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RESEARCH ARTICLE

Multi-objective Solid Green Trans-shipment Problem for Cold Chain Logistics under Fuzzy Environment

U. Johns Praveena, J. Merline Vinotha*

Abstract

In response to intense market competition and escalating environmental concern, cold chain logistics company must emphasize the customer satisfaction, preserve product quality, prevent spoilage, and minimize carbon emissions to support environmental sustainability. This paper presents a multi-objective mathematical model addressing the transshipment problem in cold chain logistics, integrating a solar refrigeration system to optimize transportation costs, spoilage rates, shipping times, and greenhouse gas emissions. To ensure realism, all parameters are analyzed within a neutrosophic fuzzy environment. Subsequently, the proposed neutrosophic fuzzy multi objective solid green transshipment model is transformed into a deterministic model utilizing a ranking function. To achieve the Pareto-optimal solution for the model, established methods such as weighted Tchebycheff metrics programming is examined. A numerical example is included to demonstrate the applicability of this model. A comparative analysis is conducted for both the transshipment problem utilizing the solar refrigeration system and the engine-driven refrigeration system. The proposed model demonstrates a decrease in total costs and carbon emissions when compared to the engine-driven refrigeration system.

Keywords: Green transshipment problem, Neutrosophic Fuzzy, Cold chain logistics, Solar refrigeration system, Solid green transshipment, Deterministic model.

Introduction

With the continuous improvement in living standards and the increasing consumer demand for fresh, high-quality perishable food products, logistics companies must prioritize maintaining the integrity, efficiency, and timeliness of product distribution through cold chain logistics which is referred to as the end-to-end process of transporting perishable items that need to be maintained at a specific temperature during their entire journey. In real world supply chains, perishable items go through intermediary stages before arriving at their destination such as distribution centre, storage warehouse and cross docking hubs. In certain situations, such as emergencies, supply disruptions or temporary shortage, source, and destination themselves can act as transshipment points. Transshipment problem was originally introduced by Orden (1956) which is the extension of transportation problem by incorporating intermediate facilities where goods can be transferred to destination. This extension provides greater flexibility and cost-effectiveness in supply chain operations, enabling more efficient routing and better management of goods in transit. In the context of cold chain logistics, transshipment problem becomes significantly more complex due to the temperature sensitive nature of perishable products which require consistent thermal regulation throughout transportation and handling. Any change from the specified temperature ranges at any point in the supply chain can result in spoilage, a reduction in product quality, or health hazards, especially concerning the transportation of food and pharmaceutical products. To address these challenges, researchers have explored various models for optimizing cold chain distribution networks to ensure product quality while minimizing operational costs. For instance, Xiong, H. (2021) applied an ant colony optimization algorithm to improve vehicle routing in cold chain logistics, aiming to reduce transportation costs while maintaining efficiency.

PG & Research Department of Mathematics, Holy Cross College (Autonomous), Affiliated to Bharathidasan University, Tiruchirappalli-620002, India.

***Corresponding Author:** J. Merline Vinotha, PG & Research Department of Mathematics, Holy Cross College (Autonomous), Affiliated to Bharathidasan University, Tiruchirappalli-620002, India, E-Mail: merlinevinotha@gmail.com

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In today's global logistics environment, various types of conveyances refrigerated trucks, freight trains, cargo ships, and air freight are used to move perishable items between regions. In addition to the conventional supply and demand constraints, conveyance constraints (such as vehicle capacity, type, and temperature control capabilities) are considered in transshipment models. When such constraints are added, the model becomes a Solid Transshipment Problem (STP), where shipments must remain intact and undivided during transit. In recent years, several researchers have analyzed this solid problem under various operational and environmental conditions, highlighting its importance in enhancing both the reliability and sustainability. Ghosh et al. (2021) explored a solid transportation problem within a fully intuitionistic fuzzy environment, which incorporated fixed charges and multiple objectives. Roy et al. (2019) tackled a solid transportation problem involving fixed costs, considering twofold uncertainty. Das et al. (2020) formulated a solid transportation problem related to the p-facility location problem using heuristic approach.

Due to the inherent complexity, and conflicting goals in in the modern world, decision-makers want to optimize multiple objectives simultaneously, such as transportation cost, time, and environmental impact, which leads to more efficient and sustainable logistics operations. Alp, S., & Ozkan, T. (2018) explored the multi-objective transshipment problem employing the goal programming. Al-Sultan, A.T. (2022) developed a multi-objective transshipment problem, considering various vehicle sizes and routes. Praveena, U. J., & Vinotha, J. M. (2015) analyzed a multi objective solid transshipment problem for perishable items with engine based freezing system (one mode of preservation technology) to increase the lifetime of such items during the time of transportation. Li, Dan, and Kang Li. (2023) developed a multi objective cold chain logistics model for minimizing carbon transaction, network cost and maximize the customer satisfaction. Ghosh, S., et.al (2022) developed a multi objective fixed charge solid transportation problem for fresh products to optimize the transportation cost, transportation time, deterioration rate, carbon emission. To improve the sustainability and efficiency of cold chain logistics, solar refrigeration systems have become an encouraging alternative, especially for the transport of perishable items. In contrast to conventional engine-driven freezing systems that depend on fossil fuels and produce greenhouse gas emissions, solar-powered refrigeration systems utilize renewable energy to sustain the necessary temperature conditions during transit. This method reduces carbon emissions and provides energy reliability, particularly in remote or off-grid locations where conventional energy sources might be unreliable.

To the best of our knowledge, multi objective solid transshipment problem for cold chain logistics with solar power refrigeration system is not yet investigated in literature. In this paper, a mathematical model for multi objective solid transshipment problem for cold chain logistics is formulated to reduce the deterioration rate of transported perishable products. Solar powered refrigeration system is incorporated in this proposed model to reduce carbon emission and increase the lifetime of such items during the time of transportation. Due to a lack of sufficient data and the presence of ambiguous situations, it is not possible to treat all the parameters of the proposed model as precise. Zadeh first introduced fuzzy set theory (FS), where the membership function ranges between 0 and 1. To address inconsistencies and intermediary information, Smarandache proposed the concept of a neutrosophic set, which encompasses truth, falsity, and indeterminacy membership functions. This paper discusses a multi-objective solid green transshipment problem incorporating a solar refrigeration system (one mode of preservation) within a trapezoidal neutrosophic fuzzy environment, where the objective functions include transportation costs, time, deterioration rates, and carbon emissions. All parameters in this model are treated as trapezoidal neutrosophic fuzzy numbers. As a result, the proposed model is converted into a deterministic form by employing a ranking function. The weighted *Tchebycheff* metrics programming method is used to identify the optimal solution to the deterministic model. A numerical example is provided to demonstrate the effectiveness of this research. The remainder of this research is classified below. In Section 2, basis definition of Neutrosophic fuzzy, Notations and Assumptions, methodology have been described. In Section 3, Numerical illustrations are performed. Finally, conclusion has been stated in Section

Methodology

Preliminaries

Definition 2.1.1 $\tilde{S}$ in a universal set E is called a single valued neutrosophic and it is defined by $\tilde{S}=\left\{\left\langle e,T_{\tilde{S}}(e),I_{\tilde{S}}(e),F_{\tilde{S}}(e)\right\rangle : e\in E\right\}$ where truth, Indeterminacy, and Falsity membership functions and satisfies the condition $0\le T_{\tilde{S}}(e)+I_{\tilde{S}}(e)+F_{\tilde{S}}(e)\le 3\forall e\in E$ (Kalaivani et al., 2023).

Definition 2.1.2 A single valued trapezoidal neutrosophic number $\tilde{S}$ (SVTrNN) on a real line set and is defined by $\tilde{S}=\left\{\left\langle s_1,s_2,s_3,s_4\right\rangle : w_{\tilde{S}},u_{\tilde{S}},v_{\tilde{S}}\right\} \text{ where } w_{\tilde{S}},u_{\tilde{S}},v_{\tilde{S}}\in[0,1]$ with the condition $s_1\le s_2\le s_3\le s_4$, whose truth, indeterminacy, falsity membership functions are follows

$$T_{\tilde{S}^F}(e)=\begin{cases} w_{\tilde{S}}\dfrac{e-s_1}{s_2-s_1} & s_1\le e\le s_2 \\ w_{\tilde{S}} & s_2\le e\le s_3 \\ w_{\tilde{S}}\dfrac{s_4-e}{s_4-s_3} & s_3\le e\le s_4 \\ 0 & \text{otherwise} \end{cases}$$

$$I_{\tilde{S}^F}(e)=\begin{cases}\frac{s_2-e+u_{\tilde{S}}(e-s_1)}{s_2-s_1} & s_1\le e\le s_2\\ u_{\tilde{S}} & s_2\le e\le s_3\\ \frac{s_3-e+u_{\tilde{S}}(s_3-e)}{s_4-s_3} & s_3\le e\le s_4\\ 1 & \text{otherwise}\end{cases}$$

$$F_{\tilde{S}^F}(e)=\begin{cases}\frac{s_2-e+v_{\tilde{S}}(e-s_1)}{s_2-s_1} & s_1\le e\le s_2\\ v_{\tilde{S}} & s_2\le e\le s_3\\ \frac{e-s_3+v_{\tilde{S}}(s_3-e)}{s_4-s_3} & s_3\le e\le s_4\\ 1 & \text{otherwise}\end{cases}$$

(Kalaivani et al., 2023)

Definition 2.1.3 Let $\tilde{S}=\{\langle s_1,s_2,s_3,s_4\rangle : w_{\tilde{S}},u_{\tilde{S}},v_{\tilde{S}}\}$ be a SVTrNN, then the score function $S(\tilde{S})$ is defined as $S(\tilde{S})=\frac{1}{12}(s_1+s_2+s_3+s_4)(2+w_{\tilde{S}}-u_{\tilde{S}}-v_{\tilde{S}})$ (Kalaivani et al., 2023).

Mathematical Model for multi objective solid green transshipment problem for cold chain logistics under fuzzy environment

This section includes a list of notations, their meanings, and the assumptions made in the proposed model. Following that, a mathematical formulation is developed for the multi-objective solid green transshipment problem using engine-based refrigeration and solar refrigeration system under Neutrosophic fuzzy environment.

Notations and Assumptions

l : sources $(l=1,2,...,m)$

h : destinations $(h=1,2,..., p)$

k : conveyance ($k=1,2,...n$)

$\tilde{t}_{lhk}$: single valued trapezoidal neutrosophic traveling time from the l^{th} source to h^{th} destination at k^{th} conveyance

$\tilde{c}_{lhk}$: single valued trapezoidal neutrosophic transportation cost from the l^{th} source to h^{th} destination at k^{th} conveyance

$\tilde{d}_{lhk}$: single valued trapezoidal neutrosophic deterioration rate from the l^{th} source to h^{th} destination at k^{th} conveyance

$\tilde{p}_{lhk}$: single valued trapezoidal neutrosophic preservation cost from the l^{th} source to h^{th} destination at k^{th} conveyance

$\tilde{D}_{lhk}$: distance from the l^{th} source to h^{th} destination at k^{th} conveyance

$\tilde{e}_{lhk}$: single valued trapezoidal neutrosophic carbon emission from the l^{th} source to h^{th} destination at k^{th} conveyance and from preservation technology (i.e.) $\tilde{e}_{lhk}=u_1\tilde{D}_{lhk}x_{lhk}+\beta u_2\tilde{t}_{lhk}x_{lhk}$

$\tilde{e}'_{lhk}$: single valued trapezoidal neutrosophic carbon emission from the l^{th} source to h^{th} destination at k^{th} conveyance and from solar refrigeration technology (i.e.) $\tilde{e}'_{lhk}=(1-s)(u_1\tilde{D}_{lhk}x_{lhk}+\beta u_2\tilde{t}_{lhk}x_{lhk})$

$\tilde{a}_l$: availability of the product at l^{th} source $(l=1,2,...,m)$

$\tilde{b}_h$: demand of the product at h^{th} destination $(h=1,2,..., p)$

x_{lhk} : quantity of products transported form the l^{th} source to h^{th} destination

η_{lhk} : the binary variable takes a value of 1 if $x_{lhk}\ge 0$ and 0 otherwise.

$\tilde{Z}_m$: objective function in neutrosophic environment where $m=1,2,3,4$

Z_m : the crisp value of an objective function $m=1,2,3,4$

β_z : freezing function to reduce the deterioration rate in %

w : solar refrigeration reduction rate for transportation cost %

s : solar refrigeration reduction rate for carbon emission %

Mathematical Formulation

Multi Objective solid green transshipment problem with engine-based refrigeration system under neutrosophic environment

The mathematical model for multi objective solid green transshipment problem with engine-based refrigeration system under neutrosophic environment has formulated as follows:

$$Min\ \tilde{Z}_1(x)=\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\tilde{c}_{lhk}x_{lhk}+\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\beta_z\tilde{t}_{lhk}\tilde{p}_{lhk}x_{lhk} \quad (1)$$

$$Min\ \tilde{Z}_2(x)=\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\tilde{t}_{lpk}\eta_{lpk} \quad (2)$$

$$Min\ \tilde{Z}_3(x)=\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\beta_z\tilde{d}_{lhk}x_{lhk} \quad (3)$$

$$Min\ \tilde{Z}_4(x)=\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\tilde{e}_{lhk}x_{lhk} \quad (4)$$

Subject to

$$\sum_{h=1,l\ne h}^{m+p}\sum_{k=1}^{n}x_{lhk}-\sum_{l=1,l\ne h}^{m+p}\sum_{k=1}^{n}x_{hlk}\le\tilde{a}_l,\quad l=1,2,3,\ldots,m \quad (5)$$

$$\sum_{l=1,l\ne h}^{m+p}\sum_{k=1}^{n}(1-\beta_z\tilde{d}_{lhk})x_{lhk}-\sum_{l=1,l\ne h}^{m+p}\sum_{k=1}^{n}(1-\beta_z\tilde{d}_{lhk})x_{hlk}\ge\tilde{b}_h,\quad h=m+1,m+2,\ldots,m+p \quad (6)$$

$$\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}x_{lhk}\le\tilde{i}_k, k=1,2,3,...n \quad (7)$$

$$\eta_{lhk}=\begin{cases}0 & if\ \ x_{lhk}=0\\ 1 & if\ \ x_{lhk}>0\end{cases} \quad (8)$$

$$x_{lhk},\eta_{lhk}\ge 0, l,h=1,2,3,\ldots,m+p, k=1,2,...,n \quad (9)$$

Multi Objective solid green transshipment problem for cold chain logistics with solar power refrigeration system under neutrosophic environment

The mathematical model for multi objective solid green transshipment problem for cold chain logistics with solar based refrigeration system under neutrosophic environment has been formulated as follows:

$$Min\ \tilde{Z}_1(x) = (1-w)\left(\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\tilde{c}_{lhk}x_{lhk} + \sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\beta_z\tilde{t}_{lhk}\tilde{p}_{lhk}x_{lhk}\right) \quad (10)$$

$$Min\ \tilde{Z}_2(x) = \sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\tilde{t}_{lpk}\eta_{lpk} \quad (11)$$

$$Min\ \tilde{Z}_3(x) = \sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\beta_z\tilde{d}_{lhk}x_{lhk} \quad (12)$$

$$Min\ \tilde{Z}_4(x) = (1-s)\sum_{h=1}^{m+p}\sum_{k=1}^{n}\tilde{e}'_{lhk}x_{lhk} \quad (13)$$

Subject to

$$\sum_{p=1,l\neq p}^{g+h}\sum_{k=1}^{K}x_{lpk} - \sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}x_{plk} \le \tilde{a}_l, \quad l=1,2,3,\dots,g \quad (14)$$

$$\sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}(1-\tilde{d}_{lpk})x_{lpk} - \sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}(1-\tilde{d}_{lpk})x_{plk} \ge \tilde{b}_p, \quad p=g+1,g+2,\dots,g+h \quad (15)$$

$$\sum_{l=1}^{g+h}\sum_{p=1}^{g+h}x_{lpk} \le \tilde{e}_k, k=1,2,3,...K \quad (16)$$

$$\eta_{lpk} = \begin{cases} 0 & if \quad x_{lpk}=0 \\ 1 & if \quad x_{lpk}>0 \end{cases} \quad (17)$$

$$x_{lpk},\eta_{lpk} \ge 0, l,p=1,2,3,\dots,g+h, k=1,2,...,K \quad (18)$$

In model engine-based system, the first objective function (1) signifies the total costs associated with transportation and preservation cost for transporting items from l^{th} source to h^{th} destination via k^{th} conveyance. The preservation cost is influenced by the engine-based preservation function, the duration of preservation, and the amount of items being transported. The second objective (2) defines the transportation time for transporting perishable items from l^{th} source to p^{th} destination at k^{th} conveyance. The third objective function (3) represents the deterioration rate of perishable items after applying engine-based preservation technology. The fourth objective function (4) defines the carbon emission rate of perishable items by using engine-based refrigeration system. The constraints (5),(6),(7),(8),(9) include the demand condition after applying engine-based preservation technology, total supply, conveyance capacity, and the non-negativity restriction of the variables.

In model solar power-based system, the first objective function (10) represents the total costs associated with transportation and preservation cost for transporting items from l^{th} source to h^{th} destination through k^{th} conveyance. The preservation cost is influenced by the solar power-based preservation function, the duration of preservation, and the amount of items being transported. The second objective (11) defines the transportation time for transporting perishable items from l^{th} source to p^{th} destination at k^{th} conveyance. The third objective function (12) represents the deterioration rate of perishable items after applying solar power-based preservation technology. The fourth objective function (13) defines the carbon emission rate of perishable items by using solar power-based refrigeration system. The constraints (14), (15), (16), (17), (18) include the demand condition after applying solar power-based preservation technology, total supply, conveyance capacity, and the non-negativity restriction of the variables.

Identical Deterministic Model

In the mathematical model, all the parameters are considered as trapezoidal neutrosophic fuzzy numbers due to handle uncertainty situations. The proposed model cannot be evaluated directly. Therefore, converting the model into deterministic model by using ranking function as follows:

Deterministic Model for Multi Objective solid green transshipment problem with engine-based refrigeration system under neutrosophic environment

$$Min\ \tilde{Z}_1(x) = \sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\Re(\tilde{c}_{lpk})x_{lpk} + \sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\beta_z\Re(\tilde{t}_{lpk})\Re(\tilde{p}_{lpk})x_{lpk} \quad (19)$$

$$Min\ \tilde{Z}_2(x) = \sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\Re(\tilde{t}_{lpk})\eta_{lpk} \quad (20)$$

$$Min\ \tilde{Z}_3(x) = \sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\beta_z\Re(\tilde{d}_{lpk})x_{lpk} \quad (21)$$

$$Min\ \tilde{Z}_4(x) = \sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\Re(\tilde{e}_{lhk})x_{lhk} \quad (22)$$

Subject to

$$\sum_{p=1,l\neq p}^{g+h}\sum_{k=1}^{K}x_{lpk} - \sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}x_{plk} \le \Re(\tilde{a}_l), \quad l=1,2,3,\dots,g \quad (23)$$

$$\sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}(1-\beta_z\Re(\tilde{d}_{lpk}))x_{lpk} - \sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}(1-\beta_z\Re(\tilde{d}_{lpk}))x_{plk} \ge \Re(\tilde{b}_p),$$
$$p=g+1,g+2,\dots,g+h \quad (24)$$

$$\sum_{l=1}^{g+h}\sum_{p=1}^{g+h}x_{lpk} \le \Re(\tilde{e}_k), k=1,2,3,...K \quad (25)$$

$$\eta_{lpk} = \begin{cases} 0 & if \quad x_{lpk}=0 \\ 1 & if \quad x_{lpk}>0 \end{cases} \quad (26)$$

$$x_{lpk},\eta_{lpk} \ge 0, l,p=1,2,3,\dots,g+h, k=1,2,...,K \quad (27)$$

Multi Objective solid green transshipment problem for cold chain logistics with solar power refrigeration system under neutrosophic environment

$$Min\ \tilde{Z}_1(x) = (1-w)\sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\Re(\tilde{c}_{lpk})x_{lpk} + \sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\beta_z\Re(\tilde{t}_{lpk})\Re(\tilde{p}_{lpk})x_{lpk} \tag{28}$$

$$Min\ \tilde{Z}_2(x) = \sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\Re(\tilde{t}_{lpk})\eta_{lpk} \tag{29}$$

$$Min\ \tilde{Z}_3(x) = \sum_{l=1}^{g+h}\sum_{p=1}^{g+h}\sum_{k=1}^{K}\beta_z\Re(\tilde{d}_{lpk})x_{lpk} \tag{30}$$

$$Min\ \tilde{Z}_4(x) = (1-s)\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}\sum_{k=1}^{n}\Re(\tilde{e}'_{lhk})x_{lhk} \tag{31}$$

Subject to

$$\sum_{p=1,l\neq p}^{g+h}\sum_{k=1}^{K}x_{lpk} - \sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}x_{plk} \leq \Re(\tilde{a}_l), \quad l = 1,2,3,\ldots,g \tag{32}$$

$$\sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}(1-\beta_z\Re(\tilde{d}_{lpk}))x_{lpk} - \sum_{l=1,l\neq p}^{g+h}\sum_{k=1}^{K}(1-\beta_z\Re(\tilde{d}_{lpk}))x_{plk} \geq \Re(\tilde{b}_p),$$
$$p = g+1, g+2,\ldots,g+h \tag{33}$$

$$\sum_{l=1}^{g+h}\sum_{p=1}^{g+h}x_{lpk} \leq \Re(\tilde{e}_k), k = 1,2,3,\ldots K \tag{34}$$

$$\eta_{lpk} = \begin{cases} 0 & if \ \ x_{lpk} = 0 \\ 1 & if \ \ x_{lpk} > 0 \end{cases} \tag{35}$$

$$x_{lpk}, \eta_{lpk} \geq 0, l, p = 1,2,3,\ldots,g+h, k = 1,2,\ldots,K \tag{36}$$

Solution Procedure

The weighted tchebycheff metrics programming is used in this paper to obtain the optimum solution for the deterministic model discussed above as follows.

Weighted Tchebycheff Metrics Programming

This optimization technique utilizes weighted distance metrics to determine a compromise solution for multi-objective linear programming problems. The fundamental concept of this method is to identify the feasible solution that is closest to an ideal solution. The distance between ideal and feasible points is assessed by utilizing a metric, which is the most used metric defined as $D_x = \left[\sum_{K=1}^{3}\left(\frac{z_k(Z_k - Z_k^{\min})}{Z_k^{\max} - Z_k^{\min}}\right)\right]^{\frac{1}{x}}, 1 \leq x < \infty.$ If $x \to \infty$ then D_x denotes as Tchebycheff metric. When $x = 1$, the Manhattan metric is achieved; when $x = 2$, the Euclidean metric is established; and as x approaches infinity, the Tchebychef metric is reached. To find a Pareto-optimal solution, the weighted ∞-norm (D_x)can be utilized as the distance metric. This method is commonly known as weighted Tchebychef metric programming. The mathematical model of weighted Tchebychef metrics for obtaining the Pareto-optimal solution to the deterministic multi objective solid green transshipment problem with engine-based system and solar power-based refrigeration system for preservation technology is described as below

P1: with engine-based refrigeration

Minimize ϕ

Subject to Constraints

$$\phi \geq \frac{z_k(Z_k - Z_k^{\min})}{Z_k^{\max} - Z_k^{\min}} \forall k = 1,2,\ldots,K$$

$$\sum_{k=1}^{K} z_k = 1, z_k \geq 0 \forall k$$

$$\sum_{h=1,l\neq h}^{m+p}\sum_{k=1}^{n}x_{lhk} - \sum_{l=1,l\neq h}^{m+p}\sum_{k=1}^{n}x_{hlk} \leq \Re(\tilde{a}_l), \quad l = 1,2,3,\ldots,m$$

$$\sum_{l=1,l\neq h}^{m+p}\sum_{k=1}^{n}(1-\beta_z\tilde{d}_{lhk})x_{lhk} - \sum_{l=1,l\neq h}^{m+p}\sum_{k=1}^{n}(1-\beta_z\Re(\tilde{d}_{lhk})x_{hlk} \geq \Re(\tilde{b}_h), \quad h = m+1, m+2,\ldots,m+p$$

$$\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}x_{lhk} \leq \Re(\tilde{i}_k), k = 1,2,3,\ldots n$$

$$\eta_{lhk} = \begin{cases} 0 & if \ \ x_{lhk} = 0 \\ 1 & if \ \ x_{lhk} > 0 \end{cases}$$

$$x_{lhk}, \eta_{lhk} \geq 0, l, h = 1,2,3,\ldots,m+p, k = 1,2,\ldots,n$$

$$\phi \geq 0$$

P2: solar power-based refrigeration

Minimize ϕ

Subject to Constraints

$$\phi \geq \frac{z_k(Z_k - Z_k^{\min})}{Z_k^{\max} - Z_k^{\min}} \forall k = 1,2,\ldots,K$$

$$\sum_{k=1}^{K} z_k = 1, z_k \geq 0 \forall k$$

$$\sum_{h=1,l\neq h}^{m+p}\sum_{k=1}^{n}x_{lhk} - \sum_{l=1,l\neq h}^{m+p}\sum_{k=1}^{n}x_{hlk} \leq \Re(\tilde{a}_l), \quad l = 1,2,3,\ldots,m$$

$$\sum_{l=1,l\neq h}^{m+p}\sum_{k=1}^{n}(1-\beta_z\tilde{d}_{lhk})x_{lhk} - \sum_{l=1,l\neq h}^{m+p}\sum_{k=1}^{n}(1-\beta_z\Re(\tilde{d}_{lhk})x_{hlk} \geq \Re(\tilde{b}_h), \quad h = m+1, m+2,\ldots,m+p$$

$$\sum_{l=1}^{m+p}\sum_{h=1}^{m+p}x_{lhk} \leq \Re(\tilde{i}_k), k = 1,2,3,\ldots n$$

$$\eta_{lhk} = \begin{cases} 0 & if \ \ x_{lhk} = 0 \\ 1 & if \ \ x_{lhk} > 0 \end{cases}$$

$$x_{lhk}, \eta_{lhk} \geq 0, l, h = 1,2,3,\ldots,m+p, k = 1,2,\ldots,n$$

$$\phi \geq 0$$

Finally, the optimal solution of proposed model is obtained using the LINGO Software (20.0).

Result

Numerical example

Consider the numerical example given in which the reputed logistics company transports the various types of fishes from two sources situated at West Bengal and Odisha in India to two different demand points located at Punjab and Himachal Pradesh in India. To maintain the quality and safety of perishable goods during long-distance transport, the company implements a solar-powered refrigeration system instead of engine-based refrigeration system as a key component of its eco-friendly cold chain logistics strategy. This system keeps temperatures within the necessary range during transit while significantly reducing reliance on conventional energy sources. During emergencies and supply chain disruptions, transshipment model plays crucial role. hence the given transportation problem is formulated as a transshipment problem to analyze the reduction of the optimal transportation costs, preservation costs, transportation time, the deterioration rate and carbon emission throughout the entire cold chain logistics transshipment process. Transportation cost, preservation cost (determined by factors such as transportation time, the quantity of items and the preservation method) are measured in dollar per ton. deterioration rate is described as percentage, and the time represented in hour. Carbon emission is calculated in kilogram. In existing literature, parameters such as source capacities, demand quantities, modes of conveyance, transportation costs, preservation costs, transportation time, deterioration rates, and carbon emissions are modelled using Pythagorean fuzzy numbers to address the uncertainty and vagueness. To handle the inconsistent and intermediate information, source, demand, conveyance, transportation cost, preservation cost, transportation time, deterioration rate, and distance are defined as TrNsNN in this proposed transshipment model and they are presented in [Table 1.], [Table 2.], [Table 3.], [Table 4.], [Table 5.]. The decision-maker aims to transport quantities of items from source to destination at conveyance to satisfy the total requirement. All fuzzy parameters are converted into crisp values using a ranking operator, after which two mathematical models are formulated to optimize the cold chain logistics process, considering the environmental benefits of solar refrigeration models are formulated.

Table 1: Transportation cost $\tilde{c}_{lpk}\,(l=1,2,3,4\;;p=1,2,3,4;k=1,2)$ in dollar

$\tilde{c}_{121}$	$\langle(4.5,6.5,7.5,8.5);0.5,0.3,0.2\rangle$	$\tilde{c}_{122}$	$\langle(3.75,4.75,6.25,7.75);0.6,0.4,0.2\rangle$
$\tilde{c}_{131}$	$\langle(4.75,6.75,7.25,9.75);0.5,0.3,0.2\rangle$	$\tilde{c}_{132}$	$\langle(15.4,20.8,25.8,30.4);0.6,0.4,0.2\rangle$
$\tilde{c}_{141}$	$\langle(13.9,18.7,22.7,27.9);0.5,0.4,0.1\rangle$	$\tilde{c}_{142}$	$\langle(10.4,14.2,16.4,21.4);0.6,0.3,0.3\rangle$
$\tilde{c}_{211}$	$\langle(4.5,6.5,7.5,8.5);0.5,0.3,0.2\rangle$	$\tilde{c}_{212}$	$\langle(3.75,4.75,6.25,7.75);0.6,0.4,0.2\rangle$
$\tilde{c}_{231}$	$\langle(11,13,18,24);0.5,0.3,0.2\rangle$	$\tilde{c}_{232}$	$\langle(12.8,15.8,21.4,26.8);0.7,0.4,0.3\rangle$
$\tilde{c}_{241}$	$\langle(20.6,27.8,34.6,40.6);0.4,0.2,0.2\rangle$	$\tilde{c}_{242}$	$\langle(17.75,25,29,34.75);0.6,0.4,0.2\rangle$
$\tilde{c}_{311}$	$\langle(4.75,6.75,7.25,9.75);0.5,0.3,0.2\rangle$	$\tilde{c}_{312}$	$\langle(15.4,20.8,25.8,30.4);0.6,0.4,0.2\rangle$
$\tilde{c}_{321}$	$\langle(11,13,18,24);0.5,0.3,0.2\rangle$	$\tilde{c}_{322}$	$\langle(12.8,15.8,21.4,26.8);0.7,0.4,0.3\rangle$
$\tilde{c}_{341}$	$\langle(0.6,0.8,1,1.2);0.6,0.4,0.2\rangle$	$\tilde{c}_{342}$	$\langle(0.5,0.65,0.85,1);0.5,0.3,0.2\rangle$
$\tilde{c}_{411}$	$\langle(13.9,18.7,22.7,27.9);0.5,0.4,0.1\rangle$	$\tilde{c}_{412}$	$\langle(10.4,14.2,16.4,21.4);0.6,0.3,0.3\rangle$
$\tilde{c}_{421}$	$\langle(20.6,27.8,34.6,40.6);0.4,0.2,0.2\rangle$	$\tilde{c}_{422}$	$\langle(17.75,25,29,34.75);0.6,0.4,0.2\rangle$
$\tilde{c}_{431}$	$\langle(0.6,0.8,1,1.2);0.6,0.4,0.2\rangle$	$\tilde{c}_{432}$	$\langle(0.5,0.65,0.85,1);0.5,0.3,0.2\rangle$

Table 2: Preservation cost $\tilde{p}_{lpk}(l=1,2,3,4\ ;\ p=1,2,3,4; k=1,2)$ in dollar

$\tilde{p}_{121}$	$\langle(8.5,11.5,14.5,16.5);0.4,0.3,0.1\rangle$	$\tilde{p}_{122}$	$\langle(11.5,15.5,18.5,23.5);0.5,0.3,0.2\rangle$
$\tilde{p}_{131}$	$\langle(6.5,8.5,10.5,13.5);0.6,0.3,0.3\rangle$	$\tilde{p}_{132}$	$\langle(5.75,7.75,9.75,11.25);0.5,0.4,0.1\rangle$
$\tilde{p}_{141}$	$\langle(10.5,13.5,16.5,22.5);0.7,0.5,0.2\rangle$	$\tilde{p}_{142}$	$\langle(7.25,9,12,15.25);0.8,0.5,0.3\rangle$
$\tilde{p}_{211}$	$\langle(8.5,11.5,14.5,16.5);0.4,0.3,0.1\rangle$	$\tilde{p}_{212}$	$\langle(11.5,15.5,18.5,23.5);0.5,0.3,0.2\rangle$
$\tilde{p}_{231}$	$\langle(12.8,16.8,20.8,26.4);0.5,0.3,0.2\rangle$	$\tilde{p}_{232}$	$\langle(14.5,18.5,24.5,29.5);0.7,0.5,0.2\rangle$
$\tilde{p}_{241}$	$\langle(10,13,17,20);0.4,0.3,0.1\rangle$	$\tilde{p}_{242}$	$\langle(7.25,9,12,15.25);0.8,0.5,0.3\rangle$
$\tilde{p}_{311}$	$\langle(6.5,8.5,10.5,13.5);0.6,0.3,0.3\rangle$	$\tilde{p}_{312}$	$\langle(5.75,7.75,9.75,11.25);0.5,0.4,0.1\rangle$
$\tilde{p}_{321}$	$\langle(12.8,16.8,20.8,26.4);0.5,0.3,0.2\rangle$	$\tilde{p}_{322}$	$\langle(14.5,18.5,24.5,29.5);0.7,0.5,0.2\rangle$
$\tilde{p}_{341}$	$\langle(1,1,2,2);0.4,0.2,0.2\rangle$	$\tilde{p}_{342}$	$\langle(1,2,3,6);0.6,0.4,0.2\rangle$
$\tilde{p}_{411}$	$\langle(10.5,13.5,16.5,22.5);0.7,0.5,0.2\rangle$	$\tilde{p}_{412}$	$\langle(7.25,9,12,15.25);0.8,0.5,0.3\rangle$
$\tilde{p}_{421}$	$\langle(10,13,17,20);0.4,0.3,0.1\rangle$	$\tilde{p}_{422}$	$\langle(4,12,22,24);0.4,0.3,0.1\rangle$
$\tilde{p}_{431}$	$\langle(1,1,2,2);0.4,0.2,0.2\rangle$	$\tilde{p}_{432}$	$\langle(1,2,3,6);0.6,0.4,0.2\rangle$

Table 3: Deterioration rate $\tilde{d}_{lpk}(l=1,2,3,4\ ;\ p=1,2,3,4; k=1,2)$ in %

$\tilde{d}_{121}$	$\langle(1.75,2,2.75,3.5);0.6,0.4,0.2\rangle$	$\tilde{d}_{122}$	$\langle(1.63,2,2.6,3.55);0.4,0.2,0.2\rangle$
$\tilde{d}_{131}$	$\langle(7.5,9.5,12.5,15.5);0.7,0.4,0.3\rangle$	$\tilde{d}_{132}$	$\langle(6.5,8.5,10.5,13.5);0.5,0.3,0.2\rangle$
$\tilde{d}_{141}$	$\langle(8.5,10.5,14.5,17.5);0.8,0.5,0.3\rangle$	$\tilde{d}_{142}$	$\langle(3.5,4.5,5.5,7.5);0.5,0.3,0.2\rangle$
$\tilde{d}_{211}$	$\langle(1.75,2,2.75,3.5);0.6,0.4,0.2\rangle$	$\tilde{d}_{212}$	$\langle(1.63,2,2.6,3.55);0.4,0.2,0.2\rangle$
$\tilde{d}_{231}$	$\langle(3.5,4.5,5.5,7.5);0.5,0.3,0.2\rangle$	$\tilde{d}_{232}$	$\langle(3.75,4.75,6.25,7.75);0.6,0.4,0.2\rangle$
$\tilde{d}_{241}$	$\langle(7.75,9.25,11.25,15.25);0.8,0.5,0.3\rangle$	$\tilde{d}_{242}$	$\langle(10,13,17,20);0.4,0.3,0.1\rangle$
$\tilde{d}_{311}$	$\langle(7.5,9.5,12.5,15.5);0.7,0.4,0.3\rangle$	$\tilde{d}_{312}$	$\langle(6.5,8.5,10.5,13.5);0.5,0.3,0.2\rangle$
$\tilde{d}_{321}$	$\langle(3.5,4.5,5.5,7.5);0.5,0.3,0.2\rangle$	$\tilde{d}_{322}$	$\langle(3.75,4.75,6.25,7.75);0.6,0.4,0.2\rangle$
$\tilde{d}_{341}$	$\langle(0.4,0.5,0.6,0.9);0.5,0.3,0.2\rangle$	$\tilde{d}_{342}$	$\langle(1,1,2,2);0.4,0.2,0.2\rangle$
$\tilde{d}_{411}$	$\langle(8.5,10.5,14.5,17.5);0.8,0.5,0.3\rangle$	$\tilde{d}_{412}$	$\langle(3.5,4.5,5.5,7.5);0.5,0.3,0.2\rangle$
$\tilde{d}_{421}$	$\langle(7.75,9.25,11.25,15.25);0.8,0.5,0.3\rangle$	$\tilde{d}_{422}$	$\langle(10,13,17,20);0.4,0.3,0.1\rangle$
$\tilde{d}_{431}$	$\langle(0.4,0.5,0.6,0.9);0.5,0.3,0.2\rangle$	$\tilde{d}_{431}$	$\langle(1,1,2,2);0.4,0.2,0.2\rangle$

Table 4: Transportation time $\tilde{t}_{lj}(l=1,2,3,4 \text{ and } p=1,2,3,4)$ in Hours

$\tilde{t}_{121}$	$\langle(6.9,8.9,11.7,13.9);0.5,0.3,0.2\rangle$	$\tilde{t}_{122}$	$\langle(5.7,7.7,9.7,11.1);0.5,0.3,0.2\rangle$
$\tilde{t}_{131}$	$\langle(25.25,35.25,40.25,50.75);0.6,0.4,0.2\rangle$	$\tilde{t}_{132}$	$\langle(23,30,37,48);0.6,0.3,0.3\rangle$
$\tilde{t}_{141}$	$\langle(26.5,34.5,42.5,55.5);0.7,0.4,0.2\rangle$	$\tilde{t}_{142}$	$\langle(10,13,17,20);0.4,0.3,0.1\rangle$
$\tilde{t}_{211}$	$\langle(6.9,8.9,11.7,13.9);0.5,0.3,0.2\rangle$	$\tilde{t}_{212}$	$\langle(5.7,7.7,9.7,11.1);0.5,0.3,0.2\rangle$
$\tilde{t}_{231}$	$\langle(12.6,16.8,20.6,25.6);0.5,0.2,0.3\rangle$	$\tilde{t}_{232}$	$\langle(15.8,20.8,25.8,32.8);0.7,0.4,0.3\rangle$
$\tilde{t}_{241}$	$\langle(24,32,40,48);0.5,0.4,0.1\rangle$	$\tilde{t}_{242}$	$\langle(25,30,37,45);0.6,0.4,0.2\rangle$
$\tilde{t}_{311}$	$\langle(25.25,35.25,40.25,50.75);0.6,0.4,0.2\rangle$	$\tilde{t}_{312}$	$\langle(23,30,37,48);0.6,0.3,0.3\rangle$
$\tilde{t}_{321}$	$\langle(12.6,16.8,20.6,25.6);0.5,0.2,0.3\rangle$	$\tilde{t}_{322}$	$\langle(16,32,48,71);0.5,0.3,0.2\rangle$
$\tilde{t}_{341}$	$\langle(3.7,4.7,5.7,8.1);0.6,0.4,0.2\rangle$	$\tilde{t}_{342}$	$\langle(4.5,6,7.5,9);0.5,0.4,0.1\rangle$
$\tilde{t}_{411}$	$\langle(26.5,34.5,42.5,55.5);0.7,0.4,0.2\rangle$	$\tilde{t}_{412}$	$\langle(10,13,17,20);0.4,0.3,0.1\rangle$
$\tilde{t}_{421}$	$\langle(24,32,40,48);0.5,0.4,0.1\rangle$	$\tilde{t}_{422}$	$\langle(25,30,37,45);0.6,0.4,0.2\rangle$
$\tilde{t}_{431}$	$\langle(3.7,4.7,5.7,8.1);0.6,0.4,0.2\rangle$	$\tilde{t}_{432}$	$\langle(4.5,6,7.5,9);0.5,0.4,0.1\rangle$

Table 5: Supply and demand $\tilde{a}_l(l=1,2)$ and $\tilde{b}_p(p=3,4)$ in ton

$\tilde{a}_1=\langle(200,400,600,800);0.5,0.4,0.1\rangle$	$\tilde{b}_1=\langle(100,300,500,700);0.4,0.2,0.2\rangle$
$\tilde{a}_2=\langle(250,450,650,850);0.4,0.2,0.2\rangle$	$\tilde{b}_2=\langle(200,220,300,400);0.2,0.3,0.1\rangle$

Table 6: Optimum solutions for multi objective solid green transshipment problem with and without solar refrigeration technology

Model	*Multi objective solid transhipment problem with solar refrigeration technology*	*Multi objective solid transhipment problem without solar refrigeration technology*
Weighted Tchebycheff metrics programming	$\Re(\tilde{Z}_1)=\$3936.5$, $\Re(\tilde{Z}_2)=51.55h$ $\Re(\tilde{Z}_3)=0.83\%$, $\Re(\tilde{Z}_4)=99878.3gm/co_2$	$\Re(\tilde{Z}_1)=\$6563.89$, $\Re(\tilde{Z}_2)=51.55h$ $\Re(\tilde{Z}_3)=0.83\%$, $\Re(\tilde{Z}_4)=133180gm/co_2$

Optimal solution and comparative study

By using method prescribed in 2.3.1, the obtained optimum solutions of deterministic multi objective solid green transshipment problem with and without solar refrigeration technology using Lingo Global Solver (20.0) are presented in [Table 6.].

Discussion

Gosh et al., (2022) introduced the idea of PT within MOSTP based on a Pythagorean fuzzy environment. The practical relevance of PT in TP is found in the fact that it is very significant, as the overall cost of transportation varies, if the effect of PT increases or decreases, and there is a trade-off between the increased cost and decreased rate of deterioration. As a result, the items can be sold for a higher price, increasing the profit and recovering the economic loss.

Baskaran et al., (2016) calculate the quantities that should be shipped from each source to each destination in order to meet demand requirements and supply constraints while minimizing the overall cost of shipping.

Akram et al., (2022) developed the MOTP in a fuzzy Fermatean setting. Next, we have created a method based on FFDEA for resolving the FFMOTP.

Conclusion

In cold chain logistics, maintaining product quality, reducing spoilage, and ensuring customer satisfaction while minimizing environmental impact are major challenges for decision-makers. The proposed neutrosophic fuzzy multi-objective solid green transshipment model effectively addresses these issues by integrating a solar refrigeration system to enhance energy efficiency and sustainability. To handle uncertainty in real-world parameters, the model has been developed under a neutrosophic fuzzy environment and later transformed into a deterministic form using a ranking function. Pareto-optimal solutions have been obtained using weighted Tchebycheff metrics programming technique. A numerical illustration validates the effectiveness of the proposed model. The comparative analysis between solar-based and engine-driven refrigeration systems reveals that the solar refrigeration-based transshipment model results in a considerable reduction in total transportation cost, spoilage rate, shipping time, and greenhouse gas emissions. Consequently, the proposed model not only supports cost efficiency but also strengthens environmental sustainability in cold chain logistics. Future research may extend this work by incorporating real-time IoT monitoring, hybrid renewable energy systems, and advanced optimization algorithms to further improve operational performance and sustainability.

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