specified times.

Node		Vehicle	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7
c_5	p_1	v_1	476.25	318.75	100				
c_5	p_2	v_1	375	375	375	320	120	60	18.75
p_1	m_3	v_1	22	21	20				
p_1	m_5	v_1		13					
p_1	m_6	v_1	15						
p_1	m_7	v_1	15	15	15				
p_1	m_{10}	v_1	15						
p_1	m_{12}	v_1	15	15					
p_1	m_{18}	v_1	20						
p_1	m_{20}	v_1	15						
p_1	m_{23}	v_1	20						
p_1	m_{24}	v_1	20	20					
p_1	m_{27}	v_1	36	30					
p_1	m_{28}	v_1	12	13					
p_1	m_{30}	v_1	22	20	20				
p_1	m_{32}	v_1	20	20	20				
p_1	m_{33}	v_2	10	5					
p_1	m_{34}	v_1	15						
p_1	m_{35}	v_1	20	20					
p_1	m_{36}	v_1	20	15					
p_1	m_{37}	v_1	14	20					
p_1	m_{40}	v_2		10	10				
p_1	m_{40}	v_1	20						
p_1	m_{41}	v_1	20						
p_1	m_{42}	v_1	15	13					
p_2	m_1	v_1	15	15	15	15	15	15	
p_2	m_1	v_2							5
p_2	m_2	v_2	10	10	10	10	10		
p_2	m_3	v_1				20	20	20	
p_2	m_4	v_2		10	10	10			
p_2	m_4	v_1	15						
p_2	m_5	v_2			10	10			
p_2	m_5	v_1	13						
p_2	m_6	v_2		10	10	10	10		
p_2	m_7	v_2						10	
p_2	m_7	v_1				15	15		
p_2	m_8	v_2	10	10	10	10	10		
p_2	m_9	v_2	10	10	10	10	10		
p_2	m_{10}	v_2		10					
p_2	m_{11}	v_2	10	5		20			
p_2	m_{12}	v_2							10
p_2	m_{12}	v_2			10	10	10	10	
p_2	m_{13}	v_1	50	35	32	28			
p_2	m_{14}	v_2	10	10					
p_2	m_{15}	v_2	10	10	10	6			
p_2	m_{16}	v_2		10	10				
p_2	m_{16}	v_1	15						
p_2	m_{17}	v_2	10	10	10	10			
p_2	m_{18}	v_2		11					
p_2	m_{19}	v_2	10	10	10				
p_2	m_{20}	v_2		10	10	10			
p_2	m_{21}	v_2	10	10					
p_2	m_{22}	v_2		10					

Table 10.
Transferred red meat among nodes (Scenario 2)

(*continued*)

Node		Vehicle	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7
p_2	m_{22}	v_1	15						
p_2	m_{23}	v_1		20	20	20			
p_2	m_{24}	v_2				10			
p_2	m_{24}	v_1			17				
p_2	m_{25}	v_2	10	10	7				
p_2	m_{26}	v_2		10					
p_2	m_{26}	v_1	20						
p_2	m_{27}	v_1			30	30			
p_2	m_{29}	v_2	10	10					
p_2	m_{31}	v_2		10	10				
p_2	m_{31}	v_1	11						
p_2	m_{32}	v_2				12			
p_2	m_{34}	v_2		10					
p_2	m_{35}	v_2				10			
p_2	m_{35}	v_1			20				
p_2	m_{36}	v_2			10				
p_2	m_{37}	v_2			10				
p_2	m_{37}	v_1	11						
p_2	m_{38}	v_2	10	10					
p_2	m_{39}	v_1	15						
p_2	m_{41}	v_1		12					

Table 10.

Node		Vehicle	Period t_1	t_2	t_3	t_4	t_5	t_6	t_7
$c2$	p_1	v_1	277.5						
$c2$	p_2	v_1	15						
$c3$	p_1	v_1	240						
$c3$	p_2	v_1	60						
$c4$	p_1	v_1	300	98.75	20				
$c4$	p_2	v_1		75	75	52.5			
$c5$	p_1	v_2						10	
$c5$	p_2	v_1	300	300	300	300	75	40	

Table 11. Transferred red meat among nodes (Scenario 3)

(4) The adverse impact of meat consumption decline (per capita) on the health of the general public highlights the significance of the reduction in the price of red meat. In other words, cost reduction not only increases the profitability of meat producers but also benefits society. Coordination and integration within the entire red meat supply chain are necessary for achieving this goal and controlling the prices in the market.

6. Conclusion

In this study, a two-stage, four-echelon location-inventory-routing problem for the red meat supply chain was presented. Important assumptions of this research include considering the vehicle fleet as heterogeneous, time horizon as multi-period and considering the carcass suppliers in the first level and retailers in the last level. Compared to previous researches, this combination and problem were not investigated. To validate the two-stage model, the

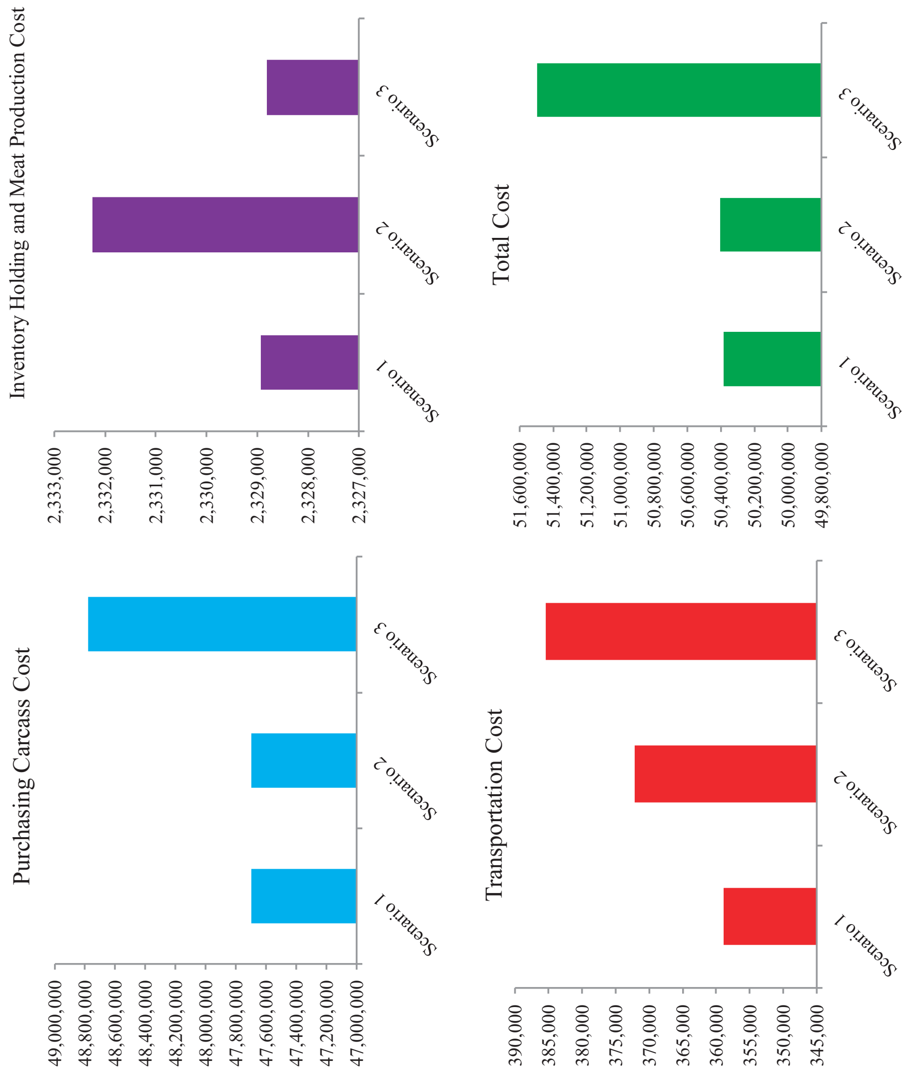

Figure 5.
Comparison of the outcomes of the three scenarios

presented models were implemented in a real case scenario. The real instance was solved using GAMS, and the outcomes indicated that the proposed model resulted in a reduction in the cost per kg of red meat by about 2%, compared to the current market price. Other outcomes obtained by solving the model include (1) the definition of the optimal quantity of meat production in packing facilities in each period, (2) a determination as to whether to produce meat at any given period, (3) whether to open cold storage facilities as part of the supply chain, (4) the definition of the quantity of product transported at each level of the supply chain, (5) the definition of the quantity of product held at each node, (6) the best vehicles and (7) the best transportation routes. Moreover, a sensitivity analysis was performed on the inventory holding capacity of the retailers. This scenario assumed that retailers have no holding capacity in their warehouses. Solving the model with this assumption indicated an increase in total costs due to higher levels of inventory held in the warehouses of packing facilities as well as the increase in the transportation cost. Eventually, another sensitivity analysis was performed on the supply capacity at carcass suppliers. In this scenario, it was assumed that each supplier can supply carcasses up to the minimum amount that was available in previous reports. After solving the model with these conditions, it was found that costs had increased. This increase is due to the supply of carcasses at higher prices from different suppliers.

According to relevant literature and the proposed model, the red meat supply chain was integrated from the livestock supply level to the customer level, given that there are three different types of products in this chain (livestock, carcasses and red meat). As some meat-producing companies may purchase packed red meat directly from other countries as imported goods and only focus on the distribution and supplier selection issues, the supply chain of packed red meat distribution may be examined in future researches. To generalise the proposed model for supply chains of other agricultural products and livestock products, the constraints of the supply chain of each product must be carefully examined and considered in the network design. Moreover, depending on the problem, conditions such as fuzzy or stochastic demand can be incorporated into the model instead of deterministic parameters. Features such as a transshipment and time window can also be added to the modelling to better distribute the red meat. Experimental design can also be used to integrate and consider other parameters for sensitivity analysis. The main advantage of experimental design is to consider the interaction of the parameters and their effects on the initial results. Other characteristics can also be included in the model if needed. For instance, the sustainability pillars especially social and environmental aspects should be considered in future models.

References

Adesogan, A.T., Havelaar, A.H., McKune, S.L., Eilittä, M. and Dahl, G.E. (2020), "Animal source foods: sustainability problem or malnutrition and sustainability solution? Perspective matters", *Global Food Security*, Vol. 25, pp. 100-125.

Al Shamsi, A., Al Raisi, A. and Aftab, M. (2014), "Pollution-inventory routing problem with perishable goods", in *Logistics Operations, Supply Chain Management and Sustainability*, Springer, Cham, pp. 585-596.

Anderluh, A., Larsen, R., Hemmelmayr, V.C. and Nolz, P.C. (2019), "Impact of travel time uncertainties on the solution cost of a two-echelon vehicle routing problem with synchronization", *Flexible Services and Manufacturing Journal*, Vol. 32 No. 4, pp. 806-828.

Bergeron, N., Chiu, S., Williams, P.T., King, S.M. and Krauss, R.M. (2019), "Effects of red meat, white meat, and nonmeat protein sources on atherogenic lipoprotein measures in the context of low compared with high saturated fat intake: a randomized controlled trial", *The American Journal of Clinical Nutrition*, Vol. 110 No. 1, pp. 24-33.

Biuki, M., Kazemi, A. and Alinezhad, A. (2020), "An integrated location-routing-inventory model for sustainable design of a perishable products supply chain network", *Journal of Cleaner Production*, Vol. 1 No. 260, p. 120842.

Boudahri, F., Bennekrouf, M. and Sari, Z. (2011), "Optimization and design of the transportation network of agri-foods supply chain: application chicken meat", *International Journal of Advanced Engineering Science and Technological*, Vol. 11 No. 1, pp. 213-220.

Cheraghalipour, A., Paydar, M.M. and Hajiaghaei-Keshteli, M. (2019), "Designing and solving a bi-level model for rice supply chain using the evolutionary algorithms", *Computers and Electronics in Agriculture*, Vol. 162, pp. 651-668.

Coelho, L.C., Cordeau, J.F. and Laporte, G. (2014), "Thirty years of inventory routing", *Transportation Science*, Vol. 48 No. 1, pp. 1-19.

doMartins, L.C., Hirsch, P. and Juan, A.A. (2021), "Agile optimization of a two-echelon vehicle routing problem with pickup and delivery", *International Transactions in Operational Research*, Vol. 28 No. 1, pp. 201-221.

Fakhrzad, M.B. and Goodarzian, F. (2021), "A new multi-objective mathematical model for a citrus supply chain network design: metaheuristic algorithms", *Journal of Optimization in Industrial Engineering*, Vol. 14 No. 2, pp. 127-144.

Frisk, M., Jonsson, A., Sellman, S., Flisberg, P., Rönnqvist, M. and Wennergren, U. (2018), "Route optimization as an instrument to improve animal welfare and economics in pre-slaughter logistics", *PloS One*, Vol. 13 No. 3, p. e0193223.

Geoffrion, A.M. and Graves, G.W. (1974), "Multi commodity distribution system design by Bender's decomposition", *Management Science*, Vol. 20 No. 5, pp. 822-844.

Gholami-Zanjani, S.M., Jabalameli, M.S. and Pishvaee, M.S. (2021), "A resilient-green model for multi-echelon meat supply chain planning", *Computers and Industrial Engineering*, Vol. 152, p. 107018.

Gholamian, M.R. and Taghanzadeh, A.H. (2017), "Integrated network design of wheat supply chain: a real case of Iran", *Computers and Electronics in Agriculture*, Vol. 140, pp. 139-147.

González-Araya, M.C., Soto-Silva, W.E. and Espejo, L.G.A. (2015), "Harvest planning in apple orchards using an optimization model", in *Handbook of Operations Research in Agriculture and the Agri-Food Industry*, Springer, New York, NY, pp. 79-105.

Govindan, K., Fattahi, M. and Keyvanshokooh, E. (2017), "Supply chain network design under uncertainty: a comprehensive review and future research directions", *European Journal of Operational Research*, Vol. 263 No. 1, pp. 108-141.

Govindan, K., Jafarian, A., Khodaverdi, R. and Devika, K. (2014), "Two-echelon multiple-vehicle location–routing problem with time windows for optimization of sustainable supply chain network of perishable food", *International Journal of Production Economics*, Vol. 152, pp. 9-28.

Hajiagha, S.H.R., Mahdiraji, H.A., Tavana, M. and Hashemi, S.S. (2018), "A novel common set of weights method for multi-period efficiency measurement using mean-variance criteria", *Measurement*, Vol. 129, pp. 569-581.

Heidari, M., Jafari, M.J. and Rahbari, M. (2018), "Modeling a multi-objective location-routing problem for hazardous materials with CO2 emissions consideration", *14th International Industrial Engineering Conference*, 2018vol, IIEC, Tehran.

Heidari, M., Rahbari, M. and Mohseni, A.R. (2019), "Modeling a multi-objective vehicle routing problem for monetary operation in the banking system", *2019 15th Iran International Industrial Engineering Conference (IIIEC)*, IEEE, Tehran, pp. 18-22.

Hiassat, A., Diabat, A. and Rahwan, I. (2017), "A genetic algorithm approach for location-inventory-routing problem with perishable products", *Journal of Manufacturing Systems*, Vol. 42, pp. 93-103.

Jafarian, A., Asgari, N., Mohri, S.S., Fatemi-Sadr, E. and Farahani, R.Z. (2019), "The inventory-routing problem subject to vehicle failure", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 126, pp. 254-294.

Javanmard, S., Vahdani, B. and Tavakkoli-Moghaddam, R. (2014), "Solving a multi-product distribution planning problem in cross docking networks: an imperialist competitive algorithm", *The International Journal of Advanced Manufacturing Technology*, Vol. 70 Nos 9-12, pp. 1709-1720.

Kitjacharoenchai, P., Min, B.C. and Lee, S. (2020), "Two echelon vehicle routing problem with drones in last mile delivery", *International Journal of Production Economics*, Vol. 225, p. 107598.

Koç, Ç. (2019), "Analysis of vehicle emissions in location-routing problem", *Flexible Services and Manufacturing Journal*, Vol. 31 No. 1, pp. 1-33.

Leksakul, K. and Apiromchaiyakul, C. (2019), "Fuzzifying approach to special cutting in poultry meat production planning", *Journal of Industrial and Production Engineering*, Vol. 36 No. 7, pp. 419-432.

Li, Q. and Liu, A. (2019), "Big data driven supply chain management", *Procedia CIRP*, Vol. 81, pp. 1089-1094.

Linnemann, A.R., Hendrix, E.M., Apaiah, R. and van Boekel, T.A. (2015), "Food chain design using multi criteria decision making, an approach to complex design issues", *NJAS-Wagen Journal of Life Science*, Vols 72-73, pp. 13-21.

Mahdiraji, H.A., Turskis, Z., Jafarnejad, A. and Rezayar, A. (2019a), "Non-cooperative two-echelon supply chains with a focus on social responsibility", *Technological and Economic Development of Economy*, Vol. 25 No. 6, pp. 1162-1187.

Mahdiraji, H.A., Kazimieras Zavadskas, E., Kazeminia, A. and Abbasi Kamardi, A. (2019b), "Marketing strategies evaluation based on big data analysis: a CLUSTERING-MCDM approach", *Economic Research-Ekonomska Istraživanja*, Vol. 32 No. 1, pp. 2882-2892.

Mahdiraji, H.A., Hafeez, K., Jafarnejad, A. and Rezayar, A. (2020), "An analysis of the impact of negative CSR 'forced labour' parameter on the profitability of supply chain contracts", *Journal of Cleaner Production*, Vol. 271, p. 122274.

Mahmoudi, M., Mahdiraji, H.A., Jafarnejad, A. and Safari, H. (2019), "Dynamic prioritization of equipment and critical failure modes", *Kybernetes*, Vol. 48 No. 9, pp. 1913-1941.

Miranda, P.A. and Garrido, R.A. (2004), "Incorporating inventory control decisions into a strategic distribution network design model with stochastic demand", *Transportation Research Part E: Logistics and Transportation Review*, Vol. 40 No. 3, pp. 183-207.

Miranda, P.A. and Garrido, R.A. (2009), "Inventory service-level optimization with in distribution network design problem", *International Journal of Production Economics*, Vol. 122 No. 1, pp. 276-285.

Mirzaei, S. and Seifi, A. (2015), "Considering lost sale in inventory routing problems for perishable goods", *Computers and Industrial Engineering*, Vol. 87, pp. 213-227.

Mohammed, A. and Wang, Q. (2017a), "Developing a meat supply chain network design using a multi-objective possibilistic programming approach", *British Food Journal*, Vol. 119 No. 3, pp. 690-706.

Mohammed, A. and Wang, Q. (2017b), "The fuzzy multi-objective distribution planner for a green meat supply chain", *International Journal of Production Economics*, Vol. 184, pp. 47-58.

Mohebalizadehgashti, F., Zolfagharinia, H. and Amin, S.H. (2020), "Designing a green meat supply chain network: a multi-objective approach", *International Journal of Production Economics*, Vol. 219, pp. 312-327.

Moons, K., Waeyenbergh, G. and Pintelon, L. (2019), "Measuring the logistics performance of internal hospital supply chains–a literature study", *Omega*, Vol. 82, pp. 205-217.

Mosca, A., Vidyarthi, N. and Satir, A. (2019), "Integrated transportation–inventory models: a review", *Operations Research Perspectives*, Vol. 6, p. 100101.

Motevalli-Taher, F., Paydar, M.M. and Emami, S. (2020), "Wheat sustainable supply chain network design with forecasted demand by simulation", *Computers and Electronics in Agriculture*, Vol. 178, p. 105763.

Mousavi, S.M. and Tavakkoli-Moghaddam, R. (2013), “A hybrid simulated annealing algorithm for location and routing scheduling problems with cross-docking in the supply chain”, *Journal of Manufacturing Systems*, Vol. 32 No. 2, pp. 335-347.

Nayeri, S., Paydar, M.M., Asadi-Gangraj, E. and Emami, S. (2020), “Multi-objective fuzzy robust optimization approach to sustainable closed-loop supply chain network design”, *Computers and Industrial Engineering*, Vol. 148, p. 106716.

Neves-Moreira, F., Almada-Lobo, B., Cordeau, J.F., Guimarães, L. and Jans, R. (2019), “Solving a large multi-product production-routing problem with delivery time windows”, *Omega*, Vol. 86, pp. 154-172.

Orjuela-Castro, J.A., Sanabria-Coronado, L.A. and Peralta-Lozano, A.M. (2017), “Coupling facility location models in the supply chain of perishable fruits”, *Research in Transportation Business and Management*, Vol. 24, pp. 73-80.

Pirkul, H. and Jayaraman, V. (1996), “Production, transportation and distribution planning in a multi-commodity tri-echelon system”, *Transportation Science*, Vol. 30 No. 4, pp. 291-302.

Pishvaee, M.S. and Rabbani, M. (2011), “A graph theoretic-based heuristic algorithm for responsive supply chain network design with direct and indirect shipment”, *Advanced Engineering Software*, Vol. 42 No. 3, pp. 57-63.

Rafie-Majd, Z., Pasandideh, S.H.R. and Naderi, B. (2018), “Modelling and solving the integrated inventory-location-routing problem in a multi-period and multi-perishable product supply chain with uncertainty: Lagrangian relaxation algorithm”, *Computers and Chemical Engineering*, Vol. 109, pp. 9-22.

Rahbari, M., Naderi, B. and Mohammadi, M. (2018), “Modelling and solving the inventory routing problem with CO 2 emissions consideration and transshipment option”, *Environmental Processes*, Vol. 5 No. 3, pp. 649-665.

Rahbari, M., Hajiagha, S.H.R., Dehaghi, M.R., Moallem, M. and Dorcheh, F.R. (2020), “Modeling and solving a five-echelon location–inventory–routing problem for red meat supply chain”, *Kybernetes*, Vol. 50 No. 1, pp. 66-99.

Saragih, N.I., Bahagia, N. and Syabri, I. (2019), “A heuristic method for location-inventory-routing problem in a three-echelon supply chain system”, *Computers and Industrial Engineering*, Vol. 127, pp. 875-886.

Schütz, P., Tomasgard, A. and Ahmed, S. (2009), “Supply chain design under uncertainty using sample average approximation and dual decomposition”, *European Journal of Operational Research*, Vol. 199 No. 2, pp. 409-419.

Soysal, M., Bloemhof-Ruwaard, J.M. and Van Der Vorst, J.G. (2014), “Modelling food logistics networks with emission considerations: the case of an international beef supply chain”, *International Journal of Production Economics*, Vol. 152, pp. 57-70.

Tavakkoli-Moghaddam, R. and Raziei, Z. (2016), “A new bi-objective location-routing-inventory problem with fuzzy demands”, *IFAC-PapersOnLine*, Vol. 49 No. 12, pp. 1116-1121.

Teigiserova, D.A., Hamelin, L. and Thomsen, M. (2019), “Review of high-value food waste and food residues biorefineries with focus on unavoidable wastes from processing”, *Resources, Conservation and Recycling*, Vol. 149, pp. 413-426.

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

Tsao, Y.C., Mangotra, D., Lu, J.C. and Dong, M. (2012), “A continuous approximation approach for the integrated facility-inventory allocation problem”, *European Journal of Operational Research*, Vol. 222 No. 2, pp. 216-228.

ur Rahman, M.S. and ur Rehman, M.S. (2020), “CPEC and Pakistan-India economic integration: prospects and challenges”, *Journal of Global Peace and Security Studies*, Vol. 1 No. 1, pp. 70-89.

van Huis, A. and Oonincx, D.G. (2017), "The environmental sustainability of insects as food and feed. A review", *Agronomy for Sustainable Development*, Vol. 37 No. 5, pp. 43-60.

Wang, X., Wang, M., Ruan, J. and Zhan, H. (2016), "The multi-objective optimization for perishable food distribution route considering temporal-spatial distance", *Procedia Computer Science*, Vol. 96, pp. 1211-1220.

Yao, Z., Lee, L.H., Jaruphongsa, W., Tan, V. and Hui, C.F. (2010), "Multi-source facility location–allocation and inventory problem", *European Journal of Operational Research*, Vol. 207 No. 2, pp. 750-762.

Yavari, M. and Geraeli, M. (2019), "Heuristic method for robust optimization model for green closed-loop supply chain network design of perishable goods", *Journal of Cleaner Production*, Vol. 226, pp. 282-305.

Zhao, J. and Ke, G.Y. (2017), "Incorporating inventory risks in location-routing models for explosive waste management", *International Journal of Production Economics*, Vol. 193, pp. 123-136, available at: http://www.sciencedirect.com/science/journal/24058963.

Zheng, X., Yin, M. and Zhang, Y. (2019), "Integrated optimization of location, inventory and routing in supply chain network design", *Transportation Research Part B: Methodological*, Vol. 121, pp. 1-20.

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