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Multi-Objective Optimization of the Fruit Supply Chain: Balancing Economic, Environmental, and Social Sustainability

Ehsan Sadeghi[1], Matin Mottaghi[2], Farnaz Barzinpour*[3]
[1]*Master student of Industrial Engineering, School of Industrial Engineering, Iran University of Science and Technology*
[2]*Master student of Industrial Engineering, School of Industrial Engineering, Iran University of Science and Technology*
[3]*Associate Professor, School of Industrial Engineering, Iran University of Science and Technology*

Abstract

This study presents a multi-objective linear mathematical model optimization for the fruit supply chain that considers three dimensions of sustainability, i.e. economic, environmental, and social. A solution approach based on the lexicographic optimization approach is employed to solve the proposed model. To evaluate the model's effectiveness, the conflict between sustainability aspects is examined, and several sensitivity analysis are conducted on demand fluctuations, lost demand costs, and product price changes. Finally, our results show that the profit rate is more sensitive to demand and income; also, the amount of CO_2 is more sensitive to demand and ultimately the percentage of responsiveness, in addition to the previous two parameters, is affected by the cost of lost demand.

Keywords: Fruit supply chain optimization; Sustainability; Multi-objective decision making; Mixed-integer linear programming; Lexicographic approach

1. Introduction

In recent years, optimizing supply chains has become a critical aspect of business operations, particularly in sectors that deal with perishable goods, such as the fruit industry. The efficiency of a supply chain directly impacts profitability, environmental sustainability, and customer satisfaction [1]. In this context, multi-objective optimization of fruit supply chains presents a unique challenge, as it involves balancing competing objectives critical for operational success and long-term sustainability [2]. Profit maximization is essential for the financial health of businesses, ensuring competitive advantages in a dynamic market. Minimizing CO_2 emissions aligns with the increasing global emphasis on reducing environmental impacts, making the fruit supply chain more sustainable [3]. Meanwhile, maximizing responsiveness is vital to meet the dynamic demands of consumers, ensuring timely deliveries and customer satisfaction [4].

The importance of solving this multi-objective optimization problem lies in its potential to provide a holistic approach to supply chain management. Traditional models often prioritize single objectives, leading to suboptimal outcomes when multiple, sometimes conflicting, goals are considered [5]. Addressing these objectives simultaneously can help companies navigate the complexities of modern supply chains, ultimately contributing to a more efficient, sustainable, and responsive operation.

This article focuses on a multi-objective fruit supply chain optimization model that addresses three primary goals: maximizing profit, minimizing CO_2 emissions, and maximizing responsiveness. By integrating a lexicography algorithm, this study introduces a method to prioritize and sequentially address these objectives, offering a balanced solution that supports business profitability and environmental responsibility. Solving this problem is crucial for enhancing operational efficiency and aligning business practices with growing sustainability concerns. As stakeholders increasingly demand more eco-friendly and responsive supply chains, this research offers a pathway toward achieving these goals while maintaining competitive profitability in the global market. Considering all individuals and layers in the mathematical model, this study will be more useful and general for whom it may concern, such as stakeholders, customers, or any manager working or active in fruit industries or agrifood supply chains. Also, based on the problem, decision-makers have the authority to use different transportation modes and it will provide for them to make their

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decisions more efficient in sustainability. One of the bold changes this model will make ,is helping decision-makers to analyze the market.

By evaluating the price and the cost of shortages in providing products for customers and giving these parameters as inputs, the model will be able to choose the level of service and solve the trade-off between maximizing profit and minimizing CO_2 emissions. This study provides an analysis of the impact of these parameters on all three aspects of the fruit supply chain that has been mentioned, also as a result, provides information about the importance of these parameters. By adding these parameters model will be able to make more realistic choices while in these matters and considerations, which individuals and decision makers are not capable of it. In the evaluation of these parameters, especially the cost of lost demand, some parameters should be taken into consideration that owners of businesses are not capable of it. Subjects such as branding and marketing damage, and costs in case of shortage occurrence are not measurable at some points, while it is a sensational topic for managers and business owners. By sensitivity analysis of the mathematical model, these topics and matters will be clearer, and it can provide thresholds for evaluation and impacts of these parameters on the problem and business.

Different sections of this study are presented as follows: Section 2 provides a literature review of the concept. In the third section, the problem description is reported, followed by the problem formulation in Section 4. Section 5 introduces numerical examples and sensitivity analysis based on objectives. Finally, Section 6 includes the conclusion of the research as well as several findings and some directions for future research.

2. Literature Review

Recent studies in supply chain optimization, particularly in industries dealing with perishable goods, have focused on multi-objective models to balance competing factors such as profit, CO_2 emission reduction, and responsiveness. Table 1 provides an overview of recent literature on the sustainable fruit supply chain from a comparative perspective. Jifroudi et al. [6] and Shirzadi et al. [7] developed models that focus on maximizing profit, but neither of them considers CO_2 emissions, responsiveness, or the complexities of multi-product and multi-transportation modes. Fahmy et al. [8] and Ge et al. [9] emphasize maximizing profit and minimizing environmental impact, though Ge et al.'s model also incorporates supply chain responsiveness. In another study, Fahmy et al. [10] expanded their framework to include multi-product and multi-transportation mode considerations, yet still omit perishable goods and shortage management. Salehi-Amiri et al. [11] focus on addressing shortages while maximizing profit and sustainability, though their model does not consider perishable goods or responsiveness. Javamardan et al. [12] integrate multi-product and multi-period elements, leaving out transportation modes and perishability. Mirzaei et al. [13] offer a model focusing on perishable goods, incorporating sustainability without addressing shortages or multi-transportation modes. Reyhani Yamchi et al. [14] created a comprehensive framework that includes profit, emissions, and responsiveness but does not fully address the complexities of transportation modes or shortages. Belamkar et al. [15] combine multi-product and transportation mode considerations but still overlook shortage management.

Our study builds upon these foundations by integrating all critical elements, such as types of sustainability, multi-product, multi-period, multi-transportation modes, and shortage management, providing a comprehensive and sustainable solution for managing perishable goods supply chains in a dynamic and competitive environment.

Table 1. Relevant papers in comparison with the proposed model

Reference	Economic		Environmental	Social		Supply Chain Level	Multi-Period	Multi-Product	Multi-Transportation Mode	Shortage	Perishability	Solution Approach
	Max Profit	Min Cost	Min CO_2 Emission	Max Job Created	Max Responsiveness							
[6]	✓					5		✓				Exact
[7]	✓					3	✓		✓			-
[8]		✓				3	✓	✓			✓	Heuristic
[9]		✓				4		✓			✓	Exact
[10]		✓				3		✓				Meta-Heuristic
[11]		✓		✓		4	✓	✓				Exact
[12]		✓	✓		✓	4	✓	✓			✓	LP-metric
[13]		✓				4	✓	✓				Meta-Heuristic
[14]		✓	✓	✓		4	✓	✓				Meta-Heuristic
[15]	✓		✓			3	✓		✓		✓	Exact
Our Study	✓		✓		✓	**5**	✓	✓	✓	✓	✓	**Lexicographic Approach**

3. Problem statement

Based on Figure 1, the supply chain includes suppliers, producers, distributors, and retailers. It covers three distinct markets, each catering to different customer needs: the first-class fruit market, which is the qualified product for customers, and the second-class products, which by different causes during process or delivery our main product perished, will be sent to compost and processed fruit markets. Different types of fruits are offered in these markets, each with varying qualities and prices. In the proposed supply chain, the supplier provides the necessary farming poisons for the garden. The garden acts as the producer, sending various types of fruit with different quality grades to the distribution center. The distribution center then allocates the fruit to the markets based on their quality and price. Second-class products are sent to the composting and process centers, functioning as retailers. The composting center sends second-class products to the compost market for compost production. Additionally, process centers receive second-class products suitable for processed fruit production from the distributors and sell the processed fruit in the respective markets. The following assumptions are applied:

- Demand is considered weekly with greater demand in the last days of the week because they are near the weekend.
- The demand is considered predefined.
- Inventory maintenance occurs only in the distribution and composting centers, with zero inventory at the beginning of the first day of the week considered.
- The model includes two types of transportation modes.
- Shortages are allowed in the demand markets.

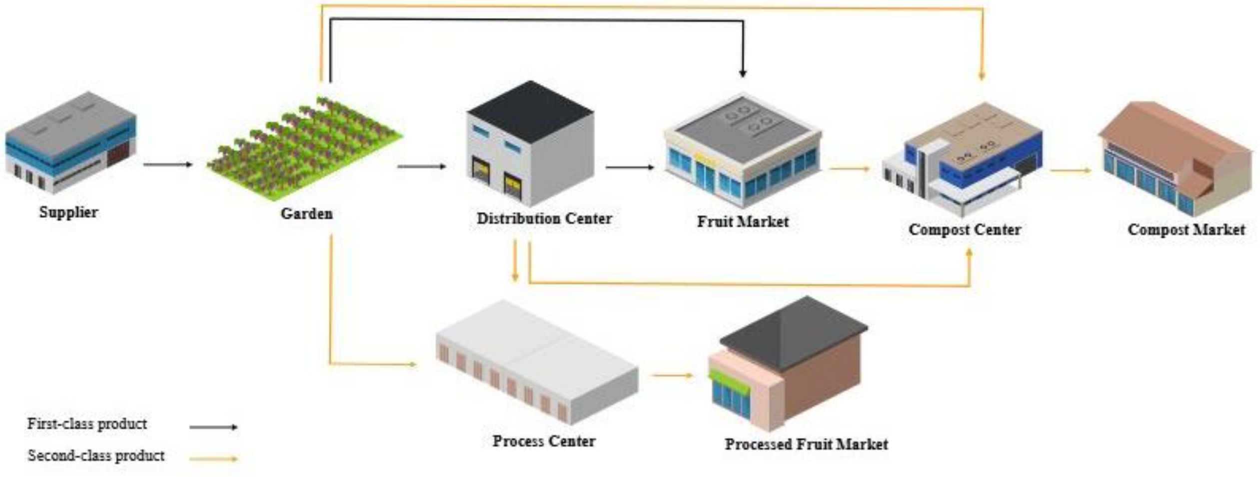


Figure 1. The structure of the proposed supply chain network

4. Mathematical Model

The optimization of the fruit supply chain requires a wide overview of the framework that integrates economic, environmental, and operational efficiency considerations. This model is designed to enhance decision-making by formulating objectives and constraints that govern production, transportation, inventory management, and waste handling. The mathematical model comprises three key objectives: maximizing profit, minimizing CO_2 emissions, and maximizing responsiveness. These objectives ensure that the supply chain remains financially viable, environmentally sustainable, and responsive to market demands. Additionally, a set of constraints is introduced to maintain balance across the supply chain, ensuring proper allocation of resources, adherence to capacity limitations, and optimization of waste management. The following sections present the objectives, constraints, and solution approach in detail.

4.1. Sets, Parameters, and Decision Variables

As it is presented, the problem and supply chain network has been formed from four echelons. We define the sets representing different entities in the fruit supply chain as:

$R:$ Set of suppliers

$I:$ Set of producers (gardens)

$J:$ Set of distribution centers

$K:$ Set of fruit markets

$L:$ Set of compost centers

$O:$ Set of compost markets

$V:$ Set of process centers

P: Set of processed fruit markets

N: Set of transportation modes

T: Set of time periods

F, F': Set of facilities in the supply chain

Based on the content, problem, and our study assumptions, we found and evaluated our fixed parameters. We define the fixed values influencing the optimization:

c_f^{Fix}: Fixed cost of working with facility $(f \in \{r, i, j, v, l\})$

c_i^{Proc}: Production cost in garden i

c_{ft}^{Proc}: Processing cost per unit in facility f at time t

c_f^{Hol}: Inventory cost per unit in facility f at time t $(f \in \{j, l\})$

e_i^{Proc}: CO_2 emissions from production in garden i at time t

e_f^{Proc}: CO_2 emissions from processing in facility f at time t

e_f^{Hol}: CO_2 emissions from inventory holding at facility f

c_n^{Tra}: Transportation cost per unit using mode

e_n^{Tra}: CO_2 emissions per unit transported by mode n

e^{Des}: Cost of destroying waste at facility

c^{Des}: Cost of destroying of product

c_r^{buy}: Cost of buying supplies from supplier r

c_f^{lost}: Cost of lost demand in facility f $(f \in \{k, o, p\})$

$sale_f$: Revenue from selling product in facility f $(f \in \{k, o, p\})$

$dis_{ff'n}$: Distance between facility f and f' by transportation mode n $(f \in \{r,i,j,v,k,l\}$, $f' \in \{i,j,v,p,k,l,o\})$

β_j: Percentage of product waste stored in distribution centers j

θ_i: Percentage of waste in garden i

Cap_f: Capacity of facility f $(f \in \{i, j, v, l\})$

d_{ft}: Demand at facility f at time t $(f \in \{k, p, o\})$

λ: Consumer product rates

γ: Returned product rate

M: A large positive number (used for constraints handling binary variables)

The mathematical model will help to make a decision on how much product should be delivered between facilities and which facilities are suggested to be worked with. The model determines the following variables based on its purpose:

y_f: Binary variable indicating if facility f is operational

Q_{ft}: Quantity of products produced by facility f at time t

$x_{ff'nt}$: Product flow from facility $f \in \{r,i,j,v,k,l\}$ to $f' \in \{i,j,v,p,k,l,o\}$ using transportation mode n at time t

IH_{ft}: Inventory level at facility f at time t

ba_{ft}: Lost demand at facility f at time t

It should be noted that the unit of measurement for distance is miles, parameters related to product volume are tons, CO_2 emissions are tons per mile, and costs and revenues are dollars.

4.2. Equations

$$
\begin{aligned}
Max\, Z^{Profit} = {} & \sum_{o=1}^{O}\sum_{t=1}^{T}(d_{ot}-ba_{ot}) *\ sale_o + \sum_{p=1}^{P}\sum_{t=1}^{T}(d_{pt}-ba_{pt}) *\ sale_p + \sum_{k=1}^{K}\sum_{t=1}^{T}(d_{kt}-ba_{kt}) \\
& *\ sale_k - (\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{n=1}^{N}\sum_{t=1}^{T}(x_{rint} * c_r^{buy}) + \sum_{o=1}^{O}\sum_{t=1}^{T}(ba_{ot} * c_o^{lost}) + \sum_{p=1}^{P}\sum_{t=1}^{T}(ba_{pt} * c_p^{lost}) \\
& + \sum_{k=1}^{K}\sum_{t=1}^{T}(ba_{kt} * c_k^{lost}) + \sum_{r=1}^{R} c_r^{Fix} y_r + \sum_{i=1}^{I} c_i^{Fix} y_i + \sum_{j=1}^{J} c_j^{Fix} y_j + \sum_{v=1}^{V} c_v^{Fix} y_v + \sum_{l=1}^{L} c_l^{Fix} y_l \\
& + \sum_{j=1}^{J}\sum_{t=1}^{T} IH_{jt} * c_j^{Hol} + \sum_{l=1}^{L}\sum_{t=1}^{T} IH_{lt} * c_l^{Hol} + \ c_2^{Tra} * (\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} x_{ri2t}\, dis_{ri2} \\
& + \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{T} x_{il2t}\, dis_{il2} + \sum_{i=1}^{I}\sum_{v=1}^{V}\sum_{t=1}^{T} x_{iv2t}\, dis_{iv2}) + \sum_{i=1}^{I}\sum_{t=1}^{T} Q_{it} * c_i^{Proc} \\
& + \sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{t=1}^{T} x_{vp1t} * c_{vt}^{Proc} + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} x_{lo1t} * c_{lt}^{Proc} + \ c^{Des} * (\sum_{i=1}^{I}\sum_{t=1}^{T} Q_{it} \\
& - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} x_{ij1t} - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{ik1t} - \sum_{i=1}^{I}\sum_{v=1}^{V}\sum_{n=1}^{N}\sum_{t=1}^{T} x_{ivnt}) \\
& + \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} (\beta_j\ * IH_{jt-1}) - x_{jl1t})
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
Min\, Z^{Emis} = {} & \sum_{i=1}^{I}\sum_{t=1}^{T} Q_{it} * e_i^{Proc} + \sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{t=1}^{T} x_{vp1t} * e_v^{Proc} + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} x_{lo1t} * e_l^{Proc} + \sum_{j=1}^{J}\sum_{t=1}^{T} IH_{jt} * e_j^{Hol} \\
& + \sum_{l=1}^{L}\sum_{t=1}^{T} IH_{lt} * e_l^{Hol} + \ e_1^{Tra} * (\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} x_{ri1t}\, dis_{ri1} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{t=1}^{T} x_{ij1t}\, dis_{ij1} \\
& + \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{T} x_{il1t}\, dis_{il1} + \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{ik1t}\, dis_{ik1} + \sum_{i=1}^{I}\sum_{v=1}^{V}\sum_{t=1}^{T} x_{iv1t}\, dis_{iv1} \\
& + \sum_{j=1}^{J}\sum_{v=1}^{V}\sum_{t=1}^{T} x_{jv1t}\, dis_{jv1} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{jk1t}\, dis_{jk1} + \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{t=1}^{T} x_{jl1t}\, dis_{jl1} \\
& + \sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{t=1}^{T} x_{kl1t}\, dis_{kl1} + \sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{t=1}^{T} x_{vp1t}\, dis_{vp1} + \sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} x_{lo1t}\, dis_{lo1}) + \ e_2^{Tra} \\
& * (\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{t=1}^{T} x_{ri2t}\, dis_{ri2} + \sum_{i=1}^{I}\sum_{l=1}^{L}\sum_{t=1}^{T} x_{il2t}\, dis_{il2} + \sum_{i=1}^{I}\sum_{v=1}^{V}\sum_{t=1}^{T} x_{iv2t}\, dis_{iv2})
\end{aligned} \tag{2}
$$

$$
\begin{aligned}
Max\, Z^{Res} = {} & \omega_1(\sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{ik1t} + \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} x_{jk1t}) / \sum_{k=1}^{K}\sum_{t=1}^{T} d_{kt} + \omega_2(\sum_{l=1}^{L}\sum_{o=1}^{O}\sum_{t=1}^{T} x_{lo1t} \,/ \sum_{o=1}^{O}\sum_{t=1}^{T} d_{ot}) \\
& + \omega_3(\sum_{v=1}^{V}\sum_{p=1}^{P}\sum_{t=1}^{T} x_{vp1t} \,/ \sum_{p=1}^{P}\sum_{t=1}^{T} d_{pt})
\end{aligned} \tag{3}
$$

The first objective (1) aims to maximize the overall profit of the fruit supply chain by considering revenues, production costs, processing costs, inventory costs, transportation costs, waste disposal costs, and transportation costs by considering the fixed costs of working and collaboration of facilities. The second objective (2) focuses on minimizing CO_2 emissions across the supply chain, which accounts for emissions from production, inventory holding, processing of products in different facilities, and transportation. This equation minimizes total carbon emissions by reducing emissions from production, storage, and transportation, thereby ensuring a more sustainable supply chain. The third objective function (3) aims to maximize responsiveness within the fruit supply chain by ensuring timely and efficient product delivery to various demand points. The equation is formulated as a weighted average of three key responsiveness factors, each representing the proportion of fulfilled demand at different supply chain stages, with the weight of ω_m. The first term measures the ratio of fruits delivered from production sites (gardens and distribution centers) to retail markets relative to total market demand. The second term captures the proportion of compost materials successfully transported from compost centers to compost markets. The third term evaluates the responsiveness of processed fruit production, representing the fraction of processed fruit delivered from processing facilities to their respective demand points. By maximizing this objective, the model prioritizes minimizing lead times, improving service levels, and ensuring that products reach end consumers as efficiently as possible.

$$Q_{rt} = \sum_{i=1}^{I}\sum_{n=1}^{N} x_{rint} \qquad \forall r, t \tag{4}$$

$$Q_{it} = \lambda * (\sum_{r=1}^{R}\sum_{n=1}^{N} x_{rint}) \qquad \forall i, t \tag{5}$$

$$(1-\theta_i) * Q_{it} = \sum_{k=1}^{K} x_{ik1t} + \sum_{j=1}^{J} x_{ij1t} \qquad \forall i, \mathrm{t} \tag{6}$$

$$\theta_i * Q_{it} = \sum_{l=1}^{L}\sum_{n=1}^{N} x_{ilnt} + \sum_{v=1}^{V}\sum_{n=1}^{N} x_{ivnt} \qquad \forall i, \mathrm{t} \tag{7}$$

$$\beta_j * IH_{jt-1} \geq \sum_{l=1}^{L} x_{jl1t} \qquad \forall j,\ t \tag{8}$$

$$\sum_{l=1}^{L} x_{kl1t} \leq \gamma * (\sum_{i=1}^{I} x_{ik1t} + \sum_{j=1}^{J} x_{jk1t}) \qquad \forall k, t \tag{9}$$

$$Q_{rt} \leq Cap_r \qquad \forall r, t \tag{10}$$

$$Q_{it} \leq Cap_i \qquad \forall i, t \tag{11}$$

$$IH_{jt-1} + \sum_{i=1}^{I} x_{ij1t} \leq Cap_j \qquad \forall j, t \tag{12}$$

$$\sum_{j=1}^{J} x_{jv1t} + \sum_{i=1}^{I}\sum_{n=1}^{N} x_{ivnt} \leq Cap_v \qquad \forall v, t \tag{13}$$

$$IH_{lt-1} + \sum_{i=1}^{I}\sum_{n=1}^{N} x_{ilnt} + \sum_{j=1}^{J} x_{jl1t} + \sum_{k=1}^{K} x_{kl1t} \leq Cap_l \qquad \forall l, t \tag{14}$$

$$IH_{jt-1} = 0 \qquad \forall j, t = 1 \tag{15}$$

$$IH_{lt-1} = 0 \qquad \forall l, t = 1 \tag{16}$$

$$IH_{jt-1} + \sum_{i=1}^{I} x_{ij1t} = IH_{jt} + \sum_{k=1}^{K} x_{jk1t} + \sum_{v=1}^{V} x_{jv1t} + \sum_{l=1}^{L} x_{jl1t} \qquad \forall j, t \tag{17}$$

$$IH_{lt-1} + \sum_{i=1}^{I}\sum_{n=1}^{N} x_{ilnt} + \sum_{j=1}^{J} x_{jl1t} + \sum_{k=1}^{K} x_{kl1t} = IH_{lt} + \sum_{o=1}^{O} x_{lo1t} \qquad \forall l, t \tag{19}$$

$$\sum_{j=1}^{J} x_{jv1t} + \sum_{i=1}^{I}\sum_{n=1}^{N} x_{ivnt} \geq \sum_{p=1}^{P} x_{vp1t} \qquad \forall v, t \tag{20}$$

$$\sum_{v=1}^{V} x_{vp1t} + ba_{pt} = d_{pt} \qquad \forall p, t \tag{21}$$

$$\sum_{i=1}^{I} x_{ik1t} + \sum_{j=1}^{J} x_{jk1t} + ba_{kt} = d_{kt} \qquad \forall k, t \tag{22}$$

$$\sum_{l=1}^{L} x_{lo1t} + ba_{ot} = d_{ot} \qquad \forall o,t \tag{23}$$

$$\sum_{i=1}^{I}\sum_{n=1}^{N} x_{rint} \leq M * y_r \qquad \forall r,t \tag{24}$$

$$\sum_{k=1}^{K} x_{ik1t} + \sum_{j=1}^{J} x_{ij1t} + \sum_{l=1}^{L}\sum_{n=1}^{N} x_{ilnt} \leq M * y_i \qquad \forall i,t \tag{25}$$

$$\sum_{i=1}^{I} x_{ij1t} \leq M * y_j \qquad \forall j,t \tag{26}$$

$$\sum_{j=1}^{J} x_{jv1t} + \sum_{i=1}^{I}\sum_{n=1}^{N} x_{ivnt} \leq M * y_v \qquad \forall v,t \tag{27}$$

$$\sum_{i=1}^{I}\sum_{n=1}^{N} x_{ilnt} + \sum_{j=1}^{J} x_{jl1t} + \sum_{k=1}^{K} x_{kl1t} \leq M * y_l \qquad \forall l,t \tag{28}$$

$$x_{rint}, x_{ik1t}, x_{ij1t}, x_{ivnt}, x_{ilnt}, x_{jk1t}, x_{jv1t}, x_{jl1t}, x_{vp1t}, x_{kl1t}, x_{lo1t}, Q_{rt}, Q_{it}, ba_{kt}, ba_{ot}, ba_{pt}, IH_{jt}, IH_{lt} \geq 0 \qquad \forall r,i,j,v,k,p,l,o,n,t \tag{29}$$

Equation (4) represents a balance equation for suppliers, guaranteeing that the total amount of their disposed materials equals the production of each supplying center. The production constraint (5) ensures that the amount of raw material transformed into final products follows a proportional relationship based on a predefined conversion factor. This constraint ensures that production output is directly dependent on the available input materials, maintaining consistency and efficiency in the supply chain process. The distribution constraint (6) ensures that the effective quantity of products available after waste loss at production facilities is equal to the total quantity distributed to other facilities and by (7) constraint guarantees that all waste is effectively managed by directing it toward composting and processed fruit production, promoting sustainability and waste reduction in the supply chain. The inventory holding constraint (8) ensures that a certain percentage of the inventory from the previous period is sufficient to meet outgoing shipments to various locations. The market supply constraint (9) ensures that the total quantity of products supplied to markets does not exceed a predefined proportion of the total incoming supply from production and distribution centers. Equations (10-14) will guarantee that facilities will not surpass their capacities, considering inventory holding at distribution centers under advisement. Equations (15-19) are balance constraints considering inventory holding management without holding stocks at the beginning of the planning horizon. Equations (20-22) are demand satisfaction constraints that will ensure that the total quantity of products supplied to the markets meets the demands and, along with it, will evaluate the back orders of periods. Equations (23-27) are facilities activation constraints that will guarantee that the flow of products will only go through facilities that are actively working.

4.3. Solution Approach

In this study, we employed a lexicographic optimization approach to solve the multi-objective fruit supply chain model. This method prioritizes the objectives based on their importance, ensuring that higher-ranked objectives are optimized first while considering lower-ranked objectives only if they do not compromise the higher-ranked ones. The ranking of the objectives is as follows: (1) maximizing profit, (2) minimizing CO_2 emissions, and (3) maximizing responsiveness. The solution process begins by optimizing the first objective, maximizing profit, to achieve the best possible financial performance for the supply chain. Once the optimal profit level is determined, it is fixed as a constraint, and the model proceeds to minimize CO_2 emissions while ensuring that the profit remains at its optimal level. Finally, once the optimal emissions level is determined, it is also fixed as a constraint, and the model focuses on maximizing responsiveness while maintaining the previously optimized levels of profit and emissions. This stepwise optimization ensures that the most critical objectives are satisfied first while allowing for further improvements in secondary objectives without compromising higher-priority goals. By applying the lexicographic approach, our study effectively balances financial viability, environmental responsibility, and supply chain efficiency, leading to a well-structured and practical decision-making framework.

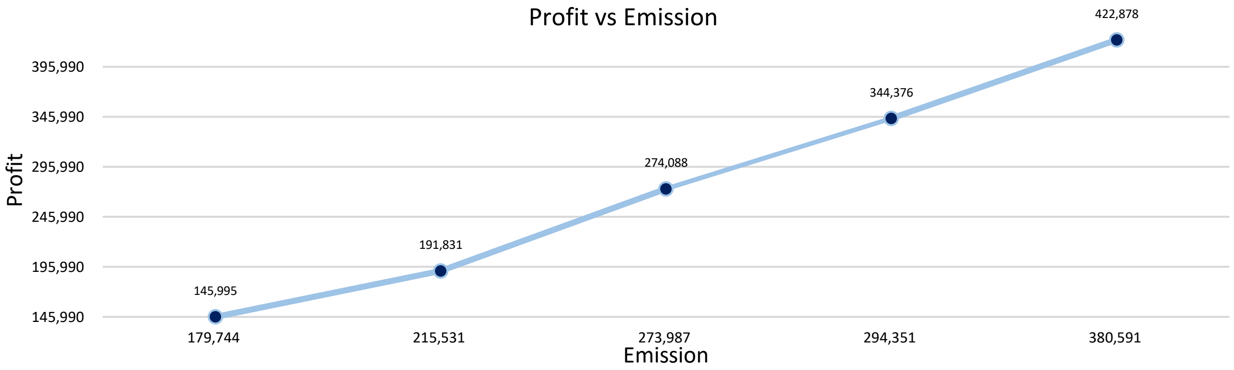
5. Computational Results and Sensitivity Analysis

To evaluate the effectiveness of our proposed model, we implement a numerical example and conduct a sensitivity analysis on key parameters. The numerical example provides insight into how the model performs under realistic conditions, while sensitivity analysis helps assess the impact of changes in critical parameters on the optimal solution. Our model involves conflicting objectives (Figure 2) that must be carefully balanced. Maximizing profit encourages higher production and sales, which may lead to increased transportation and processing emissions. On the other hand, minimizing CO_2 emissions requires controlling production and optimizing logistics, which can sometimes reduce responsiveness and profitability. Similarly, maximizing responsiveness ensures that customer demand is met efficiently, but achieving this may require additional resources, transportation, and costs, which could conflict with profit and emission objectives. The trade-offs among these objectives highlight the complexity of decision-making in the fruit supply chain.

In the sensitivity analysis, we examine the impact of variations in three key parameters: demand, cost of lost demand, and product price. Changes in customer demand can influence production levels, transportation needs, and inventory management, affecting overall profitability and emissions. The cost of lost demand determines the prioritization of fulfilling customer orders, with higher penalties potentially leading to increased inventory and transportation, impacting both emissions and costs. Fluctuations in product prices affect revenue and profitability, prompting adjustments in production and supply chain strategies. By analyzing these parameters, we gain insights into how the model adapts to market conditions and uncertainties, supporting better decision-making for supply chain stakeholders. The analysis evaluates the effects of 20% increases and decreases in each parameter from its initial value across iterations of the sample problems, with the results shown in Table 2.

Figure 2. Profit against Emission

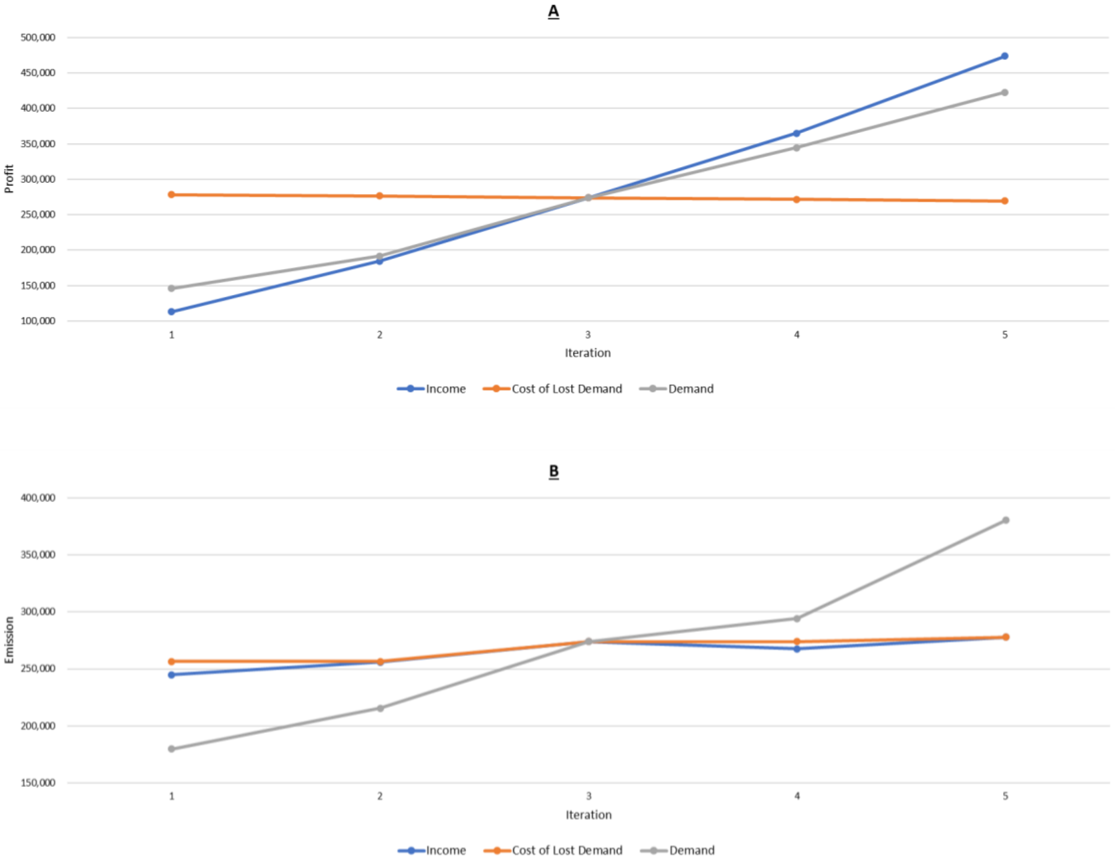
Table 2. The value of the objective functions by changing the values of important parameters



Iteration	1	2	3	4	5
Profit					
Demand	145,995	191,831	274,088	344,376	422,878
Cost of Lost Demand	278,409	276,399	274,088	271,865	269,342
Income	113,302	184,442	274,088	364,906	473,926
Emission					
Demand	179,744	215,531	273,987	294,351	380,591

Cost of Lost Demand	256,612	256,612	273,988	273,988	277,788
Income	244,939	255,972	273,987	267,740	277,788
Responsiveness					
Demand	60%	59%	59%	57%	62%
Cost of Lost Demand	55%	55%	59%	59%	59%
Income	53%	55%	59%	63%	60%

The result of our analysis and visualization of Table 2 has been shown in Figure 3. Each chart in this figure represents one of the objectives, and each line will show the value of the objective based on the fluctuation of parameters in different iterations.



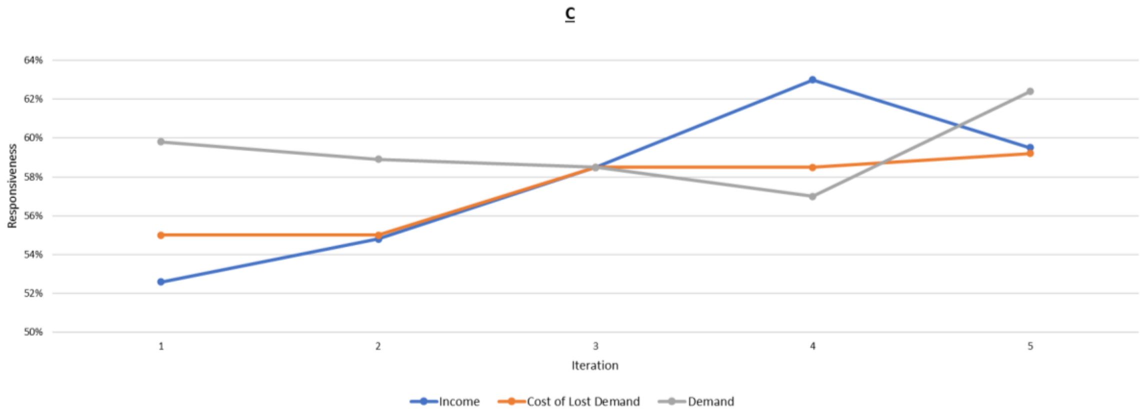


Figure 3. Sensitivity analysis of important parameters on objective functions

The three graphs represent the impact of different parameters on the three optimization objectives: profit, CO₂ emissions, and responsiveness. Each graph isolates one objective and demonstrates how it changes when varying three key parameters: demand, cost of lost demand, and the selling price of the product, which is the income from the sale of the product.

In Figure 3A we have a profit analysis in which the blue line (selling price of the product) shows a significant incline in profit as the price increases, indicating that a higher price leads to the benefits of a higher margin per unit. The gray line (demand) follows a similar upward trend, showing that increasing demand strongly increases profit. The orange line (cost of lost demand) remains relatively stable, suggesting that the cost of lost demand does not significantly impact profit within the analyzed range and does not have much impact on profit.

Also, there is CO₂ emissions analysis in Figure 3B which the gray line (demand) increases sharply, indicating that a lower demand leads to a significant reduction in emissions. The blue line (selling price of the product) shows a slight incline, suggesting that increasing the price increases emissions due to lower production. The orange line (cost of lost demand) remains stable, implying that changes in lost demand costs do not significantly influence emissions.

At the end we have responsiveness analysis in Figure 3C which the blue line (selling price of the product) initially rises, then declines, indicating that increasing price can improve responsiveness up to a certain point before negatively affecting it. The gray line (demand) follows an overall increasing trend, suggesting that higher demand can improve responsiveness. The orange line (cost of lost demand) remains relatively stable, implying a limited effect of this parameter on responsiveness.

6. Conclusion and Future Research

The sensitivity analysis highlights key trade-offs in the multi-objective optimization of the fruit supply chain. Profit is most affected by price and demand, CO₂ emissions are heavily influenced by demand, and responsiveness is impacted by both demand and price. Understanding these interactions allows decision-makers to balance objectives effectively and make informed strategic adjustments.

Further research can enhance the fruit supply chain by exploring additional factors and methodologies. The following three key areas of study are suggested. Implementing a closed-loop supply chain by utilizing compost as a raw material for fruit gardens can significantly improve sustainability. Conversely, using stochastic optimization, robust optimization, or fuzzy logic models can be a better approach considering uncertainty. These approaches can help develop more resilient and adaptive supply chains capable of responding to market fluctuations and unforeseen disruptions. Also, future studies could investigate the potential of alternative transportation modes and fuels, such as electric or hydrogen-powered vehicles, biofuels, and multimodal transportation strategies (e.g., rail and sea freight). By addressing these areas in future research, the fruit supply chain can further improve sustainability, resilience, and efficiency, contributing to a more environmentally friendly and adaptable agricultural industry.

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