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RESEARCH ARTICLE

A resilient supply chain model integrating demand variability and carbon emissions in imperfect production systems

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Abstract

To analyze and justify the importance of energy-efficient docking systems in the supply chain with varying demand, along with carbon emissions from warehouse electricity and fuel used in generators. A non-linear sustainable supply chain model considering a varying demand is formulated with the incorporation of energy-efficient docking systems. Due to real-life unpredictable situations, single-valued trapezoidal neutrosophic fuzzy parameters are considered in this model. Also, carbon emissions play a significant role in global warming; this paper includes the cost of carbon emissions from both warehouse electricity consumption and fuel used in generators. Lagrangian method is used to obtain the optimal solution of the problem. The proposed model has been solved with the prescribed method and it gives the average profit of the manufacturing firm with energy efficient docking systems is $1267235 and the average profit of the manufacturing firm without energy efficient docking systems is $1248710. This shows that the model with energy-efficient docking systems performs better than the other one. Additionally, single-valued trapezoidal neutrosophic numbers offer greater flexibility in capturing and representing uncertain information compared to triangular fuzzy numbers, as they can model not only fuzzy uncertainty but also indeterminacy and falsity, providing a more comprehensive framework for handling complex and ambiguous data. The efficiency of energy-efficient docking systems with varying demand and carbon emissions under single-valued trapezoidal neutrosophic fuzzy parameters is not yet investigated in the literature.

Keywords: Energy efficient docking systems, Supply chain model, Carbon emission, Carbon tax, Fuzzy environment, Imperfect production systems, Varying demand.

关键词： 节能对接系统、供应链模型、碳排放、碳税、模糊环境、不完善生产系统、需求变化。

Introduction

In a dynamic environment, businesses must innovate their supply chain strategies to remain successful in the competitive marketplace. The supply chain must be more flexible to adapt quickly to changing market demands, disruptions, and emerging trends, ensuring continuous efficiency and resilience in the face of uncertainty. But most supply chain models assume constant demand and perfect quality for all items received in a lot from the manufacturer. (Islam *et al.*, 2021) Developed a standard inventory model for a two-level constant demand rate during the production run time to minimize the total inventory cost. (Mishra *et al.*, 2024) developed a new inventory system with demand substitution using a simple EOQ model for two similar products, allowing for shortages and noted that the assumptions of deterministic and constant demand may be limitations of the model due to the dynamic nature of real-world demand patterns. (Tripathy *et al.*, 2022) constructed an EOQ inventory model for a non-instantaneous deteriorating item with constant demand under a progressive financial trade credit facility. The traditional EOQ models assume a constant demand and perfect quality for all items received in a lot from the manufacturer, and they do not assist decision-makers in determining lot sizes while considering environmental factors.

To address such uncertainty, the fuzzy set was first introduced by Zadeh (1965). (Riju Chaudhary *et al.*, 2023) constructed a sustainable inventory model for defective items under a fuzzy environment and provided guidance to supply chain decision-makers to optimize profits and uncertainty in the supply chain. (Poswal *et al.*, 2022) examined

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a fuzzy EOQ model for price-sensitive and stock-dependent demand under shortages. Generally, a fuzzy set is unable to manage inconsistencies and imprecise data. However, the neutrosophic set (NS) has been applied to tackle these kinds of challenges in various real-world problems. Single-valued trapezoidal neutrosophic numbers offer a more comprehensive way to model uncertainty in complex and real-world scenarios. (Kalaivani K *et al*., 2023) investigated the neutrosophic approach to the transportation problem using single-valued trapezoidal neutrosophic numbers.

In recent years, there has been a growing focus on research related to sustainable supply chains. As companies strive to balance environmental, social, and economic concerns, the need for sustainable practices across the supply chain has gained significant attention. (Jamil *et al*., 2024) Investigated a structural equation modeling framework for exploring the Industry 5.0 and sustainable supply chain determinants. In general, Warehouses play a significant role in contributing to carbon emissions within a supply chain. The energy consumption from lighting, heating, cooling, and machinery, along with transportation emissions from goods entering and leaving the warehouse, add to the overall carbon footprint. (Olakunle Oloruntobi *et al*., 2023) Examined the effective technologies and practices for reducing pollution in warehouses. In particular, the docking area in a warehouse is a major contributor to carbon emissions in the overall supply chain process, primarily due to the energy consumed during the loading and unloading of goods, as well as the emissions from transportation vehicles that frequently idle or operate inefficiently and several other factors. So, it is necessary to conduct research on carbon emissions in the docking systems.

To the best of our knowledge, the majority of the existing literature has predominantly emphasized constant demand rate and imperfect production systems. Specifically, vast research has concentrated on carbon emissions and investments in green technology in production inventory models. But, due to real-life unpredictable situations, demand is not always known. Also, the warehouse sector crucially contributes to carbon emissions with both direct and indirect environmental consequences. In particular, the docking system in a warehouse is a major contributor to the carbon emissions in a supply chain. Therefore, research on the investment of energy-efficient docking systems on varying demand and emissions under the warehouse sector to achieve sustainability is necessarily. The existing literature either deals with the green technology investment for production or constant demand rate and imperfect production systems, but not with the energy-efficient docking systems. Consequently, this leads to the existence of a research gap that does not investigates the efficiency of energy efficient docking systems with varying demand and carbon emissions fuzzy parameters. So, in this study, supply chain model for imperfect items under the concept varying demand and carbon emissions under single valued trapezoidal neutrosophic fuzzy parameters is incorporated with a energy efficient docking systems investment has been formulated and solved to address the sustainable issue parameter.

Methodology

Preliminaries

Definition

Let X be a non-empty set. Then an NS $\tilde{A}^N$ on X defined as γ where $T_{\tilde{A}^N}(x), I_{\tilde{A}^N}(x), F_{\tilde{A}^N}(x)$ are the truth membership function, the indeterminacy membership function, and a falsity function and there is no restriction on the sum of $-0 \le T_{\tilde{A}^N}(x) + I_{\tilde{A}^N}(x) + F_{\tilde{A}^N}(x) \le 3^+$ non-standard unit interval.

Definition

Let X be a non-empty set. Then an SVNS $\tilde{A}_{SN}$ on X defined as $\tilde{A}_{SN} = \langle x, T_{\tilde{A}_{SN}}(x), I_{\tilde{A}_{SN}}(x), F_{\tilde{A}_{SN}}(x) \rangle / x \in X|$ where $T_{\tilde{A}_{SN}}(x), I_{\tilde{A}_{SN}}(x), F_{\tilde{A}_{SN}}(x) \in [0,1]$ for each $x \in X, 0 \le T_{\tilde{A}_{SN}}(x), I_{\tilde{A}_{SN}}(x), F_{\tilde{A}_{SN}}(x) \le 3$.

Definition

Let m_1, m_2, m_3, m_4 such that $m_1 \le m_2 \le m_3 \le m_4$ and $T_{\tilde{m}}, I_{\tilde{m}}, F_{\tilde{m}} \in [0,1]$. Then an SVTNNs is defined as $m_{\tilde{m}} = (m_1, m_2, m_3, m_4); T_{\tilde{m}}, I_{\tilde{m}}, F_{\tilde{m}}$ is a special neutrosophic set on the real line set R, whose truth membership, indeterminacy membership, and falsity membership functions are given as follows:

$$\mu_{T_{\tilde{m}}} = \begin{cases} T_{\tilde{m}}\left(\dfrac{x-m_1}{m_2-m_1}\right), & m_1 \le x \le m_2 \\ T_{\tilde{m}}, & m_2 \le x \le m_3 \\ T_{\tilde{m}}\left(\dfrac{m_4-x}{m_4-m_3}\right), & m_3 \le x \le m_4 \\ 0, & otherwise \end{cases}$$

$$v_{I_{\tilde{m}}}(x) = \begin{cases} \dfrac{m_2 - x + I_{\tilde{m}}(x-m_1)}{m_2-m_1}, m_1 \le x \le m_2 \\ I_{\tilde{m}}, m_2 \le x \le m_3 \\ \dfrac{x - m_2 + I_{\tilde{m}}(m_4-x)}{m_4-m_3}, m_3 \le x \le m_4 \\ 1, otherwise \end{cases}$$

$$w_{F_{\tilde{m}}}(x) = \begin{cases} \dfrac{m_2 - x + F_{\tilde{m}}(x-m_1)}{m_2-m_1}, m_1 \le x \le m_2 \\ F_{\tilde{m}}, m_2 \le x \le m_3 \\ \dfrac{x - m_2 + I_{\tilde{m}}(m_4-x)}{m_4-m_3}, m_3 \le x \le m_4 \\ 1, otherwise \end{cases}$$

Mathematical Model

A non-linear sustainable supply chain model is developed that takes into account fluctuating demand and integrates energy-efficient docking systems. To address real-life uncertainties, the model incorporates single-valued trapezoidal neutrosophic fuzzy parameters. Additionally, the model accounts for the impact of carbon emissions on global warming by considering the costs associated with carbon emissions from both warehouse electricity consumption and fuel used in generators. The optimal solution to the problem is obtained using the Lagrangian method. Notations and Assumptions which are used to formulate the proposed model are given below.

Notations

q Order quantity per cycle (in units)
D Fuzzy Demand rate (in units / year)
d Defuzzified demand rate (in units / year)
r Screening rate, (in units / year),where $r \geq D$
P_C Purchasing cost per unit (in \$ / unit)
O_C Ordering cost per order / cycle(in \$ / cycle)
H_C Holding cost per unit per unit time (in \$ / unit / year)
R_C Screening cost per unit (in \$ / unit)
T_C Total cost (in \$)
T_R Total revenue (in \$)
T_P Total profit (in \$)
u Defective percentage in a lotsize of q (in units)
$f(u)$ Probability density function of u
$E[u]$ Expected value operator of u
S_P Selling price per unit of perfect item (in \$)
S_d Selling price per unit of defective item (in \$),where $S_d < S_P$
C_T Tax on carbon emission(in \$ / ton of CO_2)
W_C Average carbon emission from warehouse electricity (in ton of CO_2 /kWh)
t Electricity consumption per unit in thewarehouse (in Kwh/unit/year)
L Cycle Length (in years)
l Screening time (in years),where $l < L$
ρ efficiency of docking system in reducing emissions
γ fraction of carbon emissions after efficient docking system investment
M investment on efficient docking system

Assumptions

1. A single product has been considered.
2. Demand rate has been considered as a single-Valued Trapezoidal Neutrosophic Number.
3. Lead time has been assumed to be negligible.
4. No Shortages have been allowed.
5. Rate of production has been considered more than the demand rate.
6. Replenishment of the order (with a lot size of y) has been assumed to be instantaneous.
7. The process of inspection is perfectly capable of identification and separation of defective products from the lot.
8. Demand of the customer is completely satisfied even during the periodof inspection, as the rate of inspection has been considered way higher than the rate of demand.
9. The process of screening and demand of items proceed simultaneously,where the rate of screening has been assumed to be greater than the demand rate.
10. The order lot has been assumed to have some defective items.
11. The percentage of defective items, u , in every lot, has been assumed to follow uniform distribution with $[\alpha, \beta]$,where $0 \leq \alpha < \beta < 1$.
12. Defective items are sold at a discounted price after the completion of the inspection process.
13. CO_2 is directly emitted fromelectricity during product storage.
14. Tax on carbon emission has been assumed to belevied on carbon emission.
15. The manufacturer intends to invest in energy efficient docking systems such as High-Efficiency Dock Seals and Shelters, Air Curtains, Insulated Dock Doors, Energy-efficient Dock Lights, machinery that conserves energy, in order to transition to a more environmentally friendly manufacturing system. There is a cap on the total amount of money that can be invested. Fraction of reduction of average emission for production is $F = \gamma\left(1 - e^{-\rho M}\right)$ and $F = \gamma\left(1 - e^{-\rho M}\right) \Rightarrow M = -\left(\frac{1}{\rho}\right)\left[\ln\left(1 - \frac{F}{\gamma}\right)\right]$ which is like the relation assumed by Lou *et al*. The manufacturer might make improvements to his production methods to make them more environmentally friendly The factor ρ indicates how effective docking system is at lowering emission.This investment function is consistent in various industries, and has widely been used in literature to formulate various investing options.

Supply chain model with energy efficient docking system investment

A non-linear sustainable supply chain model considering a varying demand and carbon emissions is formulated with a incorporation of a docking system investment for a warehouse along with the imperfect production system. Lagrangian method is used to obtain the optimal solution of the problem. Extensive research has focused on investments in green technology within production inventory models. In general, the warehouse sector also plays a crucial role in carbon emissions. Here, the investment has made for the docking system in a warehouse to address the sustainable issue parameter. The carbon taxation method is used in this model to cut down on carbon emissions. In developed countries, this policies is commonly used to reduce carbon emissions that enhance environmental and economic efficiency by providing price stability and emissions certainty. Most of the existing literature assumed that the demand is constant. But, due to real-life unpredictable circumstances, demand is not always known. To address this uncertainty, single-valued trapezoidal neutrosophic numbers are used in this model. Also, the manufacturer intends to invest in energy-efficient docking systems such as high-efficiency dock seals and shelters, air curtains, insulated dock doors, automatic dock levelers, energy-efficient dock lights, insulated truck beds, and temperature-controlled loading docks in order to transition to a more environmentally friendly manufacturing system. The total profit of the manufacturing company is given by

$$E[UT_P(q)] = \frac{E[T_P(q)]}{E[L]} \tag{2.1}$$

$$E[UT_P(q)] = \frac{\left[S_P(1-E(u))d + S_d E(u) d\right] - \left[\begin{array}{l} \frac{O_C d}{q} + r_C d + P_C d + H_C\left(\frac{E\left((1-u)^2\right)q}{2} + \frac{E(u)qd}{r}\right) \\ +tW_C C_T\left(1-\gamma\left(1-e^{-\rho M}\right)\right)\left(\frac{E\left((1-u)^2\right)q}{2} + \frac{E(u)qd}{r}\right) + M \end{array}\right]}{1-E(u)} \tag{2.2}$$

Taking any discrete value of q, the first and second-order partial derivatives of the above equation, the following results can be obtained:

$$\partial E\frac{\left[UT_P(L,q)\right]}{\partial q} = 0 \text{ and } \frac{\partial E\left[UT_P(L,q)\right]}{\partial^2 q} < 0$$

For optimum solution of q, we must take,

$$q^* = \sqrt{\frac{2O_C d}{\left[H_C + tW_C C_T \times E(1-u)^2 + \frac{2E(u)d}{r}\right]}} \tag{2.3}$$

Similarly, it follows for M

$$\frac{\partial E\left[UT_P(L,M)\right]}{\partial M} = 0$$

Supply chain model without energy efficient docking system investment

A non-linear supply chain model considering variable demand is formulated along with a carbon emissions that are generated from warehouse electricity and from fuel used in generators . Lagrangian method is used to obtain the optimal solution for the problem. To follow the government regulation carbon taxation is considered in this model. Also, to handle the uncertainty, Trigular fuzzy numbers are used. If no expenditure is made on docking system investment, the manufacturer's yearly profit under a carbon tax function is as follows. The manufacturing company's entire profit is defined as

$$E\left[UT_P(q)\right] = \frac{E\left[T_P(q)\right]}{E[L]} \tag{2.4}$$

$$E\left[UT_P(y)\right] = \frac{\left[S_P(1-E(u))d + S_d E(u) d\right] - \left[\begin{array}{l} \frac{O_C d}{q} + r_C d + P_C d + \left(\frac{E(1-u)^2 q}{2} + \frac{E(p)qd}{r}\right) \\ +tW_C C_T\left(\frac{E(1-u)^2 q}{2} + \frac{E(p)qd}{r}\right) \end{array}\right]}{1-E(u)} \tag{2.5}$$

Result

In this study, energy efficient docking system investment has been incorporated for the warehouse in a supply chain along with the carbon emission and varying demand. To show the efficiency of the proposed model the following numerical example is illustrated with the prescribed parameters as given below.

Parameters:

Fuzzy Demand rate D (44000,50000,62000) units/year
Defuzzified demand rate d 51500 units/year
Screening rate r 175200 units/year
Purchasing cost P_C \$25/unit
Ordering cost, O_C \$100/order/cycle
Holding cost, H_C \$5/unit/year
Screening cost, r_C \$0.5/unit
Defective percentage, u , 0.02
Selling price of perfect item, S_P \$50
Selling price of defective item S_d \$20
Tax on carbon emission, C_T \$75/ton CO_2
Average carbon emission W_C 0.0005ton CO_2 /Kwh
Electricity consumption, t 1.44Kwh/unit/year
Greener technology efficiency ρ 0.8
Carbon emissions after investment γ 0.2

Using the equation (2.2), the average profit of the manufacturing firm with energy efficient docking system is $E\left[UT_P(q)\right]$ = \$1267235

Using the equation (2.5), the average profit of the manufacturing firm without energy efficient docking system

$E\left[UT_P(q)\right]$ = \$1248710

Table 1 shows the efficiency of the suggested paradigm.

Discussion

The existing literature has examined various strategies on carbon emissions, but it does not adequately address the contribution of a warehouse in generating emission. (Sarkar *et al.*, 2021) examined a flexible biofuel and bioenergy production system with transportation disruption under a sustainable supply chain network. While some studies focus on investments in green technology they typically neglect the ordering strategy aspect. (Mishra *et al.*, 2020) developed a sustainable production-inventory model for a controllable

Table 1: Comparison of the manufacturing firm with and without Energy efficient docking systems investment

Average profit of the manufacturing firm	With Energy Efficient Docking Systems Investment	Without Energy Efficient Docking Systems Investment
	$1267235	$1248710

carbon emissions rate under shortages. Specifically, most researches have developed models for green technology investment solely within the context of protection systems. This study aims to fill the gap by considering the emissions that are generated from warehouse electricity and from fuel used in generators and ordering strategy parameters simultaneously and thus it maximizes the profit of the supply chain using a energy-efficient docking system. In this study, a non-linear sustainable supply chain model is developed that incorporates an energy-efficient docking system investment for the warehouse, along with a variable demand parameter. To align with government regulations, the model integrates carbon taxation. The results reveal that the manufacturing firm's average profit with the investment in an energy-efficient docking system significantly surpasses the average profit of a firm operating without such an investment, highlighting the substantial financial benefits of adopting sustainable technologies.

Conclusion

In today's industrial landscape sustainability is not just a concept it is a shared responsibility. Organizations often innovate their strategy in their supply chain to maximize the profit. Most studies have examined solely on the sustainable parameter (i.e. green technology investment) or constant demand rate in the supply chain. In particular, numerous studies have focused on green technology investments within production-inventory models. In general, Warehouse sector significantly contributes to carbon emissions. So this study, seeks to fill the gap by considering both the carbon emissions that are generated from warehouse electricity and from fuel used in generators and thus it aims to maximizes the profit of the supply chain.The Energy-efficient docking systems are designed to minimize energy loss when loading or unloading goods in and out of a warehouse. They help reduce the need for additional heating or cooling, improve energy efficiency, and create a safer, more comfortable working environment. So, in this study, A non linear sustainable supply chain model has been formulated with a incorporation of a energy efficient docking system investment for the warehouse along with varying demand parameter.

Due to government regulations, Carbon taxation method is considered in this model.Lagrangian method is used to obtain the optimal solution of the docking system investment. To address uncertainty, Single valued trapezoidal neutrosophic fuzzy numbers are used in this model. Numerical examples are carried out to show the effectiveness of the proposed model. The results shows that the average profit of the manufacturing firm with energy efficient docking system investment is $1267235 and the average profit of the manufacturing firm without energy efficient docking system investment is $1248710. This work can also be extended for deteriorating items and other sustainability issue parameters. Further studies can also be broadening by considering other fuzzy parameters with respect to carbon emissions for more sustainable practices.

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