



RESEARCH ARTICLE

A Fuzzy Supply Chain Model Evaluating Energy Management Systems under Imperfect Production and Uncertain Costs

M. Monika, J. Merline Vinotha*

Abstract

To assess the impact of energy management systems in supply chain with varying cost parameters along with carbon emissions enhancing sustainability, minimizing expenses while ensuring operational efficiency. In this study, a non-linear sustainable supply chain model is developed by incorporating an energy management system and considering a varying cost parameter to reflect real-world complexities. In practical production environments, systems often fail to produce perfectly flawless items due to various unpredictable factors. To address such uncertainties, single-valued trapezoidal neutrosophic fuzzy parameters are employed in the model. Furthermore, recognizing the significant impact of carbon emissions on global warming, the model integrates the cost of carbon emissions across different processes. Finally, the Lagrangian method is applied to derive the optimal solution for the formulated problem. The proposed model has been solved using the prescribed optimization method, yielding a total cost of 398,181 for the manufacturing firm with investment in energy management systems, compared to a total cost of 461,634 for the firm without such investment. This significant reduction in total cost clearly demonstrates that the implementation of energy management systems enhances the overall performance and cost-efficiency of the manufacturing process. The efficiency of energy management systems considering varying cost parameters and carbon emissions under single-valued trapezoidal neutrosophic fuzzy environments has not yet been thoroughly investigated in the existing literature.

Keywords: Imperfect items(不合格品), Rework(返工), Energy management systems(能源管理系统), Carbon emission(碳排放), Fuzzy environment(模糊环境), Varying demand(需求波动).

Introduction

In today's highly competitive global marketplace, organizations must continually innovate their supply chain strategies to maintain a competitive edge. The primary operational objectives of most manufacturing firms are to maximize customer satisfaction while minimizing production and operational costs to establish themselves as low-cost manufacturers. According to the classical

Economic Production Quantity (EPQ) model, production is assumed to occur at a perfect quality level, with inventory being continuously released to satisfy ongoing market demand. However, real-world production environments often deviate from these assumptions due to imperfections, uncertainties, and system inefficiencies. Several researchers have contributed to addressing these practical limitations. (F. Lin et al., 2021) investigated the effects of inspection rates on integrated inventory systems involving defective items, emphasizing capacity utilization, and proposed two policies—Rework-Priority Policy (RPP) and Delivery-Priority Policy (DPP)—demonstrating that RPP is the preferred strategy in such systems. (A. A. Taleizadeh et al., 2022) developed an optimization model for a manufacturing-inventory system that incorporates a rework process, considering failure severity and operating under multiple system constraints. Similarly, (P. Gautam et al., 2022) proposed an inventory model designed to handle defective items through efficient rework, enabling them to be sold at their original price, while also accounting for energy consumption and carbon emission costs to optimize both production batch size and selling price. Furthermore, (M. Jain et al., 2025) explored the influence of memory effects

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on inventory control and pricing strategies for imperfect production systems incorporating rework processes, formulating a fractional-order inventory control model that considers both imperfect manufacturing conditions and price-sensitive demand.

Traditional inventory models such as the Economic Order Quantity (EOQ) and Economic Production Quantity (EPQ) primarily focus on minimizing inventory-related costs. However, these classical models are limited in their ability to address the occurrence of defective items or incorporate rework processes, which are common in practical manufacturing systems. To overcome such limitations and to handle uncertainties arising from fluctuating demand, variable lead times, and imprecise data, Zadeh (1965) introduced the concept of fuzzy set theory, providing a flexible mathematical framework to model ambiguity and enhance decision-making robustness in inventory management. Building upon this foundation, (S. Priyan et al., 2022) proposed a sustainable dual-channel inventory model that integrates trapezoidal fuzzy demand and energy consumption, highlighting the significance of incorporating flexibility in demand and energy parameters to better represent the uncertainties of real-world conditions. Similarly, (S. Sahoo et al., 2022) developed sustainable intuitionistic fuzzy inventory models that consider preservation technology investment and allow for shortages, with the objective of minimizing total system costs. Additionally, sensitivity analysis was conducted to assess the impact of variations in model parameters, offering deeper insights into system behavior under uncertain environments.

In recent years, the growing emphasis on sustainability has significantly influenced supply chain research, as organizations strive to integrate environmentally, socially, and economically responsible practices into their operations. Several researchers have contributed to advancing sustainable inventory and production models that address environmental challenges such as carbon emissions, energy efficiency, and resource optimization. (L. A. San-José et al., 2024) introduced a sustainable inventory model for deteriorating items with power demand and full backlogging, incorporating a carbon emission tax. The study identified the optimal inventory policy, specifically the lot size and reorder point, that maximizes profit per unit time while accounting for carbon emission costs arising from transportation, storage, and item deterioration. (Y. Feng et al., 2022) proposed a robust multi-supplier, multi-period inventory model under uncertain market demand and carbon emission constraints, where product quality, ordering cost, service level, and emergency capacity were adopted as evaluation criteria. The Analytic Hierarchy Process (AHP) was utilized to comprehensively evaluate and score each supplier. Similarly, (A. Kumar et al., 2024)

developed a fuzzy production–inventory model that integrates carbon emission considerations, where cost parameters were represented using pentagonal fuzzy numbers, and defuzzification was performed using the sign distance method to address uncertainty. (S. Priyan et al., 2023) examined the impact of green investment on reducing carbon emissions in an imperfect production system, employing trapezoidal fuzzy numbers to define emission parameters and the signed distance method for defuzzification. The results confirmed that green investment is a cost-effective strategy for minimizing CO₂ emissions and overall operational expenses. In another study, (A. Sepehri et al., 2021) proposed a sustainable production–inventory model that considers imperfect quality, incorporating preservation technology and quality improvement investments. The research demonstrated how these technologies influence total profit, and an algorithm was introduced to determine the optimal decision variables related to replenishment and pricing. In alignment with these sustainability-driven approaches, energy management systems (EMS) have emerged as a vital technological solution to further enhance operational efficiency. EMS technologies enable real-time monitoring of energy usage across warehouses and production facilities, optimizing temperature control, lighting, machinery operation, and other energy-intensive activities. By reducing overall energy consumption, EMS not only promote environmental sustainability but also create a more comfortable and productive workplace, yielding significant long-term cost savings and improved warehouse performance.

The existing literature has primarily concentrated on known and well-defined factors in both imperfect and perfect production systems. However, in practice, inventory systems rarely produce all items with perfect quality, as defects and imperfections are inherent characteristics of most manufacturing processes. In real-world scenarios, many influential factors are uncertain, variable, or imprecisely defined, underscoring the necessity for models capable of effectively handling such ambiguity and uncertainty. Extensive research has explored carbon emissions and the impact of green technology investments in production–inventory models, emphasizing the growing importance of sustainability and environmental responsibility in modern supply chain management. Moreover, the warehousing sector is recognized as a significant contributor to carbon emissions, producing substantial direct and indirect environmental effects. Consequently, investigating investments in energy management systems (EMS)—while considering varying cost parameters and emission factors within warehouse operations—has become essential for achieving sustainable and eco-efficient production systems. Despite these advancements, most existing studies address known cost and emission parameters in imperfect

production systems, whereas real-world conditions often involve unpredictable and fluctuating variables. This reveals a critical research gap: the efficiency of energy management systems under varying cost parameters and carbon emissions within an imperfect production environment has not yet been adequately examined. To bridge this gap, the present study formulates a non-linear sustainable supply chain model for imperfect items, incorporating energy management system investments, varying cost parameters, and carbon emissions under single-valued trapezoidal neutrosophic fuzzy conditions. The proposed model is solved using an appropriate optimization approach to address the sustainability-oriented objectives of modern manufacturing systems. The remainder of this paper is organized as follows.

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, an indeterminacy membership function, and a falsity function and there is no restriction on the sum of $-0 \leq T_{\tilde{A}^N}(x) + I_{\tilde{A}^N}(x) + F_{\tilde{A}^N}(x) \leq 3^+$ non-standard unit interval.

Definition

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

Definition

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

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

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

$$w_{F_{\tilde{m}}}(x) = \begin{cases} \frac{m_2 - x + F_{\tilde{m}}(x - m_1)}{m_2 - m_1}, & m_1 \leq x \leq m_2 \\ F_{\tilde{m}}, & m_2 \leq x \leq m_3 \\ \frac{x - m_2 + F_{\tilde{m}}(m_4 - x)}{m_4 - m_3}, & m_3 \leq x \leq m_4 \\ 1, & \text{otherwise} \end{cases}$$

Mathematical Model

A non-linear sustainable supply chain model is developed for an imperfect production system, incorporating energy management systems (EMS) and varying cost parameters within the supply chain framework. To effectively capture real-world uncertainties and imprecise conditions, the model employs single-valued trapezoidal neutrosophic fuzzy parameters, which provide a more flexible and realistic representation of uncertain decision variables. Furthermore, the model explicitly accounts for the impact of carbon emissions on global warming by including the associated emission costs across various processes of the inventory system. The Lagrangian optimization technique is utilized to derive the optimal solution to the proposed problem, ensuring a balance between economic efficiency and environmental sustainability. The notations and assumptions used for the formulation of the proposed model are presented below.

Notation

- p- Production rate
- h- Rate of demand
- l- Defective production rate($l=pf$)
- I- Inventory level
- I^* - Optimal production lot size
- $\tilde{S}$ - Setup cost
- $\tilde{H}$ Annual storage cost per unit
- N- Quality improvement cost
- r- Per-unit rework cost
- r' - Rejection cost per unit
- $\tilde{C}_p$ - Manufacturing cost per unit
- e- Rate of unrepaired defects (scrap items).
- f- Percentage of defective units (f is between 0 and 1)
- Q- Cycle time, made up of q_i unit time periods i ($i = 1, 2, 3, 4, \dots$)
- $\tilde{S}_1$ - Per-unit shortage cost
- b- CO₂ footprint per product unit
- w- The warehouse's carbon emissions per unit time are correlated with the inventory level.
- b- Annual scrap inventory rate [in %]
- a- Scrap unit weight
- c- Average carbon emission cost coefficient for inventory waste during planning/proposals.
- ρ - efficiency of energy management systems in reducing emissions

γ -fraction of carbon emissions after energy management system investment
 M-investment on energy management system

Assumptions

- The demand rate is steady, continuous, and predictable.
- There is no lead time involved.
- Unlike traditional EOQ models, inventory accumulates gradually during production rather than being received all at once.
- Each product is treated independently, with no interdependence among inventory items.
- Only the standard production process encounters issues; the reworking process functions smoothly and yields profitable results.
- The combined rate of demand and the rate of defective production never exceeds the production rate of flawless items.
- Reworking is initiated only after the completion of the standard manufacturing process.
- Both standard production and rework contribute to the total output used to meet demand.
- The manufacturer intends to invest in energy management systems, 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. The fraction of reduction in average emissions for production is $F = \gamma(1 - e^{-\rho M})$ where γ , u and G were defined in the notations section. $F = \gamma(1 - e^{-\rho M}) \Rightarrow M = -\left(\frac{1}{\rho}\right) \left[\ln\left(1 - \frac{F}{\gamma}\right) \right]$ This relationship is similar to that assumed by Lou et al. The manufacturer might make improvements to the production methods to make them more environmentally friendly. The fraction of reduction F is zero when $G = 0$ and tends to γ when $G \rightarrow \infty$. The factor ρ indicates how effective greener technology is at lowering emission. This investment function is consistent in various industries, and has been widely been used in literature to formulate various investment options.

Supply chain model with energy management system investment

A non-linear sustainable supply chain model is formulated for an imperfect production system, incorporating varying cost parameters, carbon emissions, and an investment in energy management systems (EMS) within the warehouse. The Lagrangian optimization method is employed to obtain the optimal solution for the proposed model. Extensive research has addressed carbon emissions and known, well-defined cost parameters within production-inventory models. However, in real-world scenarios, these factors are often uncertain and variable, creating challenges

for effective inventory management. The warehouse sector plays a critical role in carbon emissions, and the present study considers investments in EMS, such as smart thermostats and heating, ventilation, and air conditioning (HVAC) systems, to enhance energy efficiency and promote a more environmentally sustainable manufacturing system. Most existing literature assumes constant cost parameters and perfect product quality, which rarely reflects practical production environments. To address the uncertainty inherent in real-life inventory systems, this model employs single-valued trapezoidal neutrosophic numbers, providing a flexible framework to capture imprecision in decision-making. The model also evaluates the impact of energy management system investments on total profit, integrating both economic and environmental objectives to support sustainable operational decisions. Therefore, the total profit of the manufacturing company is given by the first and second-order partial derivatives of the above equation with respect to M , the following results can be obtained:

$$\begin{aligned}
 TC = & \frac{hs}{I(1-f)} + \frac{hc_p}{(1-f)} + \frac{\tilde{H}I(p-h-l)}{2p} + \frac{\tilde{H}B^2p}{2I(p-h-l)} - B\tilde{H} + \frac{\tilde{s}_1B^2p}{2I(p-h-l)} + \frac{b(p-h-l)}{Q} \\
 & + w \left\{ \frac{I(p-h-l)}{2p} + \frac{B^2p}{2I(p-h-l)} - B \right\} \\
 & + (1-\gamma(1-e^{-\rho M})) \left\{ \frac{b(p-h-l)}{Q} + w \left\{ \frac{I(p-h-l)}{2p} + \frac{B^2p}{2I(p-h-l)} - B \right\} \right\} + M
 \end{aligned} \quad (2.1)$$

$$\frac{\partial E[TC(I, B, M)]}{\partial M} = 0$$

$$\text{And } \frac{\partial^2 E[TC(I, B, M)]}{\partial M^2} < 0$$

Supply chain model without energy management system investment

The A non-linear supply chain model is formulated by considering variable cost parameters along with the carbon emissions generated across various processes of an inventory system. In practice, a production system rarely manufactures items of perfect quality at all times. To determine the optimal production quantity for a single product in a single-stage manufacturing system—where partially defective products are reworked within the same production cycle—it is necessary to account for the inherent uncertainties of real-life inventory characteristics and objectives. Such uncertainties can be effectively represented using fuzzy numbers. The Lagrangian optimization method is employed to obtain the optimal solution for the proposed problem. In the absence of any investment in energy management systems (EMS), the annual profit of the manufacturer under an imperfect production system is determined as follows. The total profit of the manufacturing company is defined as:

Table 1: Comparison of the total cost of the manufacturing firm

Total total cost of the manufacturing firm	With energy management system investment	Without energy management system investment
	398181	461634

$$TC = \frac{h\tilde{s}}{I(1-f)} + \frac{h\tilde{c}_p}{(1-f)} + \frac{\tilde{H}I(p-h-l)}{2p} + \frac{\tilde{H}B^2p}{2I(p-h-l)} - B\tilde{H} + \frac{\tilde{s}_sB^2p}{2I(p-h-l)} + \frac{b(p-h-l)}{Q} + w\left\{\frac{I(p-h-l)}{2p} + \frac{B^2p}{2I(p-h-l)} - B\right\} \quad (2.2)$$

Result

This study presents a numerical example to evaluate the effectiveness of energy management systems relative to conventional methods. To show the efficiency of the proposed model the following numerical example is illustrated with the prescribed parameters as given below.

Parameters

In this section, some numerical data based on the C.K. Sivashankari & S. (Panayappan et al., 2013) and another data based on the (Taleizadeh et al., 2018) models are utilised, the manufacture produced the $p=5000$ units of items per unit time period and the demand rate is $h=4500$ units in per unit time, the cost of setup the manufacturer apparatus is $s=100$ /unit, the cost of holding the items $H=10$ /unit and the cost of production $c_p=100$ /unit, the proportion value of f varies from 0.01 to 0.09 and amount of carbon emission associated with production is $b=2$ /ton, carbon emission unit related to holding items is $w=1$ and the 0.01% amount of average inventory in change in scrap annually, where the weight of scrap unit is 0.002 ton/unit and the average cost of carbon emission coefficient is 13/ton. The efficiency of energy management systems in reducing emissions is 0.7 and the fraction of carbon emissions after energy management system investment is 0.3.

Using the equation (2.1), the total cost of the manufacturing firm with energy management system is given by

$$E[TC(R, B, M)] = 398181$$

Using the equation (2.2), the total cost of the manufacturing firm without with energy management system is given by

$$E[TC(R, B)] = 461634$$

The above Table 1 shows the efficiency of the suggested paradigm.

Discussion

Existing studies have investigated strategies for carbon emission reduction, yet they rarely account for the significant role of warehouses in generating emissions. (A. Nsabiyeze et al., 2024) conducted a global evaluation of the effectiveness

of carbon emission reduction policies in addressing climate change within the agricultural sector. Additionally, while some research emphasizes green technology investments, it often ignores the impact of inventory ordering strategies and primarily focuses on production protection systems. (L. Jia et al., 2024) investigated the impact of the carbon emission trading system on green technology innovation in China's energy enterprises. (C. Miao et al., 2024) examined the relationship between green technology innovation and carbon emission efficiency, highlighting the moderating role of environmental uncertainty. This study addresses these limitations by considering both warehouse-generated emissions and variable cost parameters resulting from imperfect production, aiming to enhance overall supply chain profitability. To achieve this, an energy management system (EMS) investment is incorporated for the warehouse, integrated with carbon emission and cost considerations, thereby providing a holistic and sustainable supply chain model.

Conclusion

In the modern industrial landscape, uncertainty within inventory systems has become increasingly prevalent due to fluctuations in demand, supply chain disruptions, and evolving market conditions. Consequently, businesses are compelled to adopt more agile and data-driven inventory management strategies. Most existing studies have focused solely on either sustainability parameters or constant cost parameters within the supply chain, with numerous studies emphasizing carbon emissions in perfect production-inventory models. However, the warehouse sector significantly contributes to carbon emissions and has often been overlooked in previous research. This study addresses this gap by simultaneously considering carbon emissions generated across various warehouse processes and variable cost parameters, with the objective of maximizing overall supply chain profit. To achieve this, an energy management system (EMS) investment is incorporated, which improves energy efficiency by optimizing temperature control, reducing energy consumption, minimizing the need for additional heating or cooling, and creating a safer and more comfortable working environment. A non-linear sustainable supply chain model is formulated that integrates the EMS investment for the warehouse alongside variable demand parameters. To address uncertainty in real-world conditions, the model employs single-valued trapezoidal neutrosophic fuzzy numbers, and the Lagrangian method is used to determine the optimal solution. Numerical examples demonstrate the effectiveness of the proposed

model, showing that the total cost of the manufacturing firm with EMS investment is 398181 compared to 461634 without EMS investment, highlighting the significant cost savings and sustainability benefits. This framework can be further extended to incorporate deteriorating items and additional sustainability-related parameters, while future research could integrate other fuzzy parameters related to carbon emissions to promote even more eco-efficient and sustainable supply chain practices.

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