ISSN: 2710-0723

Optimization of Closed-loop Supply Chain Network for Vegetable and Fruit Agricultural Products Considering Fuzzy Demand and Purchasing Price

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Abstract

Due to the seasonal and perishable nature of vegetable and fruit agricultural products, which can easily cause sudden changes in demand and prices in a short period of time, a decision model framework was established to address the uncertainty issues related to vegetable and fruit agricultural products. The framework consists of triangular fuzzy numbers, a closed-loop supply chain network model for vegetable and fruit agricultural products, and an optimization model based on chance constrained programming, while considering demand, return rate,utilization rate. And with the goal of minimizing the sum of fixed costs, transportation costs, purchasing costs, packaging costs, storage costs, processing cost and disposal costs in the supply chain network, the model is validated through two scenarios: fuzzy demand and deterministic demand. The model calculation results indicate that under certain other conditions, the return rate is positively correlated with the total cost; The relationship between utilization rate and total cost may be either positive or negative, influenced by the combined effects of transportation costs and disposal costs in reverse logistics activities; The cost increase and facility selection corresponding to adjacent demand proportion nodes are different. Proved the effectiveness and feasibility of the model.

Keywords

Closed-loop Supply Chain Network; Opportunity Constrained Programming; Vegetable and Fruit Type Agricultural Products; Uncertain Demand.

1. Introduction

In recent years, with the rapid development of society and economy, people's living standards have also become higher and higher, and the demand for fresh agricultural products has continued to increase. While promoting diversified sales methods[1], it has also increased people's attention to whether the products are fresh[2]. Unlike other consumer goods, fresh agricultural products involve seasonality, peak demand, and perishability[3]. The high requirements for transportation conditions have led to many problems in the supply process[4], such as uncertain deterioration rates of agricultural products[5], significant price fluctuations, and serious resource waste and environmental pollution. At the juncture of today's major changes and the COVID-19, international food security, and major challenges for agricultural development[6], optimizing the design of the supply chain network of agricultural products is of great significance for improving farmers' income, stabilizing prices, improving resource utilization, and achieving the dual carbon goal.

Scholars at home and abroad have conducted extensive research on the design of supply chain networks and have achieved fruitful results. Nagurney et al.[7] designed an equilibrium model for the agricultural supply chain network to address the issue of tariff quotas. Through numerical examples, it was found that the implementation of this system can improve the

ISSN: 2710-0723

profits of enterprises. Liu Shanqiu et al[8]. constructed an objective function containing fixed construction costs and many other expenses, and used an improved genetic algorithm model to solve the objective function. Jena et al[9]. divided subsidy targets into multiple categories and studied the closed-loop supply chain network problem of implementing subsidy policies. They found that subsidies for enterprises are more beneficial to the overall situation. Wang Yong et al[10] focused on the pricing and routing problem of intelligent recycling bins, using the maximization of profits in the recycling center as a function. The results showed that while maximizing profits, it can also reduce related transportation costs. Lu Zhengnan et al[11]. investigated the decision-making problem of remanufacturing closed-loop supply chain in the context of controllable quality of recycled products.

Zhang Yuhao et al[12]. established a recycling model in three situations, and analyzed it using game theory, hoping to gain in the manufacturer led supply chain and better guide practice. Liu Xiulei et al[13].constructed an optimization model under multi-objective conditions, solved the model using triangular fuzzy numbers and scenario optimization methods, and finally provided relevant suggestions. Dondo et al[14].studied the food supply chain network and constructed a multi-objective mixed integer model with the lowest total cost. The model was analyzed by considering factors such as transportation and environmental protection, and the effectiveness of the model was demonstrated through numerical examples.

In summary, the research issues in existing literature mainly include the impact of environmental investment on supply chain design[15], supply chain design issues under different carbon quotas and carbon tax environments[16]. However, there is relatively little research on the optimization of closed-loop supply chain networks for vegetable and fruit based agricultural products. Existing literature only describes forward logistics and less considers reverse logistics; On the other hand, there is also a lack of literature that simultaneously considers the fuzzy demand and price fluctuations of agricultural products. So this article comprehensively considers the fuzzy demand, price fluctuations, and reverse logistics of vegetable and fruit based agricultural products, and establishes a relevant closed-loop supply chain network model with the goal of minimizing costs. Finally, a combination of chance constrained programming and triangular fuzzy numbers is used to solve the problem.

2. Problem Definition

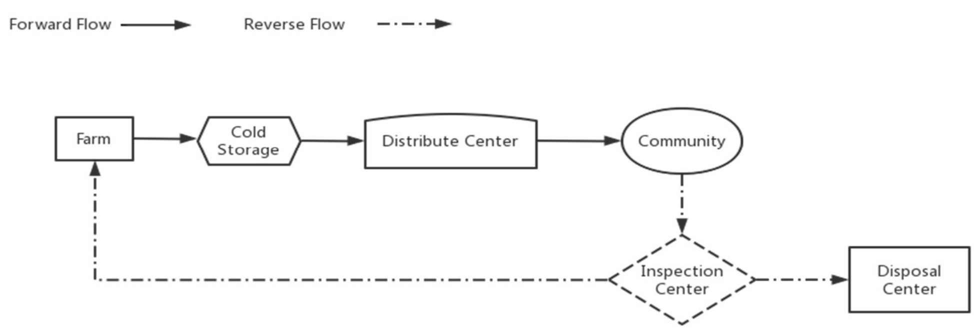

Figure 1. Proposed CLSC network of the study

In this section, for agricultural product closed-loop supply chain network design,a multi-level and multi-objective model is described. This model involves forward and reverse SCs. The forward SC includes farms, cold storage, distribution centers, communities and customers. The reverse SCs Includes inspection centers,disposal centers. In the forward logistics network: the

ISSN: 2710-0723

farms supplies the cold storage, the cold storage packages the products, transport the agricultural products to the distribution centers according to the order forms of the communities,and then the distribution centers distribute them to the communities. In the reverse logistics network: the products returned by the communities are inspected by the inspection centers and transport them to the disposal centers or farms. Finally, the recyclable products are transported to the farms to make environment-friendly enzymes which[17]can improve the soil pH and increase the soil fertility. The unrecyclable products are transported to the disposal centers.

2.1. Assumptions

(1) In reverse flow, only farm recycling and waste disposal are considered for returned products.

(2) Because the demand for agricultural products in the community fluctuates, it is reasonable to use fuzzy numbers to express it.

2.2. Notations

Sets and indices

s	Index of farms
m	Index of cold storage
t	Index of distribution centers
c	Index of communities
i	Index of inspection centers
p	Index of disposal centers
j	Index of product category

Parameters

F_s	Fixed construction cost of farm s
F_m	Fixed construction cost of cold storage m
F_t	Fixed construction cost of distribution center t
F_i	Fixed construction cost of inspection center i
F_p	Fixed construction cost of disposal center p
p_{sj}	purchasing cost of one unit of product j from farm s
p_{mj}	packing cost of one unit of product j from cold storage m
p_{tj}	storage cost of one unit of product j from distribution center t
p_{ij}	processing cost of one unit of product j from inspection center i
p_{pj}	disposal cost of one unit of product j from disposal center p
T_{smj}	unit transportation cost of product j sent from farm s to cold storage m
T_{mtj}	unit transportation cost of product j sent from cold storage m to distribution center t
T_{tcj}	unit transportation cost of product j sent from distribution center t to community c
T_{cij}	unit transportation cost of product j sent from community c to inspection center i
T_{ipj}	unit transportation cost of product j sent from inspection center i to disposal center p
T_{isj}	unit transportation cost of product j sent from inspection center i to farm s

α	utilization rate of the returned products
β	return rate of the products
Cap_{sj}	capacity of product j at farm s
Cap_{mj}	capacity of product j at cold storage m
Cap_{tj}	capacity of product j at distribution center t
Cap_{ij}	capacity of product j at inspection center i
Cap_{pj}	capacity of product j at disposal center p
$\tilde{D}_{cj}$	fuzzy demand of product j

Variables

Q_{smj}	Amount of product j sent from farm s to cold storage m
Q_{mtj}	Amount of product j sent from cold storage m to distribute center t
Q_{tcj}	Amount of product j sent from distribute center t to community c
Q_{cij}	Amount of product j sent from community c to inspection center i
Q_{ipj}	Amount of product j sent from inspection center i to disposal center p
Q_{isj}	Amount of product j sent from inspection center i to farm s
H_s	If the farm is selected, it would be 1, otherwise 0
H_m	If the cold storage is selected, it would be 1, otherwise 0
H_t	If the distribute center is selected, it would be 1, otherwise 0
H_i	If the inspection center is selected, it would be 1, otherwise 0
H_p	If the disposal center is selected, it would be 1, otherwise 0

2.3. Mathematical Programming Formulation

The objective function tries to minimize the total costs of the supply chain. such as fixed construction cost, transportation cost , purchase cost ,etc. The formula is as follow:

$$\begin{aligned}\min E[Z] = & \sum_s F_sH_s + \sum_m F_mH_m + \sum_t F_tH_t + \sum_p F_pH_p + \sum_i F_iH_i + \sum_s\sum_m\sum_j Q_{smj}T_{smj} + \sum_m\sum_t\sum_j Q_{mtj}T_{mtj} \\ & + \sum_t\sum_c\sum_j Q_{tcj}T_{tcj} + \sum_c\sum_i\sum_j Q_{cij}T_{cij} + \sum_i\sum_p\sum_j Q_{ipj}T_{ipj} + \sum_i\sum_s\sum_j Q_{isj}T_{isj} \\ & + \sum_s\sum_m\sum_j Q_{smj}E[P_{sj}] + \sum_m\sum_t\sum_j Q_{mtj}P_{mj} + \sum_t\sum_c\sum_j Q_{tcj}P_{tj} \\ & + \sum_c\sum_i\sum_j Q_{cij}P_{ij} + \sum_i\sum_p\sum_j Q_{ipj}P_{pj}\end{aligned} \tag{1}$$

The constraints comprised in the model for agricultural products are expressed as follow:

$$\sum_t Q_{tcj} \geq \tilde{D}_{cj}, \forall c, j \tag{2}$$

$$\sum_s Q_{smj} = \sum_t Q_{mtj}, \forall m, j \tag{3}$$

ISSN: 2710-0723

$$\sum_m Q_{mtj} = \sum_c Q_{tcj}, \forall t, j \tag{4}$$

$$\sum_i Q_{cij} = \beta \sum_t Q_{tcj}, \forall c, j \tag{5}$$

$$\sum_c Q_{cij} = \sum_s Q_{isj} + \sum_p Q_{ipj}, \forall i, j \tag{6}$$

$$\alpha \sum_c Q_{cij} = \sum_s Q_{isj}, \forall i, j \tag{7}$$

$$\sum_m Q_{smj} \le Cap_{sj} \bullet H_s, \quad \forall s, j \tag{8}$$

$$\sum_t Q_{mtj} \le Cap_{mj} \bullet H_m, \quad \forall m, j \tag{9}$$

$$\sum_c Q_{tcj} \le Cap_{tj} \bullet H_t, \forall t, j \tag{10}$$

$$\sum_c Q_{cij} \le Cap_{ij} \bullet H_i, \forall i, j \tag{11}$$

$$\sum_i Q_{ipj} \le Cap_{pj} \bullet H_p, \forall p, j \tag{12}$$

$$Q_{smj}, Q_{mtj}, Q_{tcj}, Q_{cij}, Q_{ipj}, Q_{isj}, \ge 0. \forall s, m, t, c, p, i, j \tag{13}$$

$$H_s, H_m, H_t, H_i, H_p \in \{0,1\}. \forall s, m, t, i, p \tag{14}$$

Formulas 2 to 7 represent the balance of goods flow in the closed-loop supply chain .Equations 8 to 12 represent the capacity constraints of each node device.Formula 13 indicates that the quantity of products in the supply chain network transportation process is nonnegative. Equation 14 represents variables.

2.4. Fuzzy Theory

Since Zadeh[18]put forward the theory of fuzzy sets, fuzzy mathematics has entered a rapid development stage. After continuous verification of reality, it is indeed an efficient and simple method. The fuzzy set expression and triangular fuzzy distribution are as follows:

$$U_\lambda = \{x \in X \mid U_{(x)} \ge \lambda\} \tag{15}$$

$$U(x) = \begin{cases} \dfrac{x - r_1}{r_2 - r_1}, x \in [r_1, r_2] \\ 0, otherwise \\ \dfrac{r_3 - x}{r_3 - r_2}, x \in [r_2, r_3] \end{cases} \tag{16}$$

It is not difficult to see that triangular fuzzy number contains three variables and increases in turn; For the most likely numerical value, this article takes r_2 as a determined value to analyze. The objective function contains fuzzy parameters, so we need to transform it, if $\xi = (r_1, r_2, r_3)$ is fuzzy value. Definition based on expected value:

$$E[\xi] = \int_0^{+\infty} Pos\{\xi \geq r\} dr - \int_{-\infty}^{0} Pos\{\xi \leq r\} dr \tag{17}$$

Then The expected value of is $E[\xi] = (r_1 + 2r_2 + r_3)/4$. Therefore, the objective function can be converted into the following equivalent explicit formula:

$$\begin{aligned} \min Z = & \sum_s F_s H_s + \sum_m F_m H_m + \sum_t F_t H_t + \sum_p F_p H_p + \sum_i F_i H_i + \sum_s \sum_m \sum_j Q_{smj} T_{smj} \\ & + \sum_m \sum_t \sum_j Q_{mtj} T_{mtj} + \sum_t \sum_c \sum_j Q_{tcj} T_{tcj} + \sum_c \sum_i \sum_j Q_{cij} T_{cij} + \sum_i \sum_p \sum_j Q_{ipj} T_{ipj} \\ & + \sum_i \sum_s \sum_j Q_{isj} T_{isj} + \sum_s \sum_m \sum_j Q_{smj} (p_{sj1} + 2 p_{sj2} + p_{sj3}) / 4 + \sum_m \sum_t \sum_j Q_{mtj} P_{mj} \\ & + \sum_t \sum_c \sum_j Q_{tcj} P_{tj} + \sum_c \sum_i \sum_j Q_{cij} P_{ij} + \sum_i \sum_p \sum_j Q_{ipj} P_{pj} \end{aligned} \tag{18}$$

There are many methods to deal with uncertainty[20,21,22].Because the demand for vegetable and fruit agricultural products fluctuates greatly and lacks accurate relevant data, we decided to adopt the method of fuzzy chance-constrained programming, and use the possibility (Pos) measure to deal with the uncertainty of demand in the model, in order to reduce the impact of fuzzy parameters on network optimization, so formula (3) can be converted into:

$$Pos\left\{\sum_t Q_{tc} \geq \tilde{D}_c\right\} \geq \lambda \tag{19}$$

Relevant theorems are introduced below.

Theorem1 If ξ is a triangular fuzzy number, and $\xi = (r_1,\ r_2,\ r_3)$, $r_1 \leq r_2 \leq r_3$ Then for any given confidence level λ, if and only if $x \geq (1-\lambda) r_1 + \lambda r_2, x \leq (1-\lambda) r_3 + \lambda r_2$, there is $Pos\{X \geq R\} \geq \lambda$.

It is certified as follows:

Sufficiency:on the basis of cut set in fuzzy set, we can get: $\frac{x - r_1}{r_2 - r_1} \geq \lambda \Rightarrow x \geq (1-\lambda) r_1 + \lambda r_2$. In the same way, we can prove $\frac{r_3 - x}{r_3 - r_2} \geq \lambda \Rightarrow x \leq (1-\lambda) r_3 + \lambda r_2$.

Necessity :if $x \geq (1-\lambda) r_1 + \lambda r_2$,we can get $\frac{x - r_1}{r_2 - r_1} \geq \lambda$,if $x \leq (1-\lambda) r_3 + \lambda r_2$,Then, $\frac{r_3 - x}{r_3 - r_2} \geq \lambda$ can be proved easily.

Accordingly, the equivalent clear formula converted from formula (2) is:

$$\sum_t Q_{tcj} \geq (1-\lambda) D_{cj1} + \lambda D_{cj2}, \forall c, j \tag{20}$$

ISSN: 2710-0723

3. Computational Results

In this section, the developed methodology of the study is validated through a case.

3.1. Case Study

This section designs a closed-loop supply chain consisting of five farms, two cold storage, four distribution centers, ten communities, one inspection centers, and two disposal centers,

The confidence level is 0.9; The fixed cost of each facility is 8000; The product return rate is 0.1; The utilization rate is 0.9,The triangular fuzzy value of demand is shown in Table 1, and the values of other relevant parameters are shown in Tables 2 to 8.

Table 1. Fuzzy demand of the community

	C=1	C=2	C=3	C=4	C=5
J=1	(1000,1100,1150)	(1300,1350,1450)	(1400,1500,1600)	(1600,1700,1800)	(1700,1800,1850)
J=2	(500 ,600 ,700)	(500,600,650)	(600,650,720)	(700,800,830)	(600,700,800)
	C=6	C=7	C=8	C=9	C=10
J=1	(1200,1300,1400)	(1500,1600,1750)	(1500,1550,1600)	(1600,1700,1710)	(1800,1900,1920)
J=2	(600,700,750)	(500,600,700)	(400,600,800)	(600,650,700,)	(750,800,900)

Table 2. Value of T_{smj} , T_{mtj} in the case

T_{smj}	S=1	S=2	S=3	S=4	S=5	T_{mtj}	T=1	T=2	T=3	T=4
M=1	J=1 1.2 J=2 1.5	J=1 1 J=2 1	J=1 2 J=2 1.2	J=1 1 J=2 1.5	J=1 1 J=2 2	M=1	J=1 2 J=2 2	J=1 1 J=2 1	J=1 2 J=2 1	J=1 2 J=2 1.5
M=2	J=1 1.5 J=2 1	J=1 1.2 J=2 1	J=1 1.5 J=2 2	J=1 2 J=2 1.5	J=1 1.2 J=2 1.5	M=2	J=1 2 J=2 3	J=1 1.5 J=2 3	J=1 1 J=2 1.5	J=1 2 J=2 1.5

Table 3. Value of T_{tcj} , T_{cij} in the case

T_{tcj}	T=1	T=2	T=3	T=4	T_{cij}	I=1
C=1	J=1 1 J=2 1.2	J=1 1 J=2 1.5	J=1 2 J=2 1.2	J=1 1 J=2 1.5	C=1	J=1 2 J=2 1.2
C=2	J=1 1.5 J=2 1	J=1 2 J=2 1	J=1 1.5 J=2 2	J=1 2 J=2 2	C=2	J=1 2 J=2 1
C=3	J=1 2 J=2 1.5	J=1 1 J=2 1.2	J=1 2 J=2 1.2	J=1 1 J=2 1.2	C=3	J=1 2 J=2 2
C=4	J=1 1.2 J=2 1.2	J=1 1.2 J=2 1.2	J=1 1 J=2 1.5	J=1 1 J=2 1.2	C=4	J=1 1.2 J=2 1.2
C=5	J=1 2 J=2 1.2	J=1 1 J=2 1.5	J=1 1 J=2 1	J=1 1 J=2 2	C=5	J=1 2 J=2 1.2
C=6	J=1 1 J=2 2	J=1 2 J=2 2	J=1 1 J=2 1	J=1 2 J=2 2	C=6	J=1 1 J=2 2
C=7	J=1 1 J=2 1.5	J=1 1 J=2 2	J=1 1 J=2 1.2	J=1 2 J=2 1.2	C=7	J=1 1 J=2 1.5
C=8	J=1 1 J=2 1.2	J=1 1.2 J=2 1.2	J=1 1 J=2 1.2	J=1 2 J=2 2	C=8	J=1 2 J=2 1.2
C=9	J=1 1 J=2 1.2	J=1 1 J=2 1.2	J=1 1.2 J=2 1.2	J=1 1 J=2 1.2	C=9	J=1 2 J=2 1.2
C=10	J=1 2 J=2 2	J=1 1 J=2 1.2	J=1 2 J=2 1.2	J=1 2 J=2 1.2	C=10	J=1 2 J=2 2

ISSN: 2710-0723

Table 4. Value of T_{isj} , T_{ipj} in the case

T_{isj}	S=1	S=2	S=3	S=4	S=5	T_{ipj}	P=1	P=2
I=1	J=1 2 J=2 1	J=1 1.2 J=2 1	J=1 1.5 J=2 1	J=1 2 J=2 1.5	J=1 1.2 J=2 1.5	I=1	J=1 1.2 J=2 1.5	J=1 1.5 J=2 1

Table 5. Value of P_{sj} , P_{mj} in the case

P_{sj}	S=1	S=2	S=3	S=4	S=5	P_{mj}	M=1	M=2
j=1	(6,7,8)	(7,8,9)	(7,8,9)	(6,7,8)	(7,8,9)	j=1	1	1
j=2	(8,9,10)	(9,10,11)	(8,9,10)	(8,9,10)	(6,7,8)	j=2	1.2	1.5

Table 6. Value of P_{tj} , P_{ij} , P_{pj} in the case

P_{tj}	T=1	T=2	T=3	T=4	P_{ij}	I=1	P_{pj}	P=1	P=2
j=1	2	2	1.5	2	j=1	2	j=1	2	2.5
j=2	3	2.5	3	2.5	j=2	2.5	j=2	3	2.5

Table 7. Value of Cap_{sj} , Cap_{mj} in the case

Cap_{sj}	S=1	S=2	S=3	S=4	S=5	Cap_{mj}	M=1	M=2
J=1	5800	6000	5500	6000	5700	J=1	8800	8400
J=2	3000	2800	2500	2500	2600	J=2	3800	4200

Table 8. Value of Cap_{tj} , Cap_{ij} , Cap_{pj} in the case

Cap_{tj}	T=1	T=2	T=3	T=4	Cap_{ij}	I=1	Cap_{pj}	P=1	P=2
J=1	6000	6200	6000	6100	J=1	8000	J=1	2000	1500
J=2	2800	3000	3000	2800	J=2	4000	J=2	1000	1500

3.2. Case Results

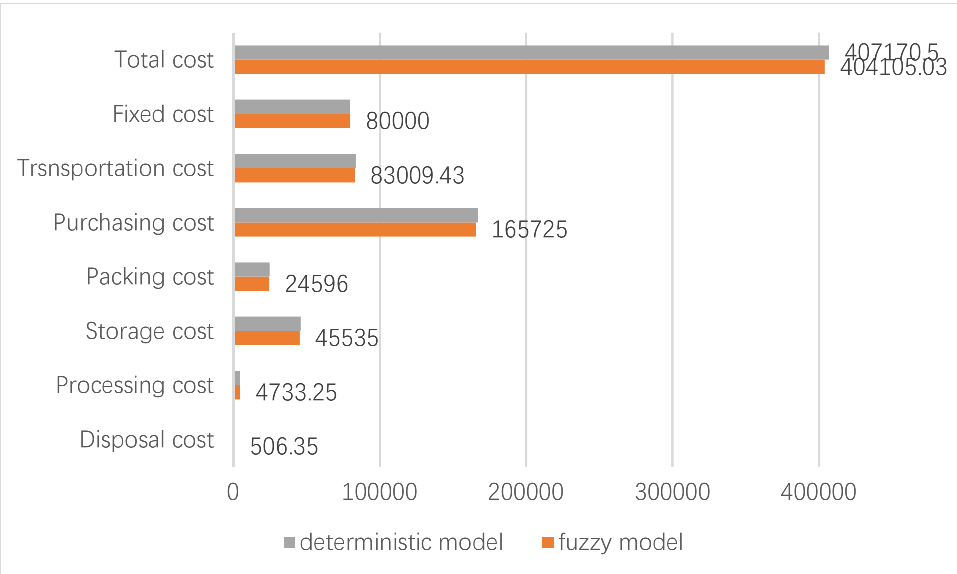

Figure 2. Cost chart of each item

ISSN: 2710-0723

To validate the model,we enter the relevant values. The result of optimization of objective is 404105.3. The corresponding sub costs were obtained and compared with the corresponding costs under the deterministic model, as shown in Figure 2. It can be concluded that, except for fixed costs, the sub item costs of the deterministic model are higher than the corresponding cost values of the fuzzy model; Among them, fixed costs, transportation costs, and purchase costs account for the most, accounting for approximately 81.3% of the total. However, waste treatment costs and recycling and testing costs do not account for a significant proportion.

3.3. Parameter Analysis

3.3.1. Sensitivity Analysis of Objective Function under Different Return Rates

The solution sets under different return rates are shown in Figure 3, and it can be seen that the trend of changes in the two models is consistent. Therefore, taking the fuzzy model as an example for analysis, it can be seen that the total cost increases with the increase of return rate. Due to the increase in recycling rate, the transportation volume of reverse logistics network has increased, thereby increasing related expenses. At the same time, the return of products to the field has also increased, and more products have been effectively utilized.

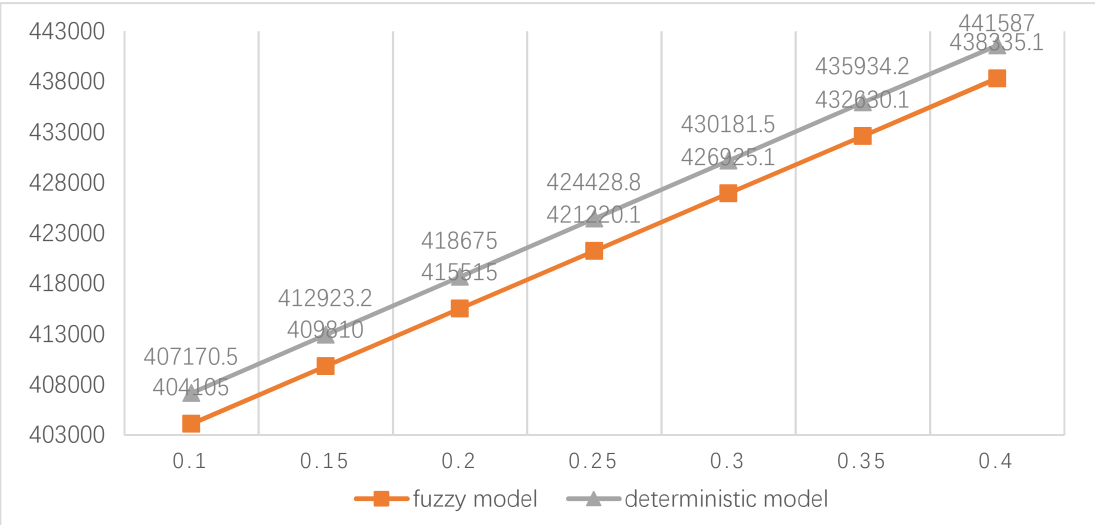

Figure 3. sensitivity analysis of return rate

3.3.2. Sensitivity Analysis of Objective Function under Utilization Rate

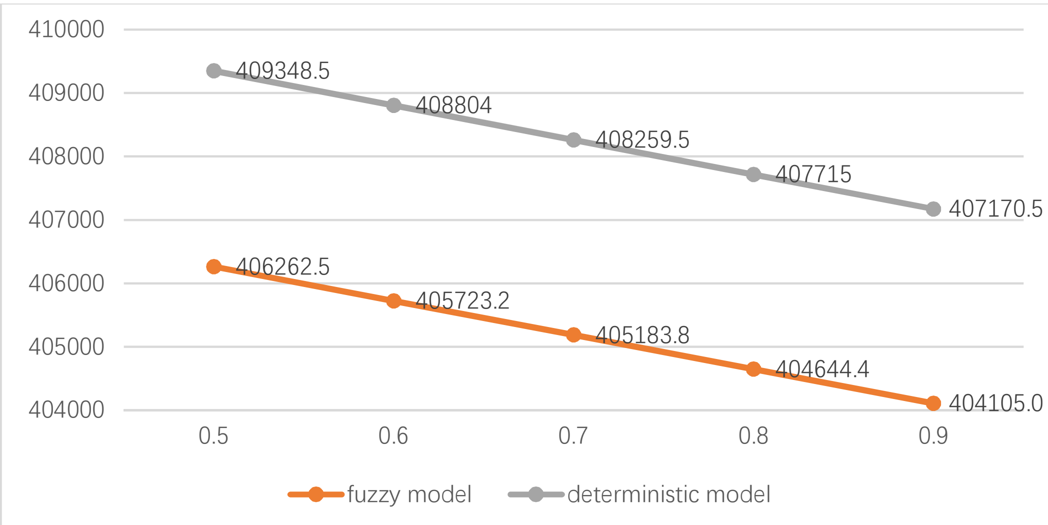

Figure 4. Sensitivity analysis of utilization rate

ISSN: 2710-0723

In Figure 4, the horizontal axis represents the land return rate, and the vertical axis represents the total cost. It can be explained that other conditions remain unchanged, and as the utilization rate of the product increases, the objective function value decreases. Overall, it can be concluded that it is due to the combined impact of transportation costs and waste treatment costs in the reverse process. In order to verify the hypothesis, the unit processing cost value of the product was lowered, and the opposite result as shown in Figure 4 was obtained, that is, there is a positive correlation between the product utilization rate and the objective function value, which will not be shown in this section. So when managers consider whether to recycle products, they should consider multiple aspects to make more reasonable decisions.

3.3.3. Sensitivity Analysis of Objective Functions under Different Demand

Figure 5 shows that as the demand increases, the overall cost shows an upward trend. At different demand nodes, the selection of facilities also varies. Taking 70% and 80% as examples, the former chooses Farm 4, 5, Distribution Center 2, 3, while the latter chooses Farm 1, 4, 5, Distribution Center 2, 3, 4. It can be seen that changes in demand have a significant impact on the optimal planning of site selection; Moreover, the cost increase in each interval is inconsistent, such as in the 70%~80% and 90%~100% intervals, where the former has a higher cost increase than the latter. This is within a certain range for managers to meet larger customer demands with a lower cost increase.

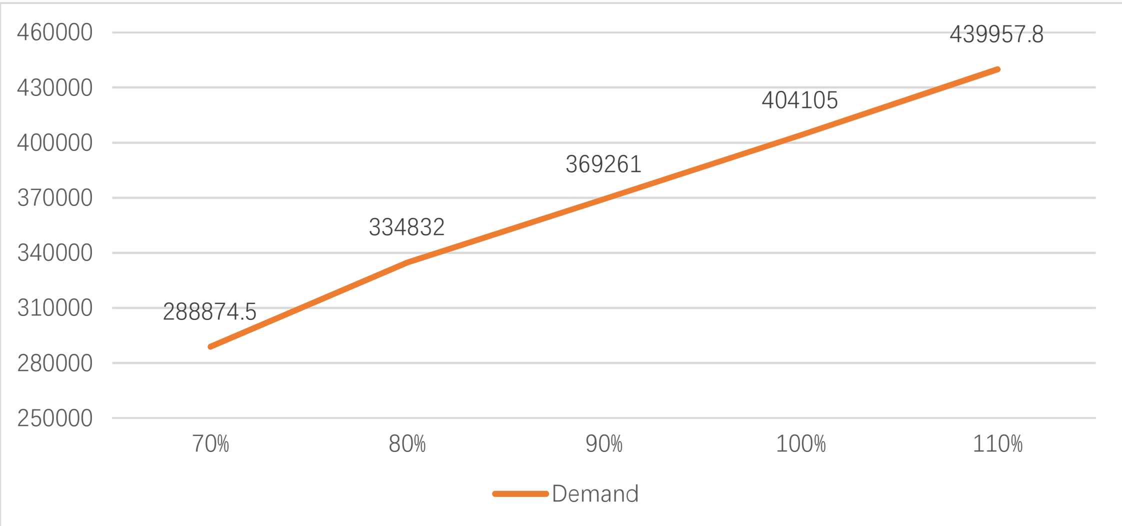

Figure 5. Sensitivity analysis of demand

4. Conclusion

In this paper, vegetable and fruit agricultural products are taken as the research object. In the case of uncertain demand and purchasing price, triangular fuzzy numbers and opportunity constraints are used to deal with the relevant variables,and the utilization rate and return rate of products are also considered, so that the closed-loop supply chain network model of vegetable and fruit agricultural products constructed is more in line with the actual situation. Specific contributions are as follows:

1) The optimal design of closed loop supply chain network of vegetables and fruits agricultural products considering fuzzy demand and purchasing price with minimum cost was realized.

2) Through the sensitivity analysis of relevant parameters, it is found that the objective function is directly related to the return rate,demand and utilization rate; The total cost is positively correlated with the return rate and demand, and negatively correlated with the utilization rate.

ISSN: 2710-0723

It is proved that the model has the ability to deal with problems and find the best solution. The next research direction will be to consider the impact of the transportation time of vegetables and fruits and the freshness of products on the closed-loop supply chain design, and improve the model on other types of products to improve its practicability and applicability.

Acknowledgments

This research was funded by the Philosophy and Social Science Foundation of Henan Province, China (grant no. 2022BJJ048).

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