



# Mathematical modeling for sustainable agri-food supply chain

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## Abstract

Recently, industry, suppliers, distributors, academia, governments, and even consumers have focused on agri-food supply chain sustainability, environmental concerns, and managing energy and other resources essential for human survival. A supply chain model is a network of facilities and operations involving processes related to procuring raw materials from suppliers, producing and developing products on production sites, and ultimately distributing products at final consumption destinations. This study aims to propose a multi-stage model for sustainable supply chain network design. After an overview of operations research methods for sustainable supply chain network design, this study proposed a hybrid method based on multi-criteria decision-making (MCDM) and optimization techniques in operations research. The criteria extracted from library resources were selected using the Delphi method in the first step. Then, the criteria for selecting suppliers, transformer sites, and critical distribution hubs were weighted using the best–worst method. After weighing the criteria using the Complex Proportional Assessment of alternatives (COPRAS) technique, eight raw material suppliers, three potential transformer sites, and five main distribution hubs were selected for supply chain network design. The second part presented a multi-objective mixed-integer linear programming model to optimize the designed supply chain network. All three sustainability dimensions, i.e., economic, social, and environmental, were considered in developing the supply chain network. In the economic dimension, we sought to minimize total costs consisting of transportation costs, the cost of construction, maintenance, and closure of transformer and distribution sites, the cost of the capacity change of transformer and distribution sites, and the cost of production. In the social dimension, we sought to maximize the number of job opportunities created in each facility. We sought to minimize carbon and nitrous oxide footprints and water consumption in the environmental dimension. Furthermore, a fourth objective function was presented to minimize product delivery time in addition to the three dimensions of sustainability. Then the proposed mathematical programming model was solved using the LP-metric method, and the necessary comparisons were made between the results. Finally, agri-food industry executives were given a decision-making tool by generating Pareto frontier graphs.

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## 1 Introduction

Growing environmental, social, and ethical concerns and increased awareness of the effects of food production and consumption on the natural environment have led to increased pressure from consumer organizations, environmental advocacy groups, and policymakers on agri-food companies to deal with the sustainability of their supply chains (Allaoui et al., 2018).

Increasing awareness of the threats to human life motivates efforts to achieve sustainability in production and modify consumption patterns. However, the movement toward sustainability has limitations due to human behavior, economic needs, and restrictions on organizations' economic systems (Osranek, 2016). On the other hand, the increased globalization and complexity of the supply chain have caused management to take into account inter-organizational dependencies and sustainability challenges, such as minimizing consumption and preserving the environment, protecting workers' rights, and ensuring that all companies within the supply chain act responsibly. Corporate management decision-making and development strategy should consider sustainability factors, including environmental and social issues, due to their destructive effects on the global supply chain and production network (Awasthi et al., 2018).

Research has focused on improving companies individually and being virtually indifferent to the entire supply chain. Although considerable research has been conducted to assess economic performance, only some studies have examined the three dimensions of sustainability and agri-food supplier decision-making, followed by a prescriptive decision-making model. Most strenuous efforts for supply chain sustainability modeling have been summarized in closed-loop and reverse logistics issues. Most studies have optimized traditional economic factors such as revenue generation or cost minimization. They have provided cost- or revenue-based assessments, and in most of these studies, environmental factors have played a weak role (Xie, 2015). Some research works began to fill this gap. However, they are limited by sustainable supply chain complexities. The supply chain network design becomes challenging when traditional economic models are combined with sustainability metrics. One of the significant challenges is the wide range of influencing factors that need to be considered. Most of them cannot be summarized and evaluated in the one-step optimization problem. Therefore, economic growth, environmental protection, social conditions, and interdisciplinary knowledge must establish a synergistic relationship. Although some efforts have recognized the agri-food supply chain characteristics, only some works have provided a holistic framework (Allaoui et al., 2018).

Network design for agri-food supply chains becomes challenging when sustainability is embraced in the traditional economic-oriented models. One of the main challenges in this context is the broad range of influencing factors associated with sustainability that need to be considered, many of which could not be fully integrated or measured in single-step optimization problems. As a result, synergies must be created between economic growth, environmental protection, and social conditions, with a multidisciplinary scientific and technical approach. Although some work has been done to identify sustainability attributes in the agro-food supply chain, more efforts have yet to be made to develop a holistic framework. This paper intends to address this gap and provide a multi-objective model for

the agri-food supply chain with environmental-social-economic considerations. After an overview of operations research methods for sustainable supply chain network design, this study proposes a hybrid method based on multi-criteria decision-making and optimization techniques in operations research.

The remainder of this study is structured as follows. Section 2 provides a systematic literature review of operational research tools and methods for sustainable supply chain design. In Sect. 3, the research supply chain conceptual model is proposed. It also presents criteria for selecting suppliers, potential transformer sites, and key distribution hubs. Section 4 presents a case study of an agri-food supply chain to understand our proposed approach better. The research results are also discussed in this section. Finally, the research conclusions and directions for future studies are provided in Sect. 5.

## 2 Literature review

In the early twenty-first century, companies have found the necessity to take a holistic view of business operations, especially Supply chain management, after outsourcing key activities due to globalization, using experiences from negotiating with stakeholders, reverse logistics, corporate social responsibility, and IT development. Although the environmental aspect of sustainability has been one of the critical elements of the triple bottom line of sustainability and an intermediary for issues such as climate change and increased energy consumption, researchers and managers often use the term sustainability interchangeably. While the environmental issue has been a starting point for a sustainable supply chain, it is now expanding daily as one of the triple bottom line (economic, environmental, and social) concepts with the same value as other concepts (Carter & Easton, 2011). Research shows that sustainable supply chain management is moving toward balancing financial goals, social performance, and ecological concerns (Seuring & Müller, 2008). A traditional supply chain aims to balance benefits across all stakeholders, improve operational efficiency across facilities, and maximize the profitability of processes and operations. However, addressing environmental concerns, social responsibilities, and economic issues is a priority in the sustainable supply chain. Figure 1 shows the conceptual model of sustainable supply chain management.

As shown in Fig. 1, the scope of sustainable supply chain management is not limited to economic, social, and environmental objectives but includes their integration across multiple supply chain operations (Chen, 2004).

As part of this study, along with the economic, environmental, and social dimensions, minimizing the delivery time of a product to the customer is one of the main objectives and concerns of the companies. The study proposes a four-objective model that incorporates sustainability dimensions to reduce the product delivery time to the customer, thereby increasing customer satisfaction and market share.

For integrating external factors and internal processes, the sustainable supply chain management operations in Delpazir Food Company should focus on balancing the following four objectives:

- (1) Maximize profits or minimize costs
- (2) Minimize environmental impacts
- (3) Satisfy social needs
- (4) Minimize product delivery time to the customer

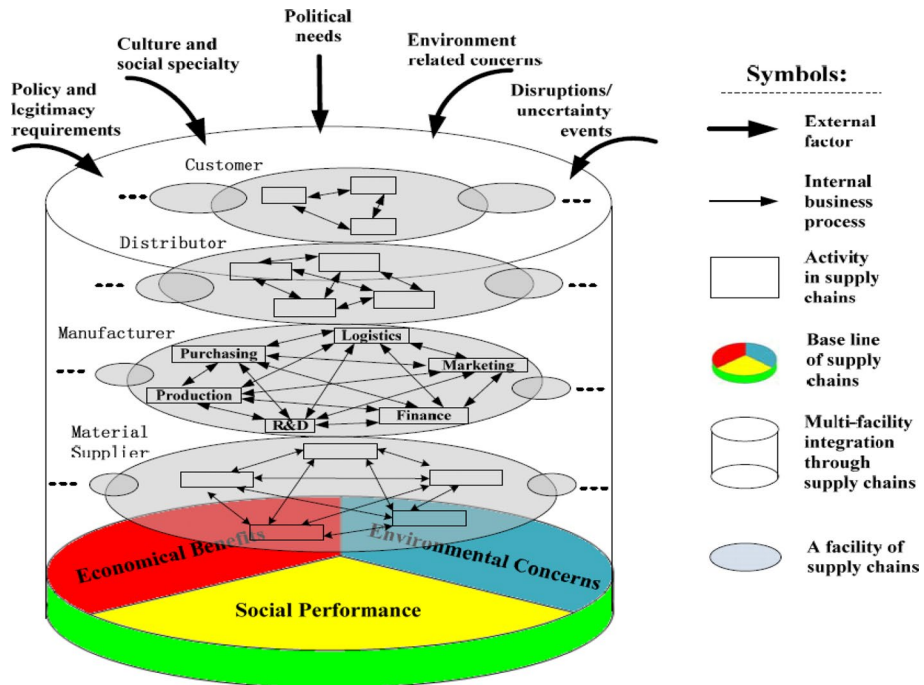


Fig. 1 Conceptual model of sustainable supply chain management (Chen, 2004)

Allaoui et al. (2018) presented a hybrid and two-step model for solving a sustainable supply chain problem to achieve a sub-optimality in three dimensions of sustainability. In the first stage, they selected partners using a combination of the analytic hierarchy process (AHP) and the ordered weighted averaging (OWA) methods and then used the results in a multi-objective optimization model to optimize the supply chain network design. In their study, the criteria used in the triple bottom line of sustainability are carbon footprints, water footprints, number of job opportunities, and the total cost of the supply chain design. Cheraghalipour et al. (2018) presented a *sustainable citrus closed-loop supply chain model* to minimize costs and maximize customer demand response in both forward and backward parts of the chain. The Multi-Objective Keshtel Algorithm (MOKA) method was used for the first time to solve this model, and the results of solving this model were compared with NSGA-II, MOSA, and NPGA methods. The study results were compared with a case study of the citrus *closed-loop* supply chain in northern Iran to ensure its applicability, showing the model's acceptability and solution method. Sazvar et al. (2018) presented a linear multi-objective model to design a sustainable supply chain network of perishable food, considering the economic, social, and environmental dimensions. They used the  $\epsilon$ -constraint method to solve this model. The indicators used in their model include minimizing costs, reducing environmental impacts, and in the social dimension, enhancing consumer health. Fathi et al. (2019) designed a Closed Loop Supply Chain Network Considering the Uncertainty in the Quality of Returning Products. The primary purpose of this study is to use a two-stage stochastic programming model and maximize expected earnings for all of the quality

status scenarios in which the target function is a combination of revenue from the sale of products and recycled materials and components Recovered, in addition to fixed costs for centers, processes, logistics, and transportation. Due to the complexity of the model, the problem was used with the Lp-shape and CPLEX algorithms, and the GAMS software was used to solve the problem. Based on the research results, the substantive response introduced by CPLEX for the C3 to C6 test questions is significantly far from the optimal responses obtained by the L-Shape method.

Rahimi and Ghezavati (2018) also designed a closed-loop sustainable supply chain under uncertainty by presenting a multi-period MOMILP model. This model considers the random demand for the returned product and the investment rate. A two-stage stochastic programming model is applied to solve the uncertainty. Puji et al. (2017) proposed a multi-objective mathematical model for designing a green closed-loop supply chain network. They sought a balance between the environmental impacts of industrialization and profit maximization as an economic indicator. In their study, the carbon footprint is considered an ecological indicator. Recycling products is regarded as one of the vital choices for achieving economic benefits by considering environmental protection measures in many industries. Insufficient investment and supply chain inefficiency play a significant role in increasing the time between recycling and reuse, which prevents the reuse of recycled products. Soleimani et al. (2017) designed a green closed-loop sustainable supply chain network in fuzzy conditions. This modeling considers suppliers, plants, distribution sites, consumers, storage and warehousing facilities, and return and recycling sites. For recycling, they adopted three levels: product recycling, component recycling, and raw material recycling site. In designing this supply chain network, they considered environmental requirements, increased profit optimization, reduced lost job opportunities, and maximized customer response. They employed genetic algorithms through different scenarios with different aspects to solve this model. The obtained results demonstrated this model's applicability and the solution method's development.

The issue under study is the design of a supply chain network for Delpazir Food Company (Fig. 2). In some research, a supply chain network may be designed for products that have not yet been produced or where there is no production site for these products. In this study, the network design has been done by considering the triple-bottom-line sustainability goals, namely economic, environmental and social, to achieve Delpazir's sustainability strategy and stakeholders' satisfaction. In this multi-tire and multi-product network, raw materials are first produced on farms and agro-industrial companies, which are the same as suppliers, then transferred to transformer sites, which are the same production plants and corporate subsidiaries, and finally sent to customers, who are the same as retail distributors, through wholesale distribution sites.

The following assumptions are made:

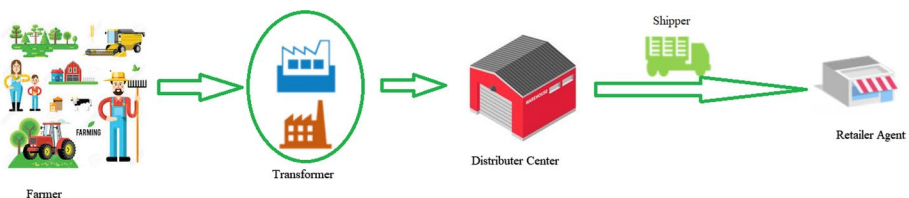


Fig. 2 Agri-food supply chain network under investigation

- The model is multi-Stage and multi-product.
- Product flow exists only between successive facilities, which is impossible between similar facilities.
- The location and number of raw material suppliers, transformer sites, distributor sites, and customers are fixed.
- Parameters such as production capacity, costs, demand, carriers' capacity, and product delivery times are considered definitively.
- The quality of raw materials and products is the same.
- The locations of potential production and distribution sites are identified.

### 3 Proposed supply chain conceptual model

This research presents a mathematical model for Delpazir's network design problem in supply chains. This model is a forward network with four levels: farms and agri-industrial companies as suppliers, transformer sites as producers, wholesale distribution sites as distributors, and retail distribution sites as customers. The model has four objective functions: (1) minimizing the total cost, (2) minimizing the environmental footprints, (3) maximizing the job opportunities created, and (4) minimizing product delivery time.

The total cost objective function consists of transportation costs, including the cost of transferring raw materials from suppliers to transformer sites, the cost of transferring from the intermediate transformers to the final transformer, the cost of moving from transformer sites to distributor sites, and also from distribution sites to customer sites, the cost of construction, maintenance, and closure of transformer and distribution sites, the cost of the capacity change of transformer and distribution sites, the cost of production, and the cost of procuring raw materials.

In the second objective function, we try to minimize environmental footprints that adversely impact the environment. From infrastructures to vehicle operations, facilities and transportation between facilities significantly impact environmental pollution. As it has been observed in the literature, most research has focused on minimizing carbon footprint as an objective function, but in this study, in addition to minimizing carbon footprints, nitrous oxide caused by in-house operations has also been considered:

1. Footprints of carbon and nitrous oxide due to product transfer from transformer sites to distributor sites.
2. Footprints of carbon and nitrous oxide due to product transfer from intermediate transformers to final transformer sites.
3. Footprints of carbon and nitrous oxide due to the transfer of raw materials from suppliers to transformer sites.
4. Footprints of carbon and nitrous oxide due to product transfer from transformer sites to distributor sites.
5. Footprints of carbon and nitrous oxide caused by the construction, maintenance, and closure of transformer sites.
6. Footprints of carbon and nitrous oxide caused by the construction, maintenance, and closure of distributor sites.
7. Footprints of carbon and nitrous oxide caused by the production of any product using the specific type of energy in the final transformer sites.

8. Footprints of carbon and nitrous oxide caused by the production of any product using the specified type of energy in the intermediate transformer sites.
9. Footprints of carbon and nitrous oxide caused by the production of any raw materials using a specific type of energy in raw material suppliers.

This study seeks to minimize water consumption as one of the critical substances in nature, which determines many events in the coming years and is one of the current super-challenges in Iran. In the parameters used in water consumption in this objective function, we have:

1. Water consumption to produce a final product unit in the product transformer using a specified type of energy.
2. Water consumption to produce an intermediate product unit in the product transformer site using a specific type of energy.
3. Constant water consumption due to the construction, maintenance, and closure of transformer sites.
4. Constant water consumption due to the construction, maintenance, and closure of distributor sites.
5. Water consumption to produce raw materials by the manufacturer.

The third objective function seeks to maximize the social effects of the supply chain, including fixed and variable job opportunities created during the establishment or construction of a production unit, as well as provide lost job opportunities due to the closure or non-establishment of these facilities in Delpazir's supply chain. The fourth objective function seeks to minimize product delivery time as one of the supply chain resilience criteria.

### **3.1 Criteria for selecting suppliers, potential transformer sites, and central distribution hubs**

Several supplier selection criteria have been collected and categorized from articles and research work, and the industry experts and specialists' views have been collected through the Delphi technique. After identifying the appropriate criteria for supplier selection, these criteria have been weighed through the best–worst method (BWM) technique. Finally, these suppliers are ranked using the complex proportional assessment method. This ranking is used in the mathematical supply chain network model as the input for the number of suppliers.

In multi-attribute decision-making (MADM) methods, multiple alternatives are evaluated according to several criteria to select the best alternative. Based on the best–worst method proposed by Rezaei (2016), the best and worst criteria are identified by the decision-maker. A pairwise comparison is made between these two (best and worst) criteria and other criteria. Then, a minimax problem is formulated and solved to determine the weight of the different criteria. This method also considers a formula for calculating the inconsistency rate to check the validity of the comparisons. Some of the salient features of the best–worst method compared to other multi-attribute decision-making methods are:

1. The best–worst method requires less comparative data.
2. The best–worst method leads to a more robust comparison, i.e., it provides more reliable solutions.

– The best–worst method Steps

*Step 1—Determine a set of decision criteria:* in this step, a set of criteria is defined as  $\{C_1, C_2, C_3, \dots, C_n\}$ , which is needed to make a decision.

*Step 2—Determine the best (most important, most desirable) and the worst (least important and least desirable) criteria:* the decision-maker defines the best and worst. No comparisons are made at this stage.

*Step 3—Determine the preference of the best criterion over all the other criteria regarding a number between 1 and 9:* the Best-to-Others (BO) vector is displayed as:

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$$

where  $a_{Bj}$  represents the preference of the best criterion (B) over the criterion  $j$  so that  $a_{BB} = 1$ .

*Step 4—Determine the preference of all criteria over the worst criterion with a number between 1 and 9:* the Others-to-Worst (OW) vector is displayed as:

$$A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T$$

where  $a_{jW}$  represents the preference of the criterion  $j$  over the worst criterion W, so that  $a_{WW} = 1$ .

*Step 5—Find the optimal weights ( $w_1^*, w_2^*, \dots, w_n^*$ ):* the pairs  $\frac{W_B}{W_j} = a_{Bj}$  and  $\frac{W_j}{W_w} = a_{jw}$  are formed to determine the optimal weight of each criterion. Then, a solution must be found to satisfy all  $j$ s conditions to maximize absolute differences  $|\frac{W_j}{W_w} - a_{jw}|$  and  $|\frac{W_j}{W_w} - a_{jw}|$  for all minimized  $j$ s. Given the non-negative and total weights, the model can be formulated as Eq. (1).

$$\begin{aligned} & \min \max_j \left\{ \left| \frac{W_j}{W_w} - a_{jw} \right|, \left| \frac{W_j}{W_w} - a_{jw} \right| \right\} \\ & \text{s.t.} \\ & \sum_{j=0} w_j = 1 \end{aligned} \tag{1}$$

$$w_j \geq 0, \text{ for all } j$$

The above model can also be converted into the following model:

$$\begin{aligned} & \text{Min } \xi \\ & \text{s.t.} \\ & \left| \frac{W_B}{W_j} - a_{Bw} \right| \leq \xi; \text{ for all } j \\ & \left| \frac{W_j}{W_w} - a_{jw} \right| \leq \xi; \text{ for all } j \\ & \sum_{j=0} w_j = 1 \\ & w_j \geq 0, \text{ for all } j \end{aligned} \tag{2}$$



The above function’s linear model is also presented as follows:

$$\begin{aligned}
 & \text{Min } \zeta \\
 & \text{s.t.} \\
 & \left| w_B - a_{Bj} * w_j \right| \leq \xi; \text{ for all } j \\
 & \left| w_j - a_{jw} * w_w \right| \leq \xi; \text{ for all } j \\
 & \sum_{j=0} w_j = 1 \\
 & w_j \geq 0, \text{ for all } j
 \end{aligned} \tag{3}$$

In this study, the criteria weights are obtained using a linear model. The optimal values of  $(w_1^* \cdot w_2^* \cdot \dots \cdot w_n^*)$  and  $\zeta^*$  are obtained by solving the above model.

The Complex Proportional Assessment method was developed by Zavadskas et al. (1994). The steps of the complex proportional assessment method are presented below.

- *Formation of the decision matrix*
- *Calculate the criteria weights:* in this step, the criteria weights must be determined by one of the weighting methods, such as the best–worst method.
- *Normalization of the decision matrix:* in this step, the decision matrix of the complex proportional assessment method must be normalized.

$$d_{ij} = \frac{q_i}{\sum_1^n x_{ij}} x_{ij} \tag{4}$$

- *Calculate the sum of normalized values:* in this step, the sum of the normalized values of the positive and negative criteria must be calculated separately for each alternative.

$$s_j^+ = \sum_{z_j=+} d_{ij} \tag{5}$$

$$s_j^- = \sum_{z_j=-} d_{ij} \tag{6}$$

- *Final ranking of the alternatives:* in this step, we rank alternatives according to the following relation: the calculation of the complex proportional assessment index. The higher the  $Q_i$  value, the better the alternative rank in the prioritization. The alternative with the highest value is the ideal solution.

$$Q_i = s_j^+ + \frac{s_{min}^- * \sum_{j=1}^n s_j^-}{s_j^- * \sum_{j=1}^n \frac{s_{min}^-}{s_j^-}} \tag{7}$$

- The final step is to determine the best alternative among the criteria. As the rank of each alternative increases or decreases, its utility degree also increases or decreases. Alternatives with the best ranking in terms of criteria are determined with  $N_j$ ’s highest utility degree, where  $N_j$  equals 100%. The total utility degree of each criterion is calcu-

lated from 0 to 100%, among which the best and worst alternatives are determined. The utility degree ( $N_j$ ) of each alternative  $A_j$  is calculated based on the following formula:

$$N_j = \frac{Q_j}{Q_{max}} * 100 \tag{8}$$

### 3.2 The proposed mathematical programming model

Index notations:

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Supplier set	$s = 1, 2, \dots, S$
Product transformer sites	$j = 1, 2, \dots, J$
Middle (intermediate) product transformers	$j' = 1, 2, \dots, J$
Distributor sites	$d = 1, 2, \dots, D$
Customers	$c = 1, 2, \dots, C$
Product set	$p = 1, 2, \dots, P$
Raw material set	$m' = 1, 2, \dots, M'$
Middle (intermediate) goods	$m = 1, 2, \dots, M$
Transport mode	$h = 1, 2, \dots, H$
Energy type	$e = 1, 2, \dots, E$
Period	$t = 1, 2, \dots, T$
Capacity level	$\alpha = 1, 2, 3$
Cities to which the product is shipped from the distributor	$f = 1, 2, \dots, F$

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Parameters:

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$OD_{pdfct}$	Product order by customer $c$ in period $t$ ;
$NMm'm$	Number of units of raw material $m'$ required to make one unit of component $m$ ;
$NM_{mp}$	Number of units of raw materials $m$ to produce a unit of product $P$ ;
$SCm'st$	Supplier capacity $S$ to provide raw materials $m'$ in period $t$ ;
$CLT_{j\alpha t}$	Lower bound on the capacity of transformer site $j$ using capacity $\alpha$ in period $t$ ;
$CLD_{d\alpha t}$	Lower bound on the capacity of distributor site $d$ using capacity $\alpha$ in period $t$ ;
$CUT_{j\alpha t}$	Upper bound on the capacity of transformer site $j$ using capacity $\alpha$ in period $t$ ;
$CUD_{d\alpha t}$	Upper bound on the capacity of distributor site $d$ using capacity $\alpha$ in period $t$ ;
$CIT_{j\alpha t}$	The initial capacity of transformer site $j$ at the beginning of the first period ( $t=1$ );
$CID_{d\alpha t}$	The initial capacity of distributor site $d$ at the beginning of the first period ( $t=1$ );
$IST_{j\alpha t}$	The initial state of transformer site $j$ using capacity $\alpha$ at the beginning of the first period (opening = 1, closure = 0);
$ISD_{d\alpha t}$	The initial state of distributor site $d$ using capacity $\alpha$ at the beginning of the first period (opening = 1, closure = 0);
$FCOT_{j\alpha t}$	Fixed cost of opening (establishing or constructing) per unit of product in transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FCOD_{d\alpha t}$	Fixed cost of opening (establishing or constructing) per unit of product in distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FCMT_{j\alpha t}$	Fixed cost of maintaining per unit of product in transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FCMD_{d\alpha t}$	Fixed cost of maintaining per unit of product in distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;

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$FCC\bar{T}_{jaet}$	Fixed cost of closing per unit of product in transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FCCD_{daet}$	Fixed cost of closing per unit of product in distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FCICT_{jat}$	Fixed cost of increasing per unit of production capacity in transformer site $j$ using capacity $\alpha$ in period $t$ ;
$FCICD_{dat}$	Fixed cost of increasing per unit of production capacity in distributor site $d$ using capacity $\alpha$ in period $t$ ;
$FCMCT_{jat}$	Fixed cost of maintaining per unit of production capacity in transformer site $j$ using capacity $\alpha$ in period $t$ ;
$FCMCD_{dat}$	Fixed cost of maintaining per unit of production capacity in distributor site $d$ using capacity $\alpha$ in period $t$ ;
$FCDCT_{jat}$	Fixed cost of decreasing per unit of production capacity in transformer site $j$ using capacity $\alpha$ in period $t$ ;
$FCD\bar{C}D_{dat}$	Fixed cost of decreasing per unit of production capacity in distributor site $d$ using capacity $\alpha$ in period $t$ ;
$TCST\ m'\ sj' ht$	Transportation cost of one unit of raw material $m'$ from the supplier $s$ to transformer $j'$ using transport mode $h$ in period $t$ ;
$TCTT_{mj' jht}$	Transportation cost of one unit of middle goods $m$ from transformer $j'$ to transformer $j$ using transport mode $h$ in period $t$ ;
$TCTD_{pj dht}$	Transportation cost of one unit of product $p$ from transformer $j$ to distributor $d$ using transport mode $h$ in period $t$ ;
$TCDC_{pdfcht}$	Transportation cost of one unit of product $p$ from distributor $d$ to customer $c$ using transport mode $h$ in period $t$ ;
$CPP_{pj aet}$	The production cost of one unit of product $p$ in transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$CPM_{mj' aet}$	The production cost of one unit of middle goods $m$ in transformer site $j'$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$PCM\ m' st$	The procurement cost of one unit of raw material $m'$ from supplier $s$ in period $t$ ;
$ETST\ m' sj' ht$	Carbon emissions caused by transporting one unit of raw material $m'$ from supplier $s$ to transformer $j'$ using transport mode $h$ in period $t$ ;
$NETST\ m' sj' ht$	Nitrous emissions caused by transporting one unit of raw material $m'$ from supplier $s$ to transformer $j'$ using transport mode $h$ in period $t$ ;
$ETTT_{mj' jht}$	Carbon emission caused by transporting one unit of middle goods $m$ from transformer $j'$ to transformer $j$ using transport mode $h$ in period $t$ ;
$NETTT_{mj' jht}$	Nitrous emission caused by transporting one unit of middle goods $m$ from transformer $j'$ to transformer $j$ using transport mode $h$ in period $t$ ;
$ETTD_{pj dht}$	Carbon emission caused by transporting one unit of product $p$ from transformer $j$ to distributor $d$ using transport mode $h$ in period $t$ ;
$NETTD_{pj dht}$	Nitrous emission caused by transporting one unit of product $p$ from transformer $j$ to distributor $d$ using transport mode $h$ in period $t$ ;
$ETDC_{pdfcht}$	Carbon emission caused by transporting one unit of product $p$ from distributor $d$ to customer $c$ using transport mode $h$ in period $t$ ;
$NETDC_{pdfcht}$	Nitrous emission caused by transporting one unit of product $p$ from distributor $d$ to customer $c$ using transport mode $h$ in period $t$ ;
$EPT_{pj aet}$	Carbon emission caused by producing one unit of product $p$ in transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$NEPT_{pj aet}$	Nitrous emission caused by producing one unit of product $p$ in transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$EPTM_{mj' aet}$	Carbon emission caused by producing one unit of middle goods $m$ in transformer site $j'$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$NEPTM_{mj' aet}$	Nitrous emission caused by producing one unit of middle goods $m$ in transformer site $j'$ using capacity $\alpha$ and energy type $e$ in period $t$ ;

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$EGPS_{m'st}$	Carbon emissions generated by producing one unit of raw material $m'$ by the supplier $s$ in period $t$ ;
$NEGPS_{m'st}$	Nitrous emissions generated by producing one unit of raw material $m'$ by the supplier $s$ in period $t$ ;
$WPT_{pj\alpha et}$	Water to produce one unit of product $p$ in transformer site $j$ using capacity $\alpha$ and energy $e$ and period $t$ ;
$WPTM_{mj'\alpha et}$	Water to produce one unit of middle goods $m$ in transformer site $j'$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$WCPS_{m'st}$	Water consumption to produce one unit of raw material $m'$ by the supplier $s$ in period $t$ ;
$FWCOT_{j\alpha et}$	Fixed water consumption for opening transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FWCMT_{j\alpha et}$	Fixed water consumption for maintaining transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FWCCT_{j\alpha et}$	Fixed water consumption for closing transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FWCOD_{d\alpha et}$	Fixed water consumption for opening distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FWCMD_{d\alpha et}$	Fixed water consumption for maintaining distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FWCCD_{d\alpha et}$	Fixed water consumption for closing distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$WSIJ_j$	Water stress index of transformer site $j$ ;
$WSID_d$	Water stress index of distributor site $d$ ;
$WSIJ_{j'}$	Water stress index of transformer site $j'$ ;
$WSIS_s$	Water stress index of supplier $s$ ;
$FEHOT_{j\alpha et}$	Fixed emission generated per unit of a product when opening transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FEHMT_{j\alpha et}$	Fixed emission generated per unit of a product when maintaining transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FEHCT_{j\alpha et}$	Fixed emission generated per unit of a product when closing transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FEHOD_{d\alpha et}$	Fixed emission generated per unit of a product when opening distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FEHMD_{d\alpha et}$	Fixed emission generated per unit of a product when maintaining distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$FEHCD_{d\alpha et}$	Fixed emission generated per unit of a product when closing distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$WW_1$	Weight of $CO_2$ in the environmental objective function;
$WW_2$	Weight of water in the environmental objective function;
$b$	The conversion factor of water weight to $CO_2$ weigh $t$ ;
$a$	The weighted conversion factor of nitrous oxide to $CO_2$ ;
$TTS_{m'sjht}$	Time to transport one unit of raw material $m'$ from the supplier $s$ to transformer site $j$ using transport mode $h$ in period $t$ ;
$TTTT_{mj'jht}$	Time to transport one unit of middle goods $m$ from intermediate product transformer site $j'$ to final product transformer $j$ using transport mode $h$ in period $t$ ;
$TTOT_{pjdh t}$	Time to transport one unit of product $p$ from opened transformer $j$ to distributor $d$ using transport mode $h$ in period $t$ ;
$TTMT_{pjdh t}$	Time to transport one unit of product $p$ from maintained transformer $j$ to distributor $d$ using transport mode $h$ in period $t$ ;
$TTOD_{pdjcht}$	Time to transport one unit of product $p$ from opened distributor $d$ to customer $c$ using transport mode $h$ in period $t$ ;

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$TTMD_{pdfcht}$	Time to transport one unit of product $p$ from maintained distributor $d$ to customer $c$ using transport mode $h$ in period $t$ ;
$TPOP_{pjct}$	Time to produce one unit of product $p$ when opening transformer site $j$ using energy type $e$ in period $t$ ;
$TPMP_{pjct}$	Time to produce one unit of product $p$ when maintaining transformer site $j$ using energy type $e$ in period $t$ ;
$TPOM_{mjct}$	Time to produce one unit of middle goods $m$ when opening transformer site $j$ using energy type $e$ in period $t$ ;
$TPMM_{mjct}$	Time to produce one unit of middle goods $m$ when maintaining transformer site $j$ using energy type $e$ in period $t$ ;
$FJOOT_{jt}$	Fixed job opportunities created during opening transformer site $j$ in period $t$ ;
$FJOMT_{jt}$	Fixed job opportunities created during maintaining transformer site $j$ in period $t$ ;
$FJOOD_{dt}$	Fixed job opportunities created during opening distributor site $d$ in period $t$ ;
$FJOMD_{dt}$	Fixed job opportunities created during maintaining distributor site $d$ in period $t$ ;
$VJOOT_{jat}$	Variable job opportunities created during the opening of transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$VJOMT_{jat}$	Variable job opportunities created during maintaining transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$VJOOD_{dat}$	Variable job opportunities created during opening distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$VJOMD_{dat}$	Variable job opportunities created during maintaining distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$CSJ_{jat}$	Capacity supply of transformer site $j$ using capacity $\alpha$ in period $t$ ;
$CSDD_{dat}$	Capacity supply of distributor site $d$ using capacity $\alpha$ in period $t$ ;

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Decision variables:

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$IVICT_{jat}$	Integer variable indicating the increased capacity of transformer site $j$ using capacity $\alpha$ in period $t$ ;
$IVACT_{jat}$	Integer variable indicating the available capacity of transformer site $j$ using capacity $\alpha$ in period $t$ ;
$IVDCT_{jat}$	Integer variable indicating the decreased capacity of transformer site $j$ using capacity $\alpha$ in period $t$ ;
$IVICD_{dat}$	Integer variable indicating the increased capacity of distributor site $d$ using capacity $\alpha$ in period $t$ ;
$IVACD_{dat}$	Integer variable indicating the available capacity of distributor site $d$ using capacity $\alpha$ in period $t$ ;
$IVDCD_{dat}$	Integer variable indicating the decreased capacity of distributor site $d$ using capacity $\alpha$ in period $t$ ;
$ART_{m'sj'ht}$	Amount of raw material $m'$ transported from supplier $s$ to transformer site $j'$ using transport mode $h$ in period $t$ ;
$AMT_{mj'jht}$	Amount of middle goods $m$ transported from transformer site $j'$ to transformer site $j$ using transport mode $h$ in period $t$ ;
$APTJ_{pjdh}$	Amount of product $p$ transported from transformer $j$ to distributor $d$ using transport mode $h$ in period $t$ ;
$APTC_{pdfcht}$	Amount of product $p$ transported from distributor $d$ to customer $c$ using transport mode $h$ in period $t$ ;
$APM_{pjact}$	Amount of product $p$ manufactured in transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ ;
$AMM_{mj'act}$	Amount of middle goods $m$ manufactured in transformer site $j'$ using capacity $\alpha$ and energy type $e$ in period $t$ ;

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$CST_{jaet}$	The current state of transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ (opening = 1, closing = 0);
$OST_{jaet}$	Opening state of transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ (opening = 1, closing = 0);
$CCST_{jaet}$	Closing state of transformer site $j$ using capacity $\alpha$ and energy type $e$ in period $t$ (closing = 1, opening = 0);
$CSD_{daet}$	The current state of distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ (opening = 1, closing = 0);
$OSD_{daet}$	Opening state of distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ (opening = 1, closing = 0);
$CCSD_{daet}$	Closing state of distributor site $d$ using capacity $\alpha$ and energy type $e$ in period $t$ (closing = 1, opening = 0);
$PST_{m'sj't}$	Purchasing state of raw material $m'$ by transformer site $j'$ from supplier $s$ (purchasing = 1, otherwise = 0);

### 3.3 Objective functions of the proposed mathematical model

The research model includes four objective functions: (1) minimizing the total costs, (2) minimizing the environmental footprints, (3) maximizing the job opportunities created, and (4) minimizing product delivery time. The first objective function involves minimizing the total costs: In this study, the costs considered for supply chain network design include transportation costs (transportation costs from supplier to manufacturer, from transformer site to manufacturer, from transformer site to distributor, and finally from distributor to customers), the costs of opening (construction), closure or maintenance of production sites, distribution, production costs, raw material procurement costs, and fixed costs of capacity change. Equation (9) shows the mathematical formula of this objective function.

$$\begin{aligned}
 Z_1 = \text{Min} & \left( \sum_p \sum_d \sum_f \sum_c \sum_h \sum_t TCDC_{pdfcht} * APTC_{pdfcht} + \sum_p \sum_j \sum_d \sum_h \sum_t TCTD_{pjdht} * APTJ_{pjdht} \right. \\
 & + \sum_{m'} \sum_s \sum_{j'} \sum_h \sum_t TCST_{m'sj'ht} * ART_{m'sj'ht} + \sum_m \sum_{j'} \sum_j \sum_h \sum_t TCJT_{mj'jht} * AMT_{mj'jht} \left. \right) \\
 & + \left( \sum_j \sum_\alpha \sum_e \sum_t (FCOT_{jaet} * OST_{jaet} + FCMT_{jaet} * CST_{jaet} + FCCT_{jaet} * CCST_{jaet}) \right) \\
 & + \sum_d \sum_\alpha \sum_e \sum_t (FCOD_{daet} * OSD_{daet} + FCMD_{daet} * CSD_{daet} + FCCD_{daet} * CCSD_{daet}) \\
 & + \sum_j \sum_\alpha \sum_t (FCICT_{jat} * IVICT_{jat} + FCMCT_{jat} * IVACT_{jat} + FCDCT_{jat} * IVDCT_{jat}) \\
 & + \sum_d \sum_\alpha \sum_t (FCICD_{dat} * IVICD_{dat} + FCMCD_{dat} * IVACD_{dat} + FCD CD_{dat} * IVD CD_{dat}) \\
 & + \sum_p \sum_j \sum_\alpha \sum_c \sum_t (CPP_{pjaet} * APM_{pjaet}) + \sum_m \sum_{j'} \sum_\alpha \sum_c \sum_t (CPM_{mj'aet} * AMM_{mj'aet}) \\
 & + \sum_{m'} \sum_s \sum_{j'} \sum_h \sum_t (PCM_{m'st} * ART_{m'sj'ht})
 \end{aligned} \tag{9}$$

The second objective function involves minimizing the environmental footprints: this objective function tries to minimize the adverse environmental impacts of the agri-food supply chain. Operations required for facilities and flow transfer between facilities

significantly impact environmental pollution. Minimizing the emissions of CO<sub>2</sub>, nitrogen oxide compounds, other greenhouse gases, and water consumption along the chain due to water stress in most parts of the world can focus on the environmental function. In this study, minimizing CO<sub>2</sub> and nitrogen oxide emissions caused by in-house operations and flow transfer between facilities and water consumption for raw material production, water consumption for the production and distribution of products is considered an environmental function. Equation (10) shows the mathematical formula of this objective function.

$$\begin{aligned}
 Z_2 = \text{Min} & \left( ww_1 * \left( \left( \sum_p \sum_d \sum_f \sum_c \sum_h \sum_t ETDC_{pdfcht} * APTC_{pdfcht} \right) \right. \right. \\
 & + \left( a * \left( \left( \sum_p \sum_d \sum_f \sum_c \sum_h \sum_t NETDC_{pdfcht} * APTC_{pdfcht} \right) \right) \right) \\
 & + \left( \sum_p \sum_j \sum_d \sum_h \sum_t ETTD_{pjdh t} * APTJ_{pjdh t} \right) + \left( a * \left( \sum_p \sum_j \sum_d \sum_h \sum_t NETTD_{pjdh t} * APTJ_{pjdh t} \right) \right) \\
 & + \left( \sum_m \sum_{j'} \sum_j \sum_h \sum_t ETTT_{m'j'jht} * AMT_{m'j'jht} \right) + \left( a * \left( \sum_m \sum_{j'} \sum_j \sum_h \sum_t NETTT_{m'j'jht} * AMT_{m'j'jht} \right) \right) \\
 & + \left( a * \left( \sum_{m'} \sum_s \sum_{j'} \sum_h \sum_t NETST_{m'sj'ht} * ART_{m'sj'ht} \right) \right) + \left( \sum_{m'} \sum_s \sum_{j'} \sum_h \sum_t ETST_{m'sj'ht} * ART_{m'sj'ht} \right) \\
 & + \sum_j \sum_\alpha \sum_e \sum_t (FEGOT_{jaet} * OST_{jaet} + FEGMT_{jaet} * CST_{jaet} + FEGCT_{jaet} * CCST_{jaet}) \\
 & + \sum_d \sum_\alpha \sum_e \sum_t (FEGOD_{daet} * OSD_{daet} + FEGMD_{daet} * CSD_{daet} + FEGCD_{daet} * CCSD_{daet}) \\
 & + \sum_p \sum_j \sum_\alpha \sum_e \sum_t (EPT_{pj aet} * APM_{pj aet}) + \left( a * \left( \sum_p \sum_j \sum_\alpha \sum_e \sum_t (NEPT_{pj aet} * APM_{pj aet}) \right) \right) \\
 & + \sum_m \sum_{j'} \sum_\alpha \sum_e \sum_t (EPTM_{m'j' aet} * AMM_{m'j' aet}) + \left( a * \left( \sum_m \sum_{j'} \sum_\alpha \sum_e \sum_t (NEPTM_{m'j' aet} * AMM_{m'j' aet}) \right) \right) \\
 & + \sum_{m'} \sum_s \sum_{j'} \sum_h \sum_t (EGPS_{m's t} * ART_{m'sj'ht}) + \left( a * \left( \sum_{m'} \sum_s \sum_{j'} \sum_h \sum_t (NEGPS_{m's t} * ART_{m'sj'ht}) \right) \right) \\
 & + ww_2 * b * \left( \left( \sum_m \sum_{j'} \sum_\alpha \sum_e \sum_t (WSIJ_{j'} * WPTM_{m'j' aet} * AMM_{m'j' aet}) \right) + \left( \sum_p \sum_j \sum_\alpha \sum_e \sum_t (WSIJ_j * WPT_{pj aet} * APM_{pj aet}) \right) \right) \\
 & + \sum_j \sum_\alpha \sum_e \sum_t WSIJ_j * (FWCOT_{jaet} * OST_{jaet} + FWCMT_{jaet} * CST_{jaet} + FWCCT_{jaet} * CCST_{jaet}) \\
 & + \sum_d \sum_\alpha \sum_e \sum_t WSID_d * (FWCOD_{daet} * OSD_{daet} + FWCMD_{daet} * CSD_{daet} + FWCCD_{daet} * CCSD_{daet}) \\
 & + \sum_{m'} \sum_s \sum_{j'} \sum_h \sum_t (WSIS_s * WCPST_{m's t} * ART_{m'sj'ht})
 \end{aligned}
 \tag{10}$$

The third objective function seeks to maximize the social effects of the supply chain in question. This function includes job opportunities created during the establishment or construction of a production unit. In this study, job opportunities are divided into fixed and variable categories. Fixed job opportunities are independent of the capacity of the facilities, such as managerial jobs. However, variable job opportunities, such as workers' jobs, vary depending on the facility's capacity.

$$\begin{aligned}
 Z_3 = & \text{Max} \sum_j \sum_\alpha \sum_e \sum_t (FJOOT_{jt} * OST_{jaet} + FJOMT_{jt} * CST_{jaet}) \\
 & + \sum_d \sum_\alpha \sum_e \sum_t (FJOOD_{dt} * OSD_{daet} + FJOMD_{dt} * CSD_{daet}) \\
 & + \sum_p \sum_j \sum_\alpha \sum_e \sum_t \left( \frac{VJOOT_{jat} * APM_{pj aet}}{CSJ_{jat}} \right) + \sum_p \sum_j \sum_\alpha \sum_e \sum_t \left( \frac{VJOMT_{jat} * APM_{pj aet}}{CSJ_{jat}} \right) \\
 & + \sum_p \sum_j \sum_d \sum_\alpha \sum_h \sum_t \left( \frac{VJOOD_{dat} * APTJ_{pjdht}}{CSDD_{dat}} \right) + \sum_p \sum_j \sum_d \sum_\alpha \sum_h \sum_t \left( \frac{VJOMD_{dat} * APTJ_{pjdht}}{CSDD_{dat}} \right)
 \end{aligned} \tag{11}$$

The fourth objective function seeks to minimize product delivery time to the customer. This function assumes that all products are potentially and actually produced on transformer sites and that each facility can procure raw materials from any supplier. The function considers the transportation time of raw materials from the supplier to the transformer site, product transportation time from the intermediate product transformer site to the final product transformer site, product transportation time from the transformer site to distribution sites, and product manufacturing time in transformer sites. All parameters are in seconds and product units.

$$\begin{aligned}
 Z_4 = & \text{Min} \left( \sum_{m'} \sum_s \sum_{j'} \sum_j \sum_h \sum_t (TTS_{m' sjht} * PST_{m' sj'}) \right. \\
 & + \left( \sum_p \sum_j \sum_d \sum_\alpha \sum_h \sum_e \sum_t (TTOT_{pjdht} * OST_{jaet} + TTMT_{pjdht} * CST_{jaet}) \right) \\
 & + \left( \sum_m \sum_{j'} \sum_j \sum_\alpha \sum_h \sum_e \sum_t (TTTT_{mj' jht} * (OST_{jaet} + CST_{jaet})) \right) \\
 & + \left( \sum_p \sum_d \sum_f \sum_c \sum_\alpha \sum_h \sum_e \sum_t (TTOD_{pdfcht} * OSD_{daet} + TTMD_{pdfcht} * CSD_{daet}) \right) \\
 & + \left( \sum_p \sum_j \sum_\alpha \sum_e \sum_t (TPOP_{pj et} * OST_{jaet} + TPMP_{pj et} * CST_{jaet}) \right) \\
 & + \left. \left( \sum_m \sum_j \sum_\alpha \sum_e \sum_t (TPOM_{mj et} * OST_{jaet} + TPMM_{mj et} * CST_{jaet}) \right) \right)
 \end{aligned} \tag{12}$$

### 3.3.1 Constraints

– Demand constraint

$$\sum_h APTC_{pdfcht} \leq OD_{pdfct} \tag{13}$$

$$\sum_h ART_{m' sj' ht} \leq PST_{m' sj' t} * SC_{m' st} \tag{14}$$

– Transformer site constraint



$$IVACT_{j\alpha 1} = CIT_{j\alpha 1} * \sum_e (OST_{j\alpha e 1} + CST_{j\alpha e 1}) \quad (\text{for } j \in J, t = 1) \tag{15}$$

$$IVACT_{j\alpha t} = IVACT_{j\alpha t-1} + IVICT_{j\alpha t} - IVDCT_{j\alpha t} \quad (j \in J, t \geq 2) \tag{16}$$

$$IVACT_{j\alpha t} \geq CLT_{j\alpha t} * \sum_e (OST_{j\alpha e t} + CST_{j\alpha e t} - CCST_{j\alpha e t}) \quad (j \in J, t \geq 2, \alpha \in \alpha) \tag{17}$$

$$IVACT_{j\alpha t} \leq 0.5 * \sum_e (CUT_{j\alpha e t}) * \sum_e (OST_{j\alpha e t} + CST_{j\alpha e t} - CCST_{j\alpha e t}) \quad (j \in J, t \geq 2, \alpha \in \alpha) \tag{18}$$

$$IVICT_{j\alpha t} \leq \sum_e CUT_{j\alpha e t} * \left( \sum_e (OST_{j\alpha e t} + CST_{j\alpha e t} - CCST_{j\alpha e t}) \right) \quad (j \in J, t \geq 2, \alpha \in \alpha) \tag{19}$$

$$IVDCT_{j\alpha t} \leq IVACT_{j\alpha t} \quad (j \in J, t \geq 2, \alpha \in \alpha) \tag{20}$$

$$IVACT_{j\alpha t} = CLT_{j\alpha t} \quad t = 1 \tag{21}$$

$$IVICT_{j\alpha t} = 0 \quad t = 1 \tag{22}$$

$$IVDCT_{j\alpha t} = 0 \quad t = 1 \tag{23}$$

– **Distributor site constraint**

$$IVACD_{d\alpha 1} = CID_{d\alpha 1} + \sum_e (OSD_{d\alpha e 1} + CSD_{d\alpha e 1}) \quad (d \in D, t = 1) \tag{24}$$

$$IVACD_{d\alpha t} \leq IVACD_{d\alpha t-1} + IVICD_{d\alpha t} - IVDCD_{d\alpha t} \quad (d \in D, t \geq 2) \tag{25}$$

$$IVACD_{d\alpha t} \geq CLD_{d\alpha t} * \sum_e (OSD_{d\alpha e t} + CSD_{d\alpha e t} - CCSD_{d\alpha e t}) \quad (d \in D, t \geq 2) \tag{26}$$

$$IVACD_{d\alpha t} \leq 0.5 * \sum_e CUD_{d\alpha e t} * \left( \sum_e (OSD_{d\alpha e t} + CSD_{d\alpha e t} - CCSD_{d\alpha e t}) \right) \quad (d \in D, t \geq 2) \tag{27}$$

$$IVICD_{d\alpha t} \leq 0.5 * \sum_e CUD_{d\alpha e t} * \left( \sum_e (OSD_{d\alpha e t} + CSD_{d\alpha e t} - CCSD_{d\alpha e t}) \right) \quad (d \in D, t \geq 2) \tag{28}$$

$$IVDCD_{d\alpha t} \leq IVACD_{d\alpha t} \tag{29}$$

$$IVACD_{d\alpha t} \leq CLD_{d\alpha t} \quad t = 1 \tag{30}$$

$$IVICD_{dat} = 0 \quad t = 1 \quad (31)$$

$$IVDCD_{dat} = 0 \quad t = 1 \quad (32)$$

Production and transportation constraints

$$\sum_p \sum_f \sum_c \sum_h APTC_{pdfcht} \leq \sum_\alpha IVACD_{dat} \quad (33)$$

$$\sum_h \sum_j APTJ_{pjdh} \geq \sum_h \sum_c \sum_f APTC_{pdfcht} \quad (34)$$

$$\sum_p \sum_j \sum_\alpha \sum_e \sum_t APM_{pj\alpha et} \geq \sum_p \sum_d \sum_f \sum_c \sum_h \sum_t APTC_{pdfcht} \quad (35)$$

$$\sum_d \sum_h APTJ_{pjdh} \leq \sum_\alpha \sum_e APM_{pj\alpha et} \quad (36)$$

$$\sum_p APM_{pj\alpha et} \leq CSJ_{j\alpha t} * (OST_{j\alpha et} + CST_{j\alpha et} - CCST_{j\alpha et}) \quad (37)$$

$$\sum_p \sum_e APM_{pj\alpha et} \leq IVICT_{j\alpha t} \quad (38)$$

$$\sum_p APM_{pj\alpha et} \leq CUT_{j\alpha et} * (OST_{j\alpha et} + CST_{j\alpha et} - CCST_{j\alpha et}) \quad (39)$$

Binary constraints

$$CST_{j\alpha et} - CCST_{j\alpha et} \leq 1 \quad (t \geq 2) \quad (40)$$

$$CST_{j\alpha et} - CCST_{j\alpha et} \geq 0 \quad (t \geq 2) \quad (41)$$

$$\sum_\alpha \sum_e (CST_{j\alpha et} + OST_{j\alpha et}) \leq 1 \quad (t \geq 2) \quad (42)$$

$$CST_{j\alpha et} = IST_{j\alpha et} \quad (t = 1) \quad (43)$$

$$(CST_{j\alpha et} + OST_{j\alpha et}) \leq 1 \quad (44)$$

$$CST_{j\alpha et} + OST_{j\alpha et} = CSD_{d\alpha et} + OSD_{d\alpha et} \quad (45)$$

$$0 \leq CSD_{d\alpha et} - CCSD_{d\alpha et} \leq 1 \quad (t \geq 2) \quad (46)$$

$$\sum_{\alpha} \sum_e (CSD_{daet} + OSD_{daet}) \leq 1 \quad (t \geq 2) \tag{47}$$

$$ISD_{daet} = OSD_{daet}(t = 1) \tag{48}$$

$$CSD_{daet} + OSD_{daet} \leq 1 \quad (t \geq 2) \tag{49}$$

$$\sum_s PST_{m'sj't} \geq 1 \tag{50}$$

$$PST_{m'sj't} \leq (OST_{jaet} + CST_{jaet} - CCST_{jaet}) \tag{51}$$

$$\sum_e (CST_{jaet} + OST_{jaet}) \leq 1 \tag{52}$$

$$CCST_{jaet} = 0 \quad (t = 1) \tag{53}$$

$$CCSD_{daet} = 0 \quad (t = 1) \tag{54}$$

Positivity, integrality, and binary constraints

$$CST_{jaet}, \quad OST_{jaet}, \quad CCST_{jaet} \in \{0, 1\} \tag{55}$$

$$CSD_{daet}, \quad OSD_{daet}, \quad CCSD_{daet} \in \{0, 1\} \tag{56}$$

$$PST_{m'sj't} \in \{0, 1\} \tag{57}$$

$$IVICT_{jat}, \quad IVDCT_{jat}, \quad IVACT_{jat} \geq 0, \quad \text{Integer} \tag{58}$$

$$IVICD_{dat}, \quad IVDCD_{daet}, \quad IVACD_{dat} \geq 0, \quad \text{Integer} \tag{59}$$

$$ART_{m'sj'ht} \geq 0, \quad \text{Integer} \tag{60}$$

$$APTJ_{pjdht} \geq 0, \quad \text{Integer} \tag{61}$$

$$AMT_{mj'jht} \geq 0, \quad \text{Integer} \tag{62}$$

$$APTC_{pdfcht} \geq 0, \quad \text{Integer} \tag{63}$$

$$AMM_{mj' \alpha et} \geq 0, \quad \text{Integer} \tag{64}$$

$$APM_{pjaet} \geq 0, \quad \text{Integer} \tag{65}$$

## 4 A case study and results

The research case study is Kadbanoo Company with the Delpazir brand. Kadbanoo, the manufacturer of Delpazir products, initiated its operation in 1949 on land of 17,500 square meters, located 57 km from Tehran and on the outskirts of Karaj. At its inception, the company's operations were limited to producing only a few types of compotes and jams. By expanding its operations for the first time in Iran, the company succeeded in producing sugar-free jam and other products such as cold sauces (mayonnaise and salad dressings), hot sauces (hot and ordinary ketchup), and vegan canned products (pasta sauce, pinto beans, etc.). The company's product portfolio consists of five product families. This company's main products are sauces, canned products (bean feed, canned eggplant, etc.), pickles, pastes, and jams. Kadbanoo has two food transformer sites to convert some raw materials into four intermediate goods on the first site: intermediate goods for canning (semi-cooked cereal ingredients with specified percentages), intermediate goods for pastes (dried tomatoes), intermediate goods for jams, and intermediate goods for pickles. Eventually, these products become the final product after being transferred to the second transformer site. The company has dozens of suppliers, including seven primary raw materials: tomatoes, legumes (beans, eggplant, peas, corn, etc.), sugar, jam raw materials, approved additives, oils, and packaging items. It has 12 central supplier provinces. The company's intermediate products are four main ingredients operating quarterly for four periods per year. Its transport mode is land transportation using four types of carriers: Nissan vans with a capacity of 2 tons, trucks with a capacity of 4 and 6 tons, and 10-ton trucks. Depending on customers' expected orders and demand, the factory's products vary in capacities of 50, 100, and 150 thousand tons. The company has two actual transformer sites and three potential ones in Karaj, Mashhad, and Shiraz. Its main distribution sites are located in five main hubs with fourteen subsidiaries, mainly managing the north and northwest, east and northeast, west and southwest, south and southeast, and central regions of Iran. The company also has three main customer groups: chain stores and hypermarkets, department stores, and medium and small retailers.

In this section, the criteria were evaluated and validated through the Delphi method by dividing them into three main economic, social, and environmental criteria (Seuring & Müller, 2008) (Table 1).

After identifying the criteria, by sending them to industry experts ( $N=7$ ), they were asked to assign a score to each sub-criterion according to the Likert scale (Appendix Table 8) in terms of importance. After assigning the importance score according to Appendix Table 8, a Delphi score (Banaeian et al., 2015) was assigned to each sub-criterion through Eq. (66). Criteria with a Delphi score greater than five are selected for the subsequent round at each stage.

$$\text{Delphi Score} = \frac{\text{Highest Score} + \text{Lowest Score} + (4 * \text{Average Score})}{6} \quad (66)$$

The results of this process (Table 2) will be completed after 2 to 5 stages. Delphi scores for all criteria that reached more than 5 (Tables 2, 3, 4, 5) were selected as criteria for weighting in the next stage.

According to Table 2, it is clear that experts agree upon the sub-criteria 7, 10, 2, and 1. The sub-criteria are weighed and ranked in the subsequent steps.

**Table 1** Supplier selection criteria

Criteria	Sub-criteria
Economic	Water availability (water stress index) (EC1)
	Product competitive price (EC2)
	Quality certified by quality control sites (EC3)
	Agricultural production capacity (EC4)
	Price stability (EC5)
	Temporal flexibility (EC6)
	Speed in transporting the procured product (EC7)
	Delivery terms (EC8)
	Delivery time (EC9)
	Capacity size (EC10)
	Financial strength (EC11)
Social	Traceability of complaints about poor quality products (SC1)
	Continuous product quality improvement (SC2)
	Product transport safety (SC3)
	Product quality (SC4)
	Goodwill (SC5)
	Product delivery speed (SC6)
	Product delivery flexibility (SC7)
	Communication (SC8)
	Experience (SC9)
	Sales agency (ease of supply) (SC10)
	Sustainable delivery (SC11)
Environmental	Sustainable raw materials (SC12)
	Water consumption per unit of production (EN1)
	Carbon footprints per unit of production (EN2)
	Production per unit of land used (EN3)
	Nitrous oxide footprints per unit of production (EN4)

Based on the Delphi method results in determining the environmental sub-criteria listed in Table 3, sub-criteria 1, 2, and 4 were selected as the criteria required for supplier selection.

Based on the Delphi method results presented in Table 4, sub-criteria 2, 6, 4, and 12 were selected as supplier selection criteria. All sub-criteria selected in the previous section were weighted using the best–worst method (Rezaei, 2016). The results and pairwise comparison matrices are presented in Appendix Table 9. In this section, a matrix of pairwise comparisons between the best and worst criteria with other criteria is formed, which is one of the inputs to obtain the criteria weights of the best–worst method (Appendix Table 10, 11). After pairwise comparisons based on the best–worst method performed in the previous section, the criteria weights were extracted using the best–worst method, shown in Table 5.

The alternatives for selecting suppliers include all Iranian provinces shown in Table 6.

For supplier selection using complex proportional assessment, this matrix should be normalized and weighted after completing the decision matrix by experts. The normalized and weighted matrices are presented in Appendix Table 12 and 13. Based on the complex

**Table 2** Delphi scores for economic sub-criteria of supplier selection

Row	Sub-criteria	Round 1	Round 2	Round 3	Round 4	Round 5
1	EC1	7.64285714	7	7.19047619	7.738095238	7.642857143
2	EC2	6.80952381	7.357142857	7.714285714	7.738095238	8
3	EC3	6.45238095	7.285714286	5.80952381	4	–
4	EC4	7.45238095	7	4.547619048	–	–
5	EC5	4.61904762	–	–	–	–
6	EC6	4.80952381	–	–	–	–
7	EC7	6.80952381	7.547619048	7.928571429	7.928571429	8.285714286
8	EC8	6.64285714	4.619047619	–	–	–
9	EC9	4.26190476	–	–	–	–
10	EC10	6.52380952	7.357142857	7.738095238	8.19047619	8.095238095
11	EC11	4	–	–	–	–

**Table 3** Delphi scores for the environmental sub-criteria of supplier selection

Row	Sub-criteria	Round 1	Round 2
1	EN1	7.80952381	8
2	EN2	7	7.285714286
3	EN3	4.80952381	–
4	EN4	6.80952381	7.095238095

**Table 4** Delphi scores for the social sub-criteria of supplier selection

Row	Sub-criteria	Round 1	Round 2	Round 3	Round4
1	SC1	6.9047619	4.738095238	–	–
2	SC2	6.54761905	6.80952381	6.904761905	7.642857143
3	SC3	7.0952381	4.80952381	–	–
4	SC4	6.83333333	6.80952381	6.904761905	7.095238095
5	SC5	4.9047619	–	–	–
6	SC6	6.9047619	6.452380952	7.452380952	7.19047619
7	SC7	4.64285714	–	–	–
8	SC8	4.9047619	–	–	–
9	SC9	4.54761905	–	–	–
10	SC10	4.73809524	–	–	–
11	SC11	6.9047619	6.642857143	4.547619048	–
12	SC12	7.19047619	7.19047619	7.261904762	6.904761905

proportional assessment calculations (Appendix 6), the provinces selected as suppliers are presented in Appendix Table 14.

LP-metric is one of the multi-criteria decision-making methods for solving multi-objective decision-making models. Goal programming and LP-metric techniques are among the methodologies used by multi-criteria decision-making. These approaches have a common root and use a definite target point in criterion space to model decision-makers' preferences. According to the Goal programming technique, this definite target point is a vector of expected levels representing the ideal values for different criteria.

**Table 5** Criteria weights based on the best–worst method for all three steps above

Suppliers		Producer’s location		Distributor’s location	
W		W		W	
EC1	0.083	EC1	0.136	EC1	0.057
EC2	0.046	EC3	0.082	EC2	0.041
EC7	0.139	EC4	0.068	EC3	0.047
EC10	0.083	EC8	0.102	EC5	0.057
SC2	0.052	EC11	0.045	EC6	0.095
SC4	0.083	EC12	0.136	EC8	0.142
SC6	0.070	EC15	0.058	EC9	0.057
SC12	0.083	SC1	0.082	SC1	0.041
EN1	0.046	SC3	0.051	SC3	0.047
EN2	0.139	EN1	0.058	SC4	0.057
EN4	0.083	EN2	0.045	SC5	0.032
		EN4	0.136	SC9	0.095
				SC10	0.057
				SC11	0.032
				SC12	0.047
				EN1	0.041
				EN3	0.057

**Table 6** Names of Iranian provinces and related notations in the Complex Proportional Assessment method

Row	Province	Notation	Row	Province	Notation
1	East Azerbaijan	A1	17	Fars	A17
2	West Azerbaijan	A2	18	Qazvin	A18
3	Ardabil	A3	19	Qom	A19
4	Isfahan	A4	20	Kurdistan	A20
5	Alborz	A5	21	Kerman	A21
6	Ilam	A6	22	Kermanshah	A22
7	Bushehr	A7	23	Kohgiluyeh and Boyer-Ahmad	A23
8	Tehran	A8	24	Golestan	A24
9	Chaharmahal & Bakhtiari	A9	25	Guilan	A25
10	South Khorasan	A10	26	Lorestan	A26
11	Khorasan Razavi	A11	27	Mazandaran	A27
12	North Khorasan	A12	28	Markazi	A28
13	Khuzestan	A13	29	Hormozgan	A29
14	Zanjan	A14	30	Hamedan	A30
15	Semnan	A15	31	Yazd	A31
16	Sistan & Baluchistan	A16	–	–	–

According to the LP-metric, this target point is also a vector of reference levels. The LP-metric minimizes the sum of the relative deviations of the objectives from their optimum value. Thus, for a problem with  $n$  objective functions, the optimal value of each objective function (from the 1st to the  $n$ th) must be calculated independently of the other  $n-1$  objective functions, taking into account all the constraints of the problem. The closer the objective functions are to their optimal values, the more desirable it is for us. We are looking for an objective function by which all functions can be closer to their optimal values. Accordingly, the sum of the relative deviations of the objectives from their optimal values must be minimized. Therefore, the objective function is defined as follows:

$$\text{Min } Z = \sum_{i=1}^k \left( \frac{f_i^* - f_i}{f_i^*} \right)^P$$

The above equation represents the optimal value of the objective function  $i$  without considering other objective functions and by considering all constraints.

*Norm:* in linear algebra and functional analysis, a norm refers to a vector or a continuous function that assigns a positive length or size to all vectors in a vector space. The LP-metric method gives different values for  $p$  ( $p=1$ ,  $p=2$ ). The first case ( $p=1$ ) minimizes the sum of relative deviations, and the second ( $p=2$ ) minimizes the squared sum of the relative deviations. A multi-objective decision-making model includes a vector of decision variables, objective functions, and constraints, and the decision-maker's goal is to maximize or minimize objective functions. Because these problems rarely have a unique solution, the decision-maker chooses a solution from a set of feasible solutions. The LP-metric minimizes the sum of the relative deviations of the objectives from their optimum value and incorporates multiple objective functions into a single objective. This approach was first proposed by Hwang and Masud (1979). The LP-metric method received more attention for two reasons:

- (1) The LP-metric requires less information from a decision-maker.
- (2) In practice, the LP-metric is simple to use.

The method uses the ideal to measure the proximity of a solution. This deviation measurement for  $\text{Min}Z$  will be as follows

$$\text{Min}Z = \sum_{i=1}^n w_i \left( \frac{z_i^* - z_i}{z_i^*} \right)^P$$

where  $w_i$  is the importance (weight) of the  $i$ -th objective. The deviation of the ideal solution of the  $i$ -th objective is divided by  $z_i^*$  to eliminate the differences in the objective scales.  $P$  also indicates the degree of emphasis on deviations; the more significant the  $P$ , the greater the emphasis on the most significant deviation. The overall objective function of the LP-metric must also be minimized to minimize deviations from the ideal solution.

For implementing the solution algorithm in this model, each objective function is first solved regardless of the other objective functions and considers the boundary conditions or constraints. The result is considered the ideal solution for this objective function. Then, the objective functions with different weighted coefficients are solved again and simultaneously. Finally, as the scenario changes, each coefficient changes, the equations are solved again, and the result specific to that scenario is determined.



This study used the coding environment in GAMS 25.1.2 software. After implementing the LP-metric algorithm in this software, the results of the model solution were transferred to Excel software. Then the results were entered into the MATLAB environment to calculate Pareto frontier graphs. A 1.8 GHz Core-i7 computer with 2.2G RAM was used to solve the model. According to the calculations and model solving in GAMS software and the use of the case study company's frameworks, the best scenario and coefficients, along with the values of the objective functions, are presented in Table 7.

Table 7 shows the values of the four objective functions of this model, namely cost minimization, environmental footprint minimization, social impact maximization, and product delivery time minimization, along with their coefficients in the LP-metric method. According to Appendix Table 14, the first objective function, i.e., the economic function, conflicts with other objective functions. If we want to optimize this objective function, the other functions deviate from the ideal state. Due to the importance of economics in manufacturing companies and the non-dissemination of environmental and social impacts on their corporate social responsibility, the first coefficients were considered the optimal values. Since this model considered several scenarios to obtain the Pareto front chart and the proposed model has four objective functions, three Pareto front charts were considered, each showing three objective functions and their relationships. Therefore, data from different scenarios with various solutions were entered into MATLAB software, and their 3D Pareto front charts are presented in Figs. 3 and 4.

## 5 Conclusion and discussion

The growing importance of environmental issues, minimizing costs, maximizing corporate profitability, and increasing the social impacts of business operations, have led people to pay more attention to a sustainable supply chain. After reviewing previous research, it was found that the chain is moving forward in the most sustainable agri-food supply chain research. This study also considered the forward supply chain. The study model had four objective functions, while other models presented in the agri-food supply chain have two to three objective functions. Another noteworthy point in designing the research model is using a hybrid model addressed in a small number of studies. This study used the Delphi technique and experts' opinions to evaluate and localize the criteria. The best-worst method was used for criteria weighting, a new method with less judgment than other methods.

The studies still need to apply this method for weighting the selected criteria. In the model under study, the supply chain had four tires (supplier, producer, distributor, and customers). This number of tires has yet to be considered in other studies. The objective functions of this model were (1) cost minimization, (2) environmental footprint minimization, (3) social impact maximization through job opportunities created, and (4) product delivery time minimization. The cost function tried to consider all the main costs along the chain and provide a comprehensive model. This function included transportation costs (transportation costs from supplier to producer, from transformer site to producer site, from transformer site to distributor, and finally from distributor to customers), the costs of opening (construction), closure or maintenance of production sites, distribution, production costs, raw material procurement costs, and fixed costs of capacity change. The second objective function tried to minimize environmental footprints that adversely impact the environment. This study considered minimizing carbon and

**Table 7** The best coefficients and values of the objective functions

	$Z_1$	$Z_2$	$Z_3$	$Z_4$	$Z_2$ -Carbon	$Z_2$ -Nitrogen	$Z_2$ -Water	$W_1$	$W_2$	$W_3$	$W_4$
Optimal	5,376,496,000,000	529,980,240	6467	77,463	9,904,464	9,874,332	377,706,420	0.5	0.3	0.1	0.1
Suboptimal	6,720,620,000,000	441,650,200	6,808	70,421	11,004,960	10,971,480	419,673,800	0.2	0.35	0.35	0.1

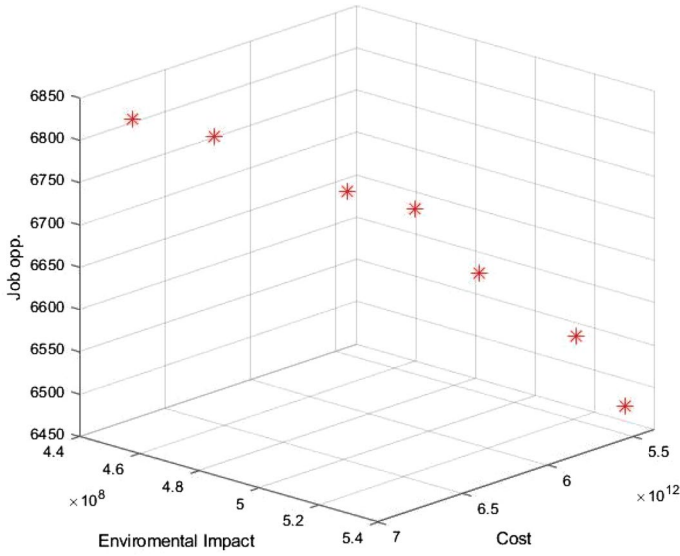


Fig. 3 Pareto frontier considering  $Z_1$ ,  $Z_2$ , and  $Z_3$

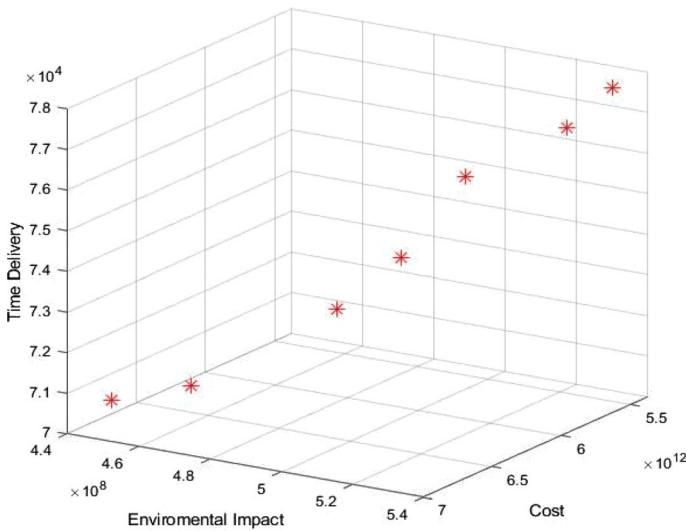


Fig. 4 Pareto frontier considering  $Z_1$ ,  $Z_2$ , and  $Z_4$

nitrous oxide emissions due to in-house operations and flow transfer between facilities. Alternatively, water consumption when converting raw materials into products is an environmental function. However, other studies considered minimizing carbon footprints and water consumption as an objective function. This objective function is one of the model’s innovations. The third objective function includes fixed and variable job opportunities as one of the social indicators in supply chain modeling. Although most

models have considered fixed job opportunities an objective function, this model also used variable job opportunities affected by production capacity. In the fourth objective function, minimizing product delivery time to customers was considered one of the components of resilience and customer satisfaction. This objective function assumes it can produce all products on potential and actual transformer sites.

On the other hand, any production site can procure raw materials from all suppliers. This function included the raw material transport time from the supplier to the transformer site, the product transport time from the intermediate transformer site to the final product transformer site, the product transport time from the transformer site to distribution sites, and the production time at transformer sites. All parameters were also in seconds and product units. Finally, the extracted model was solved using the weighted LP-metric method and GAMS software. Some output results of the Complex Proportional Assessment method for selecting the location of distribution hubs and model solution results for different scenarios are presented in Appendix Table 15 and Table 16.

Only a few articles published in the past two years have examined the three dimensions of sustainability (economic, environmental, and social) and food supplier decision-making, followed by a prescriptive model for sustainable agri-food supply chains. Most serious supply chain sustainability and modeling efforts have been summarized in closed-loop and reverse logistics problems. In most of these studies, it can be seen that in the environmental dimension, more focus has been placed on carbon emissions, and a small number of articles have focused on other greenhouse gases. In most studies, the social objective function focuses only on the fixed job opportunities created, and some consider lost job opportunities. This study included fixed and variable job opportunities. A combination of product revenue and recycled material revenue was the only objective function proposed by Fathi et al. (2019). Unlike other articles, four objective functions were used in this article, including a social issue, i.e., minimizing the product time delivery to the customer. The second objective function not only minimized carbon emissions as in other studies but also minimized nitrogen emissions and water consumption as one of the most challenging substances of the last century.

Another consideration is the solution method, which is more dependent on meta-heuristic algorithms due to the nature of such problems. This study applied an exact approach, and weighted goal programming and LP-metric methods were used like other research works. On the other hand, this study used multi-criteria decision-making methods to select factors and criteria for selecting suppliers, transformer sites, and, finally, each region's central distribution hub locations for a sustainable agri-food supply chain, which is unique.

In conclusion, some practical implications are presented as follows:

- Using the research model and validating it in other case studies
- Utilizing other economic and social factors and bringing the model closer to the real-world issues
- Applying other supply chain costs, including HR costs, branding costs, marketing costs, and other logistics subsystems
- Incorporate tax rates, working capital, cash flow, income, and numerous other factors into the model

## Appendix

See Tables 8, 9, 10, 11, 12, 13, 14, 15 and 16.

**Table 8** Verbal judgment criteria and their numerical values (Banaeian et al., 2015)

Row	Preference/verbal judgment criteria	Numerical value
1	Equal importance	1
2	Moderate importance	3
3	Strong importance	5
4	Extreme importance	7
5	Absolute importance	9
6	Intermediate values	2, 4, 6, 8

**Table 9** Selected criteria based on the Delphi method and the best and worst criteria

	Supplier selection sub-criteria	Producer’s location selection sub-criteria	Distributor’s location selection sub-criteria
Economic	EC1, EC2, EC7, EC10	EC1, EC3, EC4, EC8, EC11, EC12, EC15	EC1, EC2, EC3, EC5, EC6, EC8, EC9
Social	SC2, SC4, SC6, SC12	SC1, SC3	SC1, SC3, SC4, SC5, SC9, SC10, SC11, SC12
Environmental	EN1, EN2, EN4	EN1, EN2, EN4	EN1, EN3
Best sub-criteria	EC2	EC11	SC11
Worst sub-criteria	EN4	EN2	SC5

**Table 10** Preference matrix of the best criterion over all the other criteria for suppliers (B = EC2)

	EC1	EC2	EC7	EC10	SC2	SC4	SC6	SC12	EN1	EN2	EN4
$a_{Bj}$	9	2	4	5	6	5	8	5	3	1	5

**Table 11** Preference matrix of all the criteria over the worst criterion for suppliers (W = EN4)

	$a_{jw}$
EC1	5
EC2	9
EC7	3
EC10	7
SC2	6
SC4	5
SC6	4
SC12	6
EN1	5
EN2	9
EN4	3

**Table 12** The dimensionless decision matrix

Criteria type	+	-	+	+	+	+	+	+	-	-	-
	EC1	EC2	EC7	EC10	SC2	SC4	SC6	SC12	EN1	EN2	EN4
A1	0.022	0.031	0.038	0.038	0.038	0.041	0.032	0.033	0.032	0.034	0.034
A2	0.029	0.032	0.032	0.061	0.033	0.036	0.027	0.033	0.033	0.034	0.034
A3	0.026	0.031	0.027	0.035	0.033	0.031	0.032	0.033	0.033	0.033	0.033
A4	0.013	0.033	0.032	0.040	0.027	0.031	0.032	0.039	0.030	0.034	0.034
A5	0.034	0.035	0.043	0.012	0.033	0.026	0.038	0.039	0.034	0.033	0.033
A6	0.044	0.035	0.032	0.009	0.022	0.031	0.027	0.022	0.037	0.035	0.035
A7	0.016	0.031	0.043	0.023	0.038	0.041	0.043	0.039	0.029	0.030	0.030
A8	0.025	0.033	0.027	0.036	0.027	0.031	0.038	0.033	0.040	0.037	0.037
A9	0.067	0.032	0.027	0.012	0.027	0.031	0.027	0.022	0.037	0.034	0.034
A10	0.008	0.034	0.032	0.007	0.033	0.026	0.027	0.028	0.035	0.033	0.033
A11	0.027	0.028	0.038	0.030	0.043	0.036	0.043	0.044	0.029	0.029	0.029
A12	0.018	0.030	0.027	0.011	0.022	0.031	0.032	0.022	0.034	0.033	0.033
A13	0.044	0.030	0.043	0.163	0.043	0.036	0.043	0.044	0.029	0.034	0.034
A14	0.025	0.033	0.032	0.026	0.027	0.031	0.027	0.033	0.032	0.032	0.032
A15	0.008	0.033	0.022	0.011	0.033	0.026	0.027	0.028	0.031	0.033	0.033
A16	0.012	0.034	0.032	0.032	0.033	0.031	0.022	0.022	0.034	0.034	0.034
A17	0.033	0.028	0.043	0.082	0.043	0.041	0.043	0.044	0.028	0.028	0.028
A18	0.011	0.030	0.038	0.066	0.038	0.041	0.043	0.044	0.030	0.030	0.030
A19	0.014	0.034	0.027	0.004	0.027	0.031	0.032	0.022	0.031	0.031	0.031
A20	0.041	0.035	0.022	0.027	0.033	0.026	0.022	0.028	0.032	0.030	0.030
A21	0.011	0.032	0.032	0.016	0.022	0.031	0.027	0.028	0.033	0.034	0.034
A22	0.046	0.029	0.038	0.043	0.038	0.036	0.038	0.039	0.030	0.030	0.030
A23	0.068	0.032	0.027	0.005	0.027	0.031	0.027	0.028	0.034	0.028	0.028
A24	0.040	0.033	0.027	0.042	0.033	0.031	0.027	0.033	0.030	0.033	0.033
A25	0.099	0.035	0.022	0.019	0.027	0.026	0.027	0.028	0.032	0.034	0.034
A26	0.054	0.035	0.027	0.027	0.027	0.021	0.022	0.028	0.032	0.034	0.034
A27	0.063	0.034	0.032	0.036	0.033	0.031	0.032	0.028	0.033	0.034	0.034
A28	0.025	0.035	0.027	0.022	0.027	0.026	0.038	0.033	0.033	0.034	0.034
A29	0.037	0.030	0.043	0.013	0.038	0.041	0.032	0.033	0.029	0.030	0.030
A30	0.031	0.029	0.038	0.047	0.043	0.041	0.038	0.039	0.029	0.032	0.032
A31	0.008	0.033	0.027	0.008	0.033	0.026	0.032	0.033	0.033	0.031	0.031

Table 13 Normalized weighted matrix

	EC1	EC2	EC7	EC10	SC2	SC4	SC6	SC12	EN1	EN2	EN4	$P_i$	$R_i$	$Q_i$	$N_i$	Rank	$I/R_i$
A1	0.002	0.001	0.005	0.003	0.002	0.003	0.002	0.003	0.003	0.007	0.002	0.021	0.013	0.033	0.692	11	75.076
A2	0.002	0.001	0.005	0.005	0.002	0.003	0.002	0.003	0.003	0.007	0.002	0.021	0.014	0.034	0.701	10	73.206
A3	0.002	0.001	0.004	0.003	0.002	0.003	0.002	0.003	0.003	0.007	0.002	0.018	0.013	0.031	0.643	17	75.730
A4	0.001	0.002	0.005	0.003	0.001	0.003	0.002	0.003	0.003	0.007	0.002	0.018	0.013	0.031	0.650	16	75.949
A5	0.003	0.002	0.006	0.001	0.002	0.002	0.003	0.003	0.004	0.007	0.002	0.020	0.013	0.032	0.668	14	74.432
A6	0.004	0.002	0.005	0.001	0.001	0.003	0.002	0.002	0.004	0.007	0.002	0.016	0.015	0.028	0.581	25	68.732
A7	0.001	0.001	0.006	0.002	0.002	0.003	0.003	0.003	0.003	0.006	0.001	0.021	0.012	0.035	0.722	7	81.816
A8	0.002	0.002	0.004	0.003	0.001	0.003	0.003	0.003	0.004	0.008	0.002	0.018	0.015	0.029	0.608	22	65.702
A9	0.006	0.001	0.004	0.001	0.001	0.003	0.002	0.002	0.004	0.007	0.002	0.018	0.014	0.030	0.622	19	70.618
A10	0.001	0.002	0.005	0.001	0.002	0.002	0.002	0.002	0.004	0.007	0.002	0.014	0.014	0.026	0.547	30	74.011
A11	0.002	0.001	0.005	0.003	0.002	0.003	0.003	0.004	0.003	0.006	0.001	0.022	0.012	0.037	0.759	6	85.815
A12	0.001	0.001	0.004	0.001	0.001	0.003	0.002	0.002	0.004	0.007	0.002	0.014	0.013	0.027	0.556	29	75.697
A13	0.004	0.001	0.006	0.014	0.002	0.003	0.003	0.003	0.004	0.007	0.002	0.035	0.013	0.048	1.000	1	77.146
A14	0.002	0.002	0.005	0.002	0.001	0.003	0.002	0.003	0.003	0.007	0.001	0.017	0.013	0.030	0.628	18	76.227
A15	0.001	0.002	0.003	0.001	0.002	0.002	0.002	0.002	0.003	0.007	0.002	0.013	0.013	0.026	0.530	31	76.328
A16	0.001	0.002	0.005	0.003	0.002	0.003	0.002	0.002	0.004	0.007	0.002	0.016	0.014	0.028	0.585	24	73.289
A17	0.003	0.001	0.006	0.007	0.002	0.003	0.003	0.004	0.003	0.006	0.001	0.028	0.011	0.043	0.886	2	86.986
A18	0.001	0.001	0.005	0.006	0.002	0.003	0.003	0.004	0.003	0.006	0.001	0.024	0.012	0.038	0.781	3	81.722
A19	0.001	0.002	0.004	0.000	0.001	0.003	0.002	0.002	0.003	0.006	0.001	0.013	0.013	0.027	0.557	28	79.270
A20	0.003	0.002	0.003	0.002	0.002	0.002	0.002	0.002	0.003	0.006	0.001	0.016	0.013	0.030	0.617	21	79.289
A21	0.001	0.001	0.005	0.001	0.001	0.003	0.002	0.002	0.003	0.007	0.002	0.015	0.013	0.027	0.565	26	74.235
A22	0.004	0.001	0.005	0.004	0.002	0.003	0.003	0.003	0.003	0.006	0.001	0.024	0.012	0.038	0.779	4	82.863
A23	0.006	0.002	0.004	0.000	0.001	0.003	0.002	0.002	0.004	0.006	0.001	0.018	0.012	0.032	0.662	15	82.294
A24	0.003	0.002	0.004	0.003	0.002	0.003	0.002	0.003	0.003	0.007	0.002	0.019	0.013	0.033	0.674	13	77.003
A25	0.008	0.002	0.003	0.002	0.001	0.002	0.002	0.002	0.003	0.007	0.002	0.021	0.014	0.033	0.686	12	73.924
A26	0.005	0.002	0.004	0.002	0.001	0.002	0.002	0.002	0.003	0.007	0.002	0.018	0.014	0.030	0.619	20	72.964
A27	0.005	0.002	0.005	0.003	0.002	0.003	0.002	0.002	0.003	0.007	0.002	0.022	0.014	0.034	0.707	9	73.650

Table 13 (continued)

	EC1	EC2	EC7	EC10	SC2	SC4	SC6	SC12	EN1	EN2	EN4	$P_i$	$R_i$	$Q_i$	$N_i$	Rank	$1/R_i$
A28	0.002	0.002	0.004	0.002	0.001	0.002	0.003	0.003	0.003	0.007	0.002	0.017	0.014	0.029	0.602	23	73.474
A29	0.003	0.001	0.006	0.001	0.002	0.003	0.002	0.003	0.003	0.006	0.001	0.021	0.012	0.035	0.720	8	83.403
A30	0.003	0.001	0.005	0.004	0.002	0.003	0.003	0.003	0.003	0.007	0.001	0.023	0.012	0.037	0.764	5	80.044
A31	0.001	0.002	0.004	0.001	0.002	0.002	0.002	0.003	0.003	0.007	0.001	0.014	0.013	0.027	0.562	27	77.642



**Table 14** Complex proportional assessment results for supplier selection

Rank	1	2	3	4	5	6	7	8
Province	Khuzestan	Fars	Qazvin	Kermanshah	Hamedan	Khorasan Razavi	Bushehr	Hormozgan

**Table 15** Output of complex proportional assessment method for selecting distribution hub locations

Geographical location	North and Northwest	Central	East and Northeast	West and South-west	South and Southeast
Province (distribution hub)	Ardabil	Tehran	Mashhad	Kermanshah	Shiraz

**Table 16** Model solution results for different scenarios

Scenarios	$W_1$	$W_2$	$W_3$	$W_4$	$Z_1$	$Z_2$	$Z_3$	$Z_4$	$Z_2$ -Carbon	$Z_2$ -Nitrogen	$Z_2$ -Water
Scenario 1	0.2	0.35	0.35	0.1	5,376,496,000,000	441,650,200	6,808	70,421	11,004,960	10,971,480	4.2E+08

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## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

**Ethical approval** Not applicable.

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