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RESEARCH ARTICLE

Optimization of a Lean Vendor–Buyer Supply Chain Model under Neutrosophic Fuzzy Environment with Transportation, Loading, and Unloading Considerations

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Abstract

To analyze and justify the impact of automated truck loading system technology on minimizing lead time in warehouse loading and unloading processes for both vendor- buyer in the supply chain. A non-linear lean supply chain model is formulated for a single vendor–buyer system handling a single item, with the inclusion of freight forwarding services. The model explicitly accounts for transportation, loading, and unloading activities under two alternative loading technologies: automated truck loading systems and conventional forklift loading systems. In this framework, lead time is modeled as a function of production, loading and unloading, transportation, and in-transit durations. To reduce total lead time, automated truck loading system technology is incorporated, offering an advanced alternative to traditional forklift operations. Given the inherent uncertainty and variability in real-world supply chain environments, Single-valued Trapezoidal Neutrosophic fuzzy parameters are introduced to better capture imprecision in system parameters. To solve the formulated non-linear problem, the Lagrangian method is employed to derive the optimal solution, thereby enabling decision-makers to evaluate trade-offs between lead time reduction, efficiency, and system flexibility. The proposed model was solved using the prescribed method, and the results show that the total lead time with the incorporation of automated truck loading system technology is 5.834 days, whereas the total lead time with the forklift loading system is 10.46 days. This significant reduction in lead time demonstrates that the automated truck loading system substantially outperforms the conventional forklift loading system, thereby improving overall efficiency and responsiveness in the supply chain. From a managerial perspective, adopting automated loading technology can lead to significant improvements in supply chain efficiency, reduced operational delays, and enhanced responsiveness to customer demand.

Keywords: Lean supply chain, Lead time, Automated truck loading systems, Loading and Unloading, Forklifts, Fuzzy environment.

Introduction

In a rapidly changing environment, supply chain agility is crucial for business leaders to stay competitive and successful. A supply chain faces numerous constraints that can impact its performance, with timely delivery standing out as a critical factor. Ensuring on-time delivery not only enhances customer satisfaction but also plays a pivotal role in driving profitability across the entire supply chain. Lead time is a critical factor in logistics and inventory management, representing the time aspect that directly affects service levels and significantly influences stock control and demand planning. Shorter lead times enhance efficiency and positively impact the financial performance of the supply chain. (HM Alzoubi et al., 2022) examined the impact of supply chain integration and agile practices on lead time and concluded the positive relationship between supply chain integration and the reduction of lead time. (J Zhao et al., 2021) examined the impact of revenue-sharing and cost-sharing contract mechanisms on the lead time of a two-level photovoltaic supply chain. (MD Roy et al., 2021) proposed lead time reduction strategies dependent on production rate and lot size within a supply chain model characterized by stochastic demand, controllable setup cost, and trade-credit financing. (D Castellano et al., 2023) established an inventory model that optimizes production and inventory replenishment along with lead time decisions

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in a two-echelon sustainable supply chain that faces quality challenges, while ensuring a specified fill rate constraint. (Y Zhai et al., 2023) investigated the impact of a production lead-time hedging strategy on delivery time decisions under two distinct game-theoretic models, and determined the resulting profits for both the retailer and the manufacturer.

A lean supply chain strives to enhance the customer satisfaction meanwhile it eliminates the waste at each and every point of the supply chain. It leverages cutting-edge technologies and seamless integration to drive efficiency and eliminate waste across all operations. By integrating innovations such as automation, real-time data analytics, and smart logistics in the supply chain organizations can significantly reduce costs and enhance responsiveness. (R Sharma et al., 2022) presented a research framework designed to assist both academicians and practitioners in recognizing current research trends and patterns of artificial intelligence in supply chain management. (M Abdirad et al., 2021) reviewed the current literature on Industry 4.0 in SCM that brings out some interesting findings, which will be helpful for the academic and industry, especially top managers. (A Raja Santhi et al., 2022) studied the significance of Blockchain Technology in Manufacturing Supply Chain and Logistics and concluded that blockchain technology has the potential to revolutionize supply chain and logistics by making them more secure, agile, trustworthy, and transparent. (BK Dey et al., 2021) described the involvement of controllable lead time and variable demand for a smart manufacturing system under a supply chain management. (ID Wangsa et al., 2021) conducted a study on an Integrated Inventory Model incorporating Electric Vehicles, Freight Costs, and Stochastic Lead Time.

Operations in warehouses—such as loading, unloading, transit, and storage—serve as the backbone of efficient supply chain management. These critical activities ensure the smooth flow of goods, reduce lead times, and support timely delivery to end customers. A well-managed warehouse operation enhances inventory accuracy, minimizes handling costs, and maximizes space utilization. As global supply chains grow more complex, the importance of streamlined warehouse operations becomes ever more vital to maintaining competitiveness and customer satisfaction. In recent times, Research professionals strongly emphasized sustainability, particularly in the realm of supply chain management. Incorporating advanced technologies into a supply chain and utilizing renewable energy are effective strategies for achieving a lean supply chain. (D Oliveira-Dias et al., 2022) investigated the emerging information technologies to achieve the lean and agile supply chain. (Pawel Zajac et al., 2022) analyzed the energy consumption of a forklift under different parameters, including speed, curve radius, and curving speed, and established a framework for evaluating energy use and transport cycle time in various scenarios. (C Liu et al., 2022) investigated the impacts of green logistics management and supply chain system construction based on internet of things technology. (H Bukhari et al., 2025) developed a sustainable green supply chain and logistics management using adaptive fuzzy-based particle swarm optimization. (X Wang et al., 2025) investigated the Critical Success Factors for Enhancing Intelligent Loading and Unloading in Urban Supply Chains: A Comprehensive Approach Based on Fuzzy DEMATEL-AISM-MICMAC. (NA Mohamad Zambri et al., 2025) examined the significant importance of ForkMatic (automated railed forklift). (CT You et al., 2025) investigated logistics operators' satisfaction with Automated Storage and Retrieval Systems in the Logistics Industry.

In this order, Automated truck loading system (ATLS) has become widely used in the material handling industry to refer to the automation of loading or unloading trucks and trailers with product, whether it is on or without pallets, slip sheets, racks, or containers. Automated Guided Vehicle Systems (AGV) or engineered conveyor belt systems that are integrated into vehicles are used to automate the shipping, receiving, and logistics processes. The motivation to study ATLS arises from the growing demand for faster, safer, and more cost-efficient supply chain operations in an increasingly competitive global market. Traditional forklift-based loading systems are still widely practiced; however, they are labor-intensive, time-consuming, and vulnerable to human error and operational delays. In contrast, ATLS has the potential to significantly reduce lead time, minimize dependence on manual labor, and enhance overall supply chain responsiveness.

To the best of our knowledge, the majority of the existing literature has predominantly focused on the use of forklifts and manual processes for loading and unloading goods in warehouses, particularly within the context of traditional inventory processes. There exists a research gap which does not consider the advanced technologies beyond traditional supply chain processes. Moreover, lead time plays a crucial role in ensuring the efficiency and responsiveness of business operations. Here, lead-time consists of the production time, loading and unloading, transportation time, and in-transit time. Therefore, research on supply chain models that consider lead time in the context of advanced technologies is essential for achieving lean supply chain. Most studies have examined solely the use of forklifts and manual processes in the production inventory models for transporting the products. But, automated truck loading systems technology has also significantly streamlined logistics operations, enhanced safety, and offered a high return on investment through increased throughput and reduced operational costs. So, in this study, a non-linear supply chain model considering lead time, which is modeled as a function of the production time, loading and unloading time, transportation time, and in-transit time is scrutinized in the context of two systems, namely forklifts and automated truck loading systems technology. The novelty of this work lies in developing a non-linear lean supply chain model that explicitly incorporates ATLS alongside forklift systems for comparative analysis, while modeling lead time comprehensively by considering production, loading/unloading, transportation, and in-transit times, and introducing single-valued trapezoidal neutrosophic fuzzy parameters to realistically capture uncertainty in supply chain operations.

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 $-0 \le T_{\tilde{A}^N}(x) + I_{\tilde{A}^N}(x) + F_{\tilde{A}^N}(x) \le 3^+$ 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:

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

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

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

Mathematical Model

A non-linear sustainable supply chain model considering lead-time, which consists of production time, loading and unloading time, transportation time, and in-transit time, is formulated and solved analytically. The model is solved in the context of two methods, namely (i) Automated truck loading systems technology, (ii) Forklift loading system. To address real-life uncertainties, the model incorporates single-valued trapezoidal Neutrosophic fuzzy parameters. The Lagrangian method is used to obtain the optimal solution of the problem. Notations and Assumptions which are used to formulate the proposed model are given below.

Notation

Q	Lot size of the buyer (units)
P	Vendor's production level (units/year)
w	Weight of a product (lbs./unit)
c_f	Forklift load capacity (lbs.)
d_f	Distance from the shipping and receiving facilities to a truck (miles)
v_f	Forklift traveling speed (mph)
ρ	Distance between the two parties
v_t	Average truck speed (mph)
t_s	In-transit time (years)
λ	Conveyor speed
μ	Maximum load

Assumptions

- A single vendor-buyer system for a single item, with freight forwarding services, exists.
- The demand is assumed to be normally distributed with a mean and standard deviation.
- The vendor produces the product with a limited production level which is assumed to be higher than the buyer's demand.
- The product will be delivered to the buyer in each shipment. The delivery process is done with freight forwarding services. The freight provides a shuttle service (pick-up), and the product will be collected by the freight and shipped to the buyer.
- The linear distance is assumed as the total distance between the parties.
- The lead-time consists of the production time, loading

and unloading, transportation time, and in-transit time.

- For loading and unloading activities, an automated truck loading system was considered that conserves energy, in order to transition to a more environmentally friendly manufacturing system.
- The forklift loading system was also considered for loading and unloading activities to compare it with the automated truck loading system solutions.

Supply chain model with automated truck loading system

A single vendor-buyer system for a single item, with freight forwarding services, exists. The product will be delivered to the buyer in each shipment. The delivery process is carried out using freight forwarding services. The first step occurs when the buyer orders goods from the vendor, with a fixed order cost and lot size. Subsequently, the vendor manufactures a batch size with a limited production level. The freight will collect and deliver the product to the buyer. An automated truck loading system was incorporated for loading and unloading activities, which reduces lead time. The product will be unloaded from the truck to the in-transit warehouse. The loading and unloading activities will be the same for the buyer. Next, the entire lot from the vendor will be stored in the in-transit warehouse during the in-transit time. Transportation time by a truck will be calculated, which includes the speed of the truck and total distance. The lead time consists of production time, loading time, unloading time, transportation time, and in-transit time.

Production time is given by

$$PT(Q) = \frac{Q}{P}$$

Loading time is measured when the products are loaded from the vendor warehouse to the truck and from the in-transit warehouse to the truck. Unloading time occurs when the products are unloaded from the truck to the in-transit warehouse and from the truck to the buyer warehouse. For loading and unloading activities, an automated truck loading system was used. Loading and unloading time is given by

$$LUT_1 = \frac{d_f w}{\mu\lambda}$$

The lot is delivered by the freight forwarding truck. The transportation time by a truck, including the average truck speed (v_t) in mph and the total distance between the two parties, is given by $\rho = (2d_v + d_b)$ where (d_v) is the vendor's distance to the freight (miles), (d_b) is the freight's distance to the buyer (miles). Hence, the transportation time is given by:

$$TT = \frac{\rho}{v_t}$$

The entire lot is delivered and will be stored in the in-transit warehouse. Therefore, the in-transit time is given by

$$IT = t_s$$

Therefore, the total lead time, incorporating automated truck loading system technology, is given by

$$L(Q_1) = \frac{Q}{P} + \frac{d_f w}{\mu\lambda} + \frac{\rho}{v_t} + t_s \quad (2.1)$$

Supply chain model with forklift loading system

The freight forwarding services of the supply chain under consideration consist of a single vendor and a single buyer. The vendor manufactures a batch size with a limited production level. The product will be loaded from the shipping and receiving area to a truck by a forklift. For loading and unloading activities, the same forklift is used. The forklift load capacity is given as (c_f) in lbs and the forklift traveling speed for load and unload is given as (v_f) in mph. The weight of a product is given as w in lbs/unit. The distance from the shipping and receiving facilities to the truck, is given by (d_f) in miles.

Hence, the loading and unloading times occur 4 times and are given by:

$$LUT_2 = \frac{4Qwd_f}{c_f v_f}$$

Therefore, the total lead time incorporated with an automated truck loading system technology is given by

$$L(Q_2) = \frac{Q}{P} + \frac{4Qwd_f}{c_f v_f} + \frac{\rho}{v_t} + t_s \quad (2.2)$$

Alternatively, it can be rewritten as:

$$L(Q_2) = \frac{Q(c_f v_f + 4wd_f)}{Pc_f v_f} + \frac{\rho}{v_t} + t_s$$

Result

This study provides a numerical example to examine how automated truck loading system technology reduces the total lead time when compared to the forklift loading system. To show the efficiency of the proposed model the following numerical example is illustrated with the prescribed parameters as given below.

Parameters

Production rate $p = 60000 unis / year$

Order quantity $Q = 1371.18 units$

Weight of a unit part $w = 22 lbs / unit$

Distance from Vendor to freight $d_v = 50 miles$

Distance from freight to buyer $d_b = 600 miles$

Speed average of truck $v_t = 20 miles / hour$

Transit time $t_s = 1 day$

Maximum load $\mu = 0.9 lbs$

Conveyor speed $\lambda = 1 meter / \sec$

Forklift load capacity $c_f = 3300 lbs$

Distance from shipping and receiving facilities to truck $d_f = 0.015 miles$

Forklift travelling speed $v_f = 6 miles / hour$

Using the equation (2.1), the total lead time incorporated with an automated truck loading system is given by

$$L(Q_1) = 5.834 days$$

Using the equation (2.2), the total lead time incorporated without a forklift loading system is given by

$$L(Q_2) = 10.46 days$$

The Table 1 shows the efficiency of the suggested paradigm.

Discussion

The Previous research has explored the impact of forklifts for loading and unloading activities on traditional inventory processes, with much of the focus on green investments aimed at reducing emissions in supply chains. (F de Lima Nunes et al., 2024) developed a Structural Equation Model for evaluation of forklift management through an analysis in Brazilian warehouses. (DS Bhalerao et al., 2025) investigated the design analysis of manual forklift and suggested that forklift system can be used as an alternative to costly material handling machines. Most researchers overlooked the importance of lead time since it plays a vital role in the supply chain, directly impacting efficiency and customer satisfaction. There exists a research gap which does not consider significance of advanced technological systems in the context of lead time in the traditional process of the supply chain. The novelty of this work is that lead time has been considered on different aspects of the supply chain along with the automated truck loading system technology and forklift loading system. This study analyzes a non-linear supply chain model that accounts for lead time which consists of transportation, loading and unloading activities, all within the framework of a fuzzy environment.

Conclusion

This study develops a non-linear lean supply chain model for a single vendor–buyer system dealing with a single item, integrating freight forwarding services while explicitly considering both Automated Truck Loading System (ATLS) and forklift-based loading methods. Unlike most prior works, lead time here is modeled holistically as a function of production, loading/unloading, transportation, and in-transit delays. By incorporating ATLS technology into the framework, the model demonstrates substantial reductions in total lead time, thereby enhancing efficiency and responsiveness across the supply chain. To address uncertainties inherent in real-world operations, single-valued trapezoidal Neutrosophic fuzzy parameters are introduced, ensuring greater robustness and adaptability. The Lagrangian method is employed to obtain the optimal solution, and numerical illustrations validate the effectiveness of the proposed approach. Despite its contributions, this study has certain limitations. It focuses on a single vendor–buyer setup with a single product, which may restrict its applicability to larger, more complex networks. Future research can further enrich this work in several directions. First, the model can be extended to multi-retailer and multi-echelon supply chains, enabling broader applicability in complex distribution networks. Second, sustainability-oriented parameters—such as carbon emissions, fuel consumption, and energy optimization—can be incorporated to align with global green supply chain practices. Finally, integrating other advanced automation technologies, such as robotic handling systems and AI-driven scheduling, can further reduce inefficiencies and open new avenues for real-time, data-driven supply chain optimization.

Table 1: Comparison of the total lead time with Automated truck loading system and Forklift loading system

Total lead time of the supply chain	With Automated truck loading system	Without Forklift loading system
	5.834 days	10. 46 days

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