A Multi-Objective Linear Optimization Model for Designing Sustainable Closed-Loop Agricultural Supply Chain

Hossein Reyhani Yamchi
Department of Management
University of Tabriz
Tabriz, Iran
h.reyhaniyamchi@gmail.com

Younis Jabarzadeh
Department of Management
University of Tabriz
Tabriz, Iran
yjabarzade@tabrizu.ac.ir

Nader Ghaffarinasab
Department of Industrial Engineering
University of Tabriz
Tabriz, Iran
ngnasab@tabrizu.ac.ir

Vikas Kumar
Bristol Business School
University of the West of England
Bristol, UK
Vikas.Kumar@uwe.ac.uk

Jose Arturo Garza-Reyes
Derby Management School
University of Derby
Derby, UK
j.reyes@derby.ac.ir

Abstract

Demand for agricultural products will grow by nearly 70 percent in 2050 and high volume of chemical pesticides and agricultural fertilizers along with considerable waste in this sector induces serious environmental concerns. Hence it is not a priority but a necessity to modify unsustainable procedures to make them sustainable. The aim of this study is developing and analyzing a multi-objective (MO) linear mathematical model for sustainable close-loop agricultural supply chain (CLASC) with a deteriorating product to determine (1) the optimal flow to every echelon and (2) the optimal location of some facilities to achieve three objectives: reducing costs and carbon dioxide (CO_2) emissions throughout the proposed supply chain (SC) network, and increasing the responsiveness. Finally, a numerical example is used to evaluate the optimization model.

Keywords
Closed loop network, sustainable Agricultural supply chain, multi objective optimization and reverse logistics

1. Introduction

Resource scarcity is a prominent threat to ecosystems, and climate changes affect the environment. Eventually, awareness of environmental pressure leads to increased demand for sustainable production. Moreover, the development of government regulation on environmental issues has prompted the industries to redesign the SC network to achieve three dimensions of the sustainable output: economic, social, and environmental, called triple bottom line (TBL).

The concept of closed loops (CLs), which refers to the integration of forward and reverse SC activities (Guide et al., 2003), is one of the options considered to ensure SC stability (Chaabane et al., 2012). This topic has been extensively studied and has given rise to the subject area of the closed-loop supply chain (CLSC) (Paksoy et al., 2011). In CLSCs, items that are not used long-term and are partially recoverable are considered (Flapper et al., 2005). SC planning, especially in the area of production and transportation planning, has been extensively studied (Catala et al., 2013; Mula et al., 2006), but it is less common in the agricultural food industry. Agriculture is a significant national source and a great employer. Recently, the ASC, which refers to the chain that produces and distributes agricultural products (Ahumada and Villalobos, 2009; Aramyan et al., 2006), has been considered extensively. The two main types of ASC are fresh and non-perishable agri-food chains. In the SC of agricultural products, the raw materials used for production usually disappear either because of consumption or because of their loss of value (e.g., fruit rot). Wasted agri-foods can be valuable in other SCs. So compared to the discrete parts industry, there is no value in waste products to be recycled in CLASC. Food wastes (FW) can be used in a wide range of applications including energy production, animal feed production, chemical and pharmaceutical applications as well as compost production. Supposing that the gardeners consume the compost produced in the return stream, the SC can be assumed to be CL. Therefore, CLASC may need to rethink business processes and redesign distinct logistics structures fundamentally.

In recent years the demand for fresh fruit has been increased intensively. Consequently, Fruit production is considered as one of the major economic sectors in developing countries such as Iran that has ranked first in fruit production in the Middle East and eighth among the top ten fruit-producing countries in the world recently (FAOStat, 2010). Annually in the gardens, distribution centers, and fruit markets, large quantities of fruits are inedible due to rotting that can cause enormous losses for producers, distributors, and consumers. Given these considerable losses, the necessity of reverse logistics (RL) implementation, which involves return product flows in the fruit supply chain (FSC), is unavoidable (Cheraghalipour et al., 2018).

A review of the literature shows the gaps in mathematical modeling research on sustainable CLASC design optimization. There is no research work to address the problem of agricultural products CL network design using a MO optimization model to address trade-offs between the three pillars of sustainability in the system. Therefore, this paper presents a mathematical model for designing a CLSC network of fruits that is capable of integrating both forward and reverse flows for product processing. One of the main methods of recycling organic waste is vermicomposting that the result of this process is not only a considerable amount of organic fertilizer but also saving human health and the environment. Thus, in this article, vermicomposting facilities are considered in reverse logistic. Mixed-Integer linear programming developed in the form of a MO formula designed to address costs, CO2 emissions and responding to customer demand in each sector (forward and reverse), and providing decision-makers with a tool Comprehensive SC evaluation is used to select the most sustainable solution for the SC.

2. Literature review

Recently, the demand for agricultural production increased because of fresh fruits' popularity. Only in the last decade, the agricultural food industry has been identified as a critical concept for competitiveness in SC (Lucas and Chhajed, 2004). One of the earliest researches carried out by Ahumada and Villalobos in 2009 discussed the simulation models in the ASC of a variety of agricultural foods as well as vegetables. Subsequently, a new version of mathematical models for the crop industry, such as fruits and vegetables, was presented by Zhang and Wilhelm (2011). Due to optimize freshness of the fruit, Amorim et al. (2012) have studied the production and distribution of biodegradable foods. Nadal-Roig and Pla-Aragones (2015) developed a transport planning model for FSC. In this model, some depository hubs provided a fruit logistics center on demand through the off-season. Soto-Silva et al. (2016) introduced a fresh fruit SC model, along with a brief review. Several studies, such as the MO optimization model, developed by Sarker and Ray (2009), concentrated on the MO analysis of ASC planning problems. Sarker and Ray's method admitted as the ε-constrained method and some MO metaheuristic algorithms.

Additionally, due to assess the environmental impacts of SC activities, several explorers have used the carbon emission index extensively as a validated indicator. Paksoy et al. (2010) have evaluated the minimization of CO2 emission, the cost in forward logistic, and the minimization of SC costs only in RL in the MO linear programming model. The

environmental impacts of facility construction and transportation of products alongside the objective of the total cost function in a reverse paper recycling SC have been modeled by Pishvaee et al. (2012). They used a fuzzy programming approach to handle the uncertainty of parameters in their model.

El Korchi and Millet (2011) have studied the criteria to obtain a sustainable SC that contains economic, social, and environmental considerations simultaneously. In a sustainable rubber recovery network, established by Dehghanian and Mansour (2009), end-of-life ecological effects of used tires was assessed by a life cycle analysis, social impact was evaluated by measuring social responsibility, and the economic impact was determined by profit purpose function. An analytical hierarchy process (AHP) was also used to calculate the social effects as well as a MO genetic algorithm to find Pareto-Optimal solution. One of the environmental issues in SCs attracted the attention of experts is the amount of waste produced and in response, it's recycling (Paksoy et al. , 2010) as the aim is to recover the value of some products after they have been consumed instead of being buried or burned (Dekker et al., 2012). Value recovery of a product typically involves RL activities such as reuse, repair, recycling, and rebuilding (Jayaraman, 2006). Therefore, RL includes all activities that start with the used product (meaning not be user requirements) until they can be reused in a market (Fleischmann et al. 1997). Thus, the significance of RL has resulted in the benefit of this strategic tool for the economic benefits of a company and has a positive social image for companies (Kannan et al., 2012).

In a CLSC, material flows are circular, and manufactured products are not disposed after being used but instead dismantled, reused, recovered, or recycled as raw materials (Hassini et al., 2012). Wang et al. (2011) have proposed a nonlinear model for the problem of CLSC design in which the pervasive tree approach is used to model the problem. A mixed-integer linear programming model has been introduced by Pishvaee et al. (2010) to minimize transportation costs and fixed construction costs in a multi-echelon RL network using a simulated annealing algorithm.

MO optimization is currently being used to solve different decision-making problems and test the performance of different configurations and operational strategies in the SC (Aramyan et al., 2011 and Ramudhin et al., 2010). A MO probabilistic model was presented by Ramezani et al. (2013) for the integrated logistics network design under uncertainty in which levels of decision making in the forward network include suppliers, production centers, and distribution centers and in the reverse network include collection centers and disposal centers. The objective functions (OFs) used in the model are intended to maximize profit, customer responsiveness, and quality. Özkır and Başlıgil (2012) examined the critical features of CLSC creation, including product recovery processes. After defining CLSC levels, including of customers, collection centers, production centers, recovery centers, and distribution centers, they provide a MO optimization model with the objectives of maximizing business satisfaction, customer satisfaction, and ultimately total profits. FW mainly occurs in the primitive and last stages of the SC, namely agricultural production, inspection, and storage immediately after harvest and consumption (FAO, 2013). That can be utilized in a wide range of industrial applications, containing energy production, animal feed production, chemical, or pharmaceutical applications (Girotto et al., 2015).

Stindt and Sahamie (2014) argue that researches on CLSCs in the process industries are limited, and challenges for non-integral products are not sufficiently addressed. The models developed in the agri-food SC are different from those developed for the discrete sector industries because of the need to improve product value during specific recovery and reverse flow of waste due to corruption, which is generated from the production process and not by customers. Few ASC decision support models in the literature consider material flows as closed loops that use waste material for production in the same SC. The CLSC of industrial mushrooms was presented by Banasik et al. (2017) in which the first framework for the CLASC was introduced. The crop medium could be reused or recycled in the studied mushroom SC. As such, a complex integer linear programming model for the CLSC design challenge to balance economic and environmental indicators was examined. Cheragalipour et al. (2018) developed a new mathematical model solved by some renowned meta-heuristic algorithms to reduce citrus CLSC costs and maximize meeting customer demand in forward and reverse flow. In this model, rotten citrus fruits are collected from all progressive stages in the SC and transferred to composting centers and then processed into organic fertilizer. Eventually, these fertilizers are purchased by the producer (gardener) and entered to the SC.

The environmental and economic implications of CLs in the field of ASC, especially in real case studies, should be examined According to the research by Mirabella et al. (2014). Also, conventional waste recovery options (reuse, repair, recover, and recycle) do not apply to individual products, and there are challenges in reviewing recovery options for process industries. Based on the case study in our study, we will make the first attempt to create a framework for sustainable CLASC. .

3. Problem definition

In line with national and international regulatory frameworks, the concept of sustainable SC has been translated by industries into a set of strategic decisions and operational practices, some of which have indirect effects on the entire

SC. Even though research on sustainable SC has long been introduced, further research developments in this area, given its expanse, are still needed. Especially in the field of sustainability research at the ASC is rarely seen. It should be noted that no research has assessed the negative environmental impacts of ASC.
In this paper, a mathematical model for optimizing the CLSC performance of apple fruit, including economic, social, and environmental performance indicators, is developed in a sustainable SC network scheme. In fact, in addition to measuring total costs, for all financial costs in a specific CLSC scheme, social performance is assessed based on responding to customer demand as well as environmental performance based on CO_2 emissions. Since the three SC performance indices are exerted in mathematical modeling, MO optimization is performed to construct the sustainable SC mathematical model. The designed logistics network is a multi-period and single-product consisting of five types of echelon with names of producers (gardens), distribution centers, fruit customers, composting centers, and compost markets, as shown in Figure 1. Given the balance between the three sustainability performance indicators, this model allows decision-makers to achieve the best CLSC design of apple fruit, to determine what facilities (distribution/ composting centers) should be incorporated in the network, and the amount of products flows between different echelons. Also, it optimizes the level of inventory in distribution centers. In this model, there are three product forms (fresh product, wasted product, and composted product) which details the product movement based on the product form as follows:

- Fresh produce shipped from producer to customer and distribution center that lasts for up to three periods as the apple fruit harvest time. Besides, part of the customer's unfulfilled demand for fruit is satisfied by distribution centers. This part of the flow is assumed to last up to eight periods.
- Wasted products are collected from fruit customers, distribution centers, and gardens and transported to composting centers. These products flow from the gardens for up to three months and from the other two up to 8 months.
- Composted products that are obtained from the conversion of wasted products in the composting centers and are flowed to the compost markets.

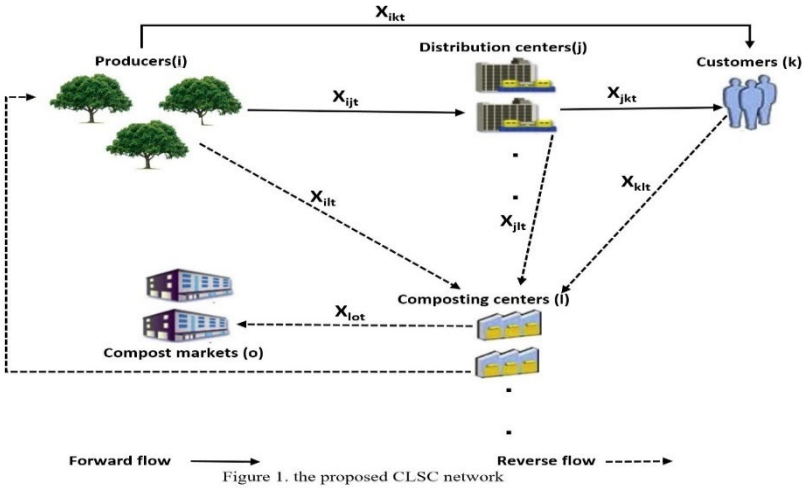

Figure 1. the proposed CLSC network

The assumptions underlying this model are:

- The locations of customers, producers (gardens) are fixed and predetermined.
- In any echelon in forwarding flow, the quality of the fruit may decline and, as a result, become unusable and transferred to reverse logistics.
- The initial inventory of distribution centers is zero.
- Products shipped from gardens are considered variable because not all gardens products are considered on the network and product shipped from each of them is expected to be less than or equal to the maximum production. Other crops that are not shipped from the gardens are considered to be wasteful and result in reduced financial and environmental performance.
- Customers' demands in both markets are given.
- Percentage of products in markets, distribution centers, and gardens are wasted and can be transferred to composting centers.

4. Model formulation

4.1 Indices

$i = 1, 2, \ldots, I$	The production locations (Gardens)
$j_1 = 1, 2, \ldots, J_1$	The fixed points of the distribution locations
$j_2 = 1, 2, \ldots, J_2$	The potential points of the distribution locations
$j = j_1 + j_2$	All points of the distribution locations
$k = 1, 2, \ldots, K$	The customer locations (fruit markets)
$l_1 = 1, 2, \ldots, L_1$	The fixed points of the compositing locations
$l_2 = 1, 2, \ldots, L_2$	The potential points of the compositing locations
$l = l_1 + l_2$	All points of the composting locations
$t = 1, 2, \ldots, t', \ldots, T$	Time periods
$o_1 = 1, 2, \ldots, O_1$	The compost markets
$o_2 = 1, 2, \ldots, O_2$	Some of producers/ Gardens as compost customers
$o = o_1 + o_2$	The compost customer locations

4.2 Parameters

f_j	Fixed cost of opening a fruit distribution center j
f_l	Fixed cost of opening a composting center l
d_c	Transportation cost per unit of distance per unit of product (\$/*km.ton*)
$d_{rr'}$	Distance from Location r to Location r' (*km*)
ch_{jt}	Holding cost per unit of inventory from distribution center j at Time t (\$/*ton*)
cp_{jt}	Processing and packing cost per unit of products from distribution center j at time t
cr_{lt}	Compost manufacturing cost per unit of products from compositing center l at time t
cp'	Production cost per unit of products from producers
ρ	Weighted coefficient (importance) to respond the fruit demand
d_{kt}	Demand of processed product by customer k at time t
$1 - \rho$	Weighted coefficient (importance) to respond the compost demand
d_{ot}'	Demand of reprocessed product (compost) by compost market o at time t
fe_j	Fixed emissions to establish (opening) distribution center j
fe_l	Fixed emissions to establish (opening) composting center l
eh_j	Holding emissions in distribution center j
ep_j	Emissions of processing and packing per unit of products from distribution center j
ec_l	Emission for reprocessing product in compositing center l
ep_i'	Production emission per unit of products from producers
de	Transportation emissions per unit of distance per unit of product
α_t	Waste percentage of harvested product by producers at time t
M	A big positive number
λc_{it}	Production capacity of producer i at time t
λh_j	Holding capacity of distribution center j
θ_t	Waste percentage of stored product by customers at time t
β_t	Waste percentage of stored product by distribution centers at time t
λr_l	Compost manufacturing capacity of composting center l
φ	Conversion rate of the fruit to compost
wc	Destroying cost per unit of wasted fruits
we	Destroying emissions per unit of wasted fruits

4.3 Decision variables

W_j	1 If distribution center j is opened at location, 0 otherwise
Y_l	1 If composting center l is opened at location, 0 otherwise
$X_{rr't}$	Flow of product from location r *(i, j, k, l, o)* to location r' *(i, j, k, l, o)* at time t (*ton*)
Ih_{jt}	Quantity of stored processed products by distribution center j at time t (*ton*)
λ_{it}	Quantity of production entered into the supply chain by producer i at time t

4.4 Objective Functions

4.4.1 Minimize Costs

Min Z= $Z_1 + Z_2 + Z_3 + Z_4 + Z_5$

$$Z_1 = \sum_{j=1}^{J} f_j W_j + \sum_{l=1}^{L} f_l Y_l$$

$$Z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{t'} X_{ijt} d_{ij} dc + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{t'} X_{ikt} d_{ik} dc + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} X_{jkt} d_{jk} dc + \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{t'} X_{ilt} d_{il} dc$$
$$+ \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} X_{jlt} d_{jl} dc + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} X_{klt} d_{kl} dc + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} X_{lot} d_{lo} dc$$

$$Z_3 = \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} Ih_{jt} ch_{jt}$$

$$Z_4 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{t'} X_{ijt} cp_{jt} + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} X_{lot} cr_{lt} + \sum_{i=1}^{I}\sum_{t=1}^{t'} \lambda_{it} cp'$$

$$Z_5 = \sum_{i=1}^{I}\sum_{t=1}^{t'} \left(\lambda c_{it} - \lambda_{it}\right) wc + \left(\sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{t'} \left(\alpha_t \lambda_{it} - X_{ilt}\right) + \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} \left(\beta_t Ih_{i(t-1)} - X_{jlt}\right) \right) wc$$
$$+ \left(\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} \left(\theta_t \left(X_{ikt} + X_{jkt}\right) - X_{klt}\right) \right) wc \tag{6}$$

First objective function (Z) minimizes the total costs which is comprised of fixed opening costs (Z_1), transportation costs (Z_2), holding cost of distribution centers (Z_3), production cost of producers, processing cost of distribution centers and reprocessing costs of composting centers (Z_4), and destroying Cost of wasted fruits (Z_5). The mathematical formulation of the objective function is described in Eqs. (1)(6).

4.4.2 Maximize Responsiveness

$$Max\ Z' = \rho \times \left[\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{t'} X_{ikt} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} X_{jkt} \right] \Big/ \left[\sum_{k=1}^{K}\sum_{t=1}^{t'} d_{kt} \right]$$
$$+ \left(1-\rho\right) \times \left[\sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} X_{lot} \right] \Big/ \left[\sum_{o=1}^{O}\sum_{t=1}^{T} d'_{ot} \right] \tag{7}$$

The second objective function (Z') maximizes the responsiveness to customer demand in both flows. This function consists of two fractions: the first fraction dividing the amount of input flows into the customer's areas in the forward flow by the total amount of fruit customers' demands and the second fraction dividing the amount of input flows into the customer's areas in the reverse flow by the total amount of compost markets demands. The maximum value of this function is when the amount of incoming streams to the customer's areas is equal to the demands level in both streams, which is equal to 1 and is between 0 and 1. The mathematical formulation of the objective function is described in Eq. (7).

4.4.3 Minimize Carbon Emission

Min $Z^{emission} = Z^{PE} + Z^{PH} + Z^{PR} + Z^{PT} + Z^{PD}$ (8)

$$Z^{PE} = \sum_{j=1}^{J} fe_j W_j + \sum_{l=1}^{L} fe_l Y_l \tag{9}$$

$$Z^{PH} = \sum_{j=1}^{J}\sum_{t=1}^{T} Ih_{jt}\, eh_j \tag{10}$$

$$Z^{PR} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} X_{ijt}\, ep_j + \sum_{l=1}^{L}\sum_{o=1}^{L}\sum_{t=1}^{T} X_{lot}\, ec_l + \sum_{i=1}^{I}\sum_{t=1}^{t'} \lambda_{it} ep'_i \tag{11}$$

$$Z^{PT} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{t'} X_{ijt}\, d_{ij}\, de + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{t'} X_{ikt}\, d_{ik}\, de + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} X_{jkt}\, d_{jk}\, de + \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{t'} X_{ilt}\, d_{il}\, de$$
$$+ \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} X_{jlt}\, d_{jl}\, de + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} X_{klt}\, d_{kl}\, de + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} X_{lot}\, d_{lo}\, de \tag{12}$$

$$Z^{PD} = \sum_{i=1}^{I}\sum_{t=1}^{t'} \left(\lambda c_{it} - \lambda_{it}\right) we + \left(\sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{t'} \left(\alpha_t\, \lambda_{it} - X_{ilt}\right) + \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} \left(\beta_t\, Ih_{i(t-1)} - X_{jlt}\right) \right) we$$
$$+ \left(\sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{l=1}^{L} \left(\theta_t \left(X_{ikt} + X_{jkt}\right) - X_{klt}\right) \right) we \tag{13}$$

The third objective function ($Z^{emission}$) minimizes the amount of CO_2 emissions which is comprised fixed CO_2 emissions due to establishing the new potential facilities (Z^{PE}), CO_2 emissions due to holding inventory (Z^{PH}), CO_2 emissions due to processing and reprocessing (Z^{PR}), CO_2 emissions due to transportation (Z^{PT}), and emission of CO_2 due to destroying rotten fruits (Z^{PD}). The mathematical formulation of the objective function is described in Eqs. (8) – (13).

4.5 Subject to:

The constraints of the mathematical model are given next, Eqs.(14) – (32).

$$\lambda_{it} \times \left(1 - \alpha_t\right) = \sum_{j=1}^{J} X_{ijt} + \sum_{k=1}^{K} X_{ikt} \qquad \forall i \in I,\, t \in t' \tag{14}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{t'} X_{ijt} \le M \times W_j \qquad \forall j \in J \tag{15}$$

$$\lambda_{it} \le \lambda c_{it} \qquad \forall i \in I,\, t \in t' \tag{16}$$

$$Ih_{j(t-1)} + \sum_{i=1}^{I} X_{ijt} = Ih_{jt} + \sum_{k=1}^{K} X_{jkt} + \sum_{l=1}^{L} X_{jlt} \qquad \forall j \in J,\, t \in T \tag{17}$$

$$Ih_{jt} \le \lambda h_j \qquad \forall j \in J, t \in T \tag{18}$$

$$\sum_{j=1}^{J} X_{jkt} + \sum_{i=1}^{I} X_{ikt} \le d_{kt} \qquad \forall k \in K,\, t \in T \tag{19}$$

$$\sum_{l=1}^{L} X_{lot} \le d'_{ot} \qquad \forall o \in O,\, t \in T \tag{20}$$

$$\sum_{l=1}^{L} X_{ilt} \le \alpha_t \times \lambda_{it} \qquad \forall i \in I,\, t \in t' \tag{21}$$

$$\sum_{i=1}^{I}\sum_{t=1}^{t'} X_{ilt} \le M \times Y_l \qquad \forall l \in L \tag{22}$$

$$\sum_{l=1}^{L} X_{jlt} \le \beta_t \times Ih_{j(t-1)} \qquad \forall j \in J,\, t \in T \tag{23}$$

$$\sum_{j=1}^{J}\sum_{t=1}^{T} X_{jlt} \le M \times Y_l \qquad \forall l \in L \tag{24}$$

$$\sum_{l=1}^{L} X_{klt} \le \theta_t \times d_{kt} \qquad \forall k \in K, t \in T \tag{25}$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T} X_{klt} \le M \times Y_l \qquad \forall l \in L \tag{26}$$

$$\left[\sum_{i=1}^{I} X_{ilt} + \sum_{j=1}^{J} X_{jlt} + \sum_{k=1}^{K} X_{klt}\right] \times \varphi = \sum_{o=1}^{O} X_{lot} \qquad \forall l \in L, t \in T \tag{27}$$

$$\sum_{o=1}^{O} X_{lot} \le \lambda r_l \qquad \forall l \in L, t \in T \tag{28}$$

$$\sum_{i=1}^{I} X_{ikt} + \sum_{j=1}^{J} X_{jlt} \ge \sum_{l=1}^{L} X_{klt} \qquad \forall k \in K, t \in T \tag{29}$$

$$Y_l, W_j \in \{0,1\} \qquad \forall l \in L, j \in J \tag{30}$$

$$X_{rr't} \ge 0 \qquad \forall r \in \{I,J,K,L,O\}, r' \in \{I,J,K,L,O\}, t \in T \tag{31}$$

$$Ih_{jt} \ge 0, \lambda_{it} \ge 0 \qquad \forall i \in I, j \in J, t \in T \tag{32}$$

Constraint (14) ensures that amount of the entered products minus the wasted amount is equal to the quantity of products shipped from producers to distribution centers and customers. Constraint (15) ensures that the products are shipped to a potential location only if a distribution center is opened in that location. Constraint (16) ensures that the entered product of each producer is less than or equal to the anticipated maximum production rate. Constraint (17) ensures that each distribution center inventory level in each period is equal to previous period inventory level plus the quantity of products received from producers minus the quantity of products shipped to customers and composting centers. Constraint (18) shows that distribution center inventory in each period is less than or equal to holding capacity of the distribution center. The fact that each customer's demand in each period is greater than or equal to the quantity of products received from producers and distribution center is enforced by constraint (19). Constraints (20) show that the quantity of vermicompost shipped to compost markets in each period is less than or equal to demand of each compost markets. Constraints (21) shows that returned product shipped to composting centers from each producer is less than or equal to waste rate of production. Constraints (22), (24), and (26) express the fact the returned products may be shipped from a producers, distribution centers, and markets to a composting center only if a composting center are opened in a potential location for such facility, respectively. Similar to constraint (21), constraint (23), and Constraint (25), confine the shipped products to the maximum capacity of the facilities. Constraint (27) ensures that all received returned product from the producers, distribution centers and customers multiplied by the conversion rate is equal to the total reprocessed product (vermicompost) sent to compost markets. Constraint (28), show that the quantity of vermicompost shipped to compost markets in each period I less than or equal to manufacturing capacity of each compost markets. Constraint (29), show that the quantity of fruits that shipped from customer area to composting centers in each period is less than sum of inputs to customer area. Finally, the binary and non- negativity restrictions on the corresponding decision variables are shown in constraints (30) and (31) and (32).

5. Results and discussion

The purpose of this section is to indicate the application of mathematical models by numerical examples. A numerical test problem is considered for this purpose. Most of the data for the first and second OFs are obtained from the case in Cheragalipour et al. (2018), and the data of CO_2 emissions are adopted from Nurjanni et al. (2017). Available and potential facilities were determined using the map available in Cheragalipour et al. (2018) and distances between these locations were obtained using google Maps. The details of the distances are demonstrate in Table 1. Since it is difficult to estimate parameter values in the real world, it is assumed that some parameters follow a uniform distribution. The goal is to consider a realistic model using uniform distribution. The details of the parameters and indices data are given in Table 2 and Table 3, respectively.

Since our problem is MO, we use the sum-weighted method, which is the most popular method of solving these problems. In this way, our problem can convert to a single-objective optimization problem. In this method, the OFs are combined with appropriate weights. Determining the weight of functions is a challenge. Weights (w_1, w_2, w_3 in this case) are determined by the decision makers. Some methods, such as AHP, can also be used to determine the

weight of objectives. It is noteworthy that w_1, $w_2$and $w_3 \geq 0$ and $w_1 + w_2 + w_3 = 1$. Eq. (33) shows the formula for our problem:

$$\text{Min } Z_t = W_1 \, Z_1^N + W_2 \, Z_2^N + W_3 \, Z_3^N \qquad (33)$$

St.

Eqs. (14)-(32)

Z_1^N , Z_2^N and Z_3^N in eq. (34) are the normalized objective functions.

Table 1. Distance between the mentioned location of Iran (km)

		Distribution center				Composting center				Fruit customer			Compost customer	
		Tonekabon	Chalus	Babol	Neka	Noshahr	Amol	Sari	Juybar	Chalus	Babolsar	Amol	Behshahr	Sari
garden	Ramsar	25	80	210	277	90	179	250	248	84	197	184	300	248
	Noor	115	61	76	142	52	45	115	114	65	63	41	167	114
	Sari	225	173	43	26	163	72	12	22	178	50	76	50	4
Distribution center	Tonekabon	0	59	200	254	69	150	228	229	57	176	158	275	228
	Chalus	59	0	130	197	13	104	174	171	15	120	102	222	172
	Babol	200	130	0	71	125	34	44	31	135	22	34	94	43
	Neka	254	197	71	0	193	100	30	51	202	79	102	28	32
Composting center	Noshahr	69	13	125	193	0	97	168	144	15	127	95	214	170
	Amol	150	104	34	100	97	0	74	66	106	30	10	125	70
	Sari	228	174	44	30	168	74	0	20	170	42	73	52	8
	Juybar	229	171	31	51	144	66	20	0	168	28	71	72	20

Table 2. model parameters tuning

Parameter	value	unit
T	8	month
t'	3	month
f_j	[36363,31818]	$
f_l	[9090,10909]	$
d_c	0.073	($/km.ton)
ch_{jt}	uniform∼ [38,45]	$/ton
cp_{jt}	uniform∼[50,59]	$/ton
cr_{lt}	uniform∼[50,68]	$/ton
cp'	uniform∼[63,82]	$/ton
ρ	0.6	percentage
d_{kt}	uniform∼[1,9]	ton
d'_{ot}	uniform∼[1,4]	ton
fe_j	[830000,840000]	$kg\ CO_2eq$
fe_l	[1200000,1300000]	$kg\ CO_2eq$
eh_j	[260,280,270,240]	$(kg\ CO_2eq)$/ton
ep_j	[240,260,230,210]	$(kg\ CO_2eq)$/ton
ec_l	[180,200,190,160]	$(kg\ CO_2eq)$/ton
ep'_i	[300,310,305]	$(kg\ CO_2eq)$/ton
de	0.062	$(kg\ CO_2eq)$/km.ton
α_t	[0.1,0.12,0.15,0,0,0,0,0]	percentage
λc_{it}	uniform∼[30,100]	ton
λh_j	[60,80,40,20]	ton
θ_t	[0.12,0.13,0.14,0.145,0.145,0.148,0.15,0.15]	percentage
β_t	[0.12,0.12,0.13,0.135,0.14,0.145,0.145,0.15]	percentage
λr_l	uniform∼[3,5]	ton
φ	1.1	percentage
wc	68	$/ton
we	310	$(kg\ CO_2eq)$/ton

Table 3. List of problem indices

i={Ramsar, Noor, Sari}
j_1={Tonekabon, Chalus}
j_2={Babol, Neka}
k={Chalus, Babolsar, Amol}
l_1={Noshahr, Amol}
l_2={Sari, Juybar}
o_1={Behshahr}
o_2={Sari}

The test problem is solved in GAMS software with CPLEX solver by 0considering six different combinations of weights. All computational work was performed on a personal computer (64-bit operating system, 2.6 GHz CPU, and 12.00 GB). The model was resolved in less than 4 seconds, and optimal solutions were obtained. In the table 4 the values for all three OFs are given by different weights. When the goal is only to minimize the cost OF (W_1=1), the model nullifies all network flows and yields the lowest cost, $131702, which is the total cost of waste destroying. When the goal is only to maximize the responsiveness OF (W_2=1), the model tries to meet all of demand and reach a value of 1, regardless of cost and CO_2 emissions. Only then will new distribution centers and composting centers be established.

Table 4. The result of the optimization model for test problem

No.	weights			Objective functions			Distribution center		Composting center	
	Z	Z'	$Z^{emission}$	Z ($)	Z' $(Percentage)$	$Z^{emission}$ $(kg\ CO_2eq)$	W_{Babol}	W_{Neka}	Y_{Sari}	Y_{Juybar}
1	1	0	0	131702	0.015	600288	0	0	0	0
2	0	1	0	251172	1	4923594	1	1	1	1
3	0	0	1	131987	0.152	598935	0	0	0	0
4	1/3	1/3	1/3	154385	0.917	717037	0	0	0	0
5	0.2	0.3	0.5	149446	0.823	687993	0	0	0	0
6	0.2	0.5	0.3	159576	1	745935	0	0	0	0

The third case is when the goal is to minimize the emission, which yields the same logical solutions as the first as expected. While the weights of all three OFs are equal, the model tries to reach the minimum values of cost ($154385) and emission (717037kg CO_2-eq) with the highest response (0.917). The fifth case simulates when the environment is the top priority for decision-makers over the other two goals. The emission OF is of greater importance (W_3=0.5) than the other OFs in this case that causes the emission value (687993kg CO_2-eq) to be higher than the third case and lower than the fourth case.

6. Conclusion

In this study, a five-echelon sustainable agricultural closed-loop supply chain model for apple fruit in a region of Iran was proposed. It is a Tri-objective model and seeks to meet the three sustainability indicators in the supply chain, which are to minimize total supply chain costs, to minimize CO2 emissions from different network activities while maximizing responsiveness to customers' demands in each market. The proposed model was transformed into a single objective function by a weighted-sum method and was solved by giving different weights in GAMS software. The model was solved by considering a test problem and obtained rational optimal solutions confirmed the validity of the model.

There are some potential future works. This model can also be solved by considering stochastic demand. Other methods of solving multi-objective optimization problems such as Weighted Tchebycheff and ε-constraint methods can be exerted. Since our model is NP-hard, solving this model for large problems requires the use of specific algorithms such as genetic and Scatter Search, because it is hard to solve large problems in a reasonable time. Finally, using the model proposed in this research in real cases and analyzing achieved results will be very valuable.

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