Application of Fuzzy Set Theory in Inventory Control Optimization of E-commerce Enterprises

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Abstract. With the rapid development of mobile internet technologies, the e-commerce industry has undergone profound structural and operational transformations. To achieve sustainable growth, e-commerce enterprises must enhance their market competitiveness, improve operational efficiency, and deliver high-quality services. In this context, effective inventory control has become a critical factor in maintaining the core competitiveness of e-commerce enterprises. This study is grounded in fuzzy set theory and systematically identifies key fuzzy parameters inherent in inventory management scenarios, followed by the construction of corresponding fuzzy operational expressions. Based on the practical characteristics of inventory management in e-commerce enterprises, a multi-parameter fuzzy inventory model is developed under the constraint of zero stockouts. Furthermore, a specific category of materials from an e-commerce enterprise is selected for empirical case analysis to validate the proposed model. The results indicate that the inventory costs estimated using the fuzzy inventory model are significantly lower than the actual inventory costs observed in enterprise operations, thereby demonstrating the effectiveness and practical applicability of the proposed approach.

Keywords: E-commerce enterprises; Inventory management; Fuzzy set theory

1 Introduction

E-commerce is a revolutionary business activity that not only changes the business model but also reshapes consumers' traditional shopping patterns. With the rapid development of e-commerce, people's understanding of information dissemination, entertainment consumption, and commodity buying and selling has gradually changed, which has also driven changes in work scenarios and market forms. Currently, the e-commerce market is gradually developing into a new type of transaction scenario, providing efficient and convenient transaction services for both buyers and sellers. Although the e-commerce market is still in the early stages of development and evolution, its core goal is still to facilitate successful transactions between buyers and sellers;

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However, as the Internet continues to penetrate deeply into all areas of daily life, the traditional passive transaction model will be replaced by a new model with stronger interaction, making e-commerce more closely linked with people's lives and business activities.

At present, e-commerce in China is moving from a high-speed development stage to a mature stage, deeply penetrating into areas such as consumption and circulation, and becoming a new growth point to promote national economic and social development. Supported by core links such as logistics, information flow, and supply chain, e-commerce has gradually formed a new type of industrial cluster. With the rise of new retail models, enterprises in various industries are accelerating their optimization and upgrading pace, and the integration of online and offline is constantly deepening, making the overall competition in the industry increasingly fierce. This poses higher requirements for the management capabilities and inventory control level of e-commerce enterprises. It is particularly important to quickly respond to customer demand, reduce stock shortages, and control inventory within a reasonable range. Inventory control, as a key node in the sales and procurement supply chain of e-commerce enterprises, plays a crucial role in the normal operation and sustainable development of the enterprise. With the rapid development of mobile Internet and Internet information technology, the industry has put forward a series of higher-level management requirements for inventory control, that is, inventory control is the management and control of commodity circulation quantity in the operation activities of enterprises, so that the inventory structure and quantity of enterprises are always kept within a reasonable range, and timely adjust the inventory scale according to the dynamic changes in sales to avoid overstock of inventory or shortage of goods. The classical deterministic Economic Order Quantity (EOQ) model has established a robust theoretical foundation for inventory management; however, its core premise relies on the assumption that parameters such as demand quantity, ordering cost, and holding cost are deterministic values. This stringent mathematical assumption confronts a severe practical paradox in highly uncertain e-commerce environments: e-commerce demand exhibits intense nonlinear fluctuations driven by promotional activities, social media sentiment, and seasonal transitions, while logistics rates, warehousing capital costs, and payment channel fees demonstrate significant dynamic fuzziness that defies precise numerical characterization. Constrained by its inability to effectively represent such non-probabilistic uncertainty, the traditional EOQ model frequently engenders ordering strategy deviations in practical applications, consequently resulting in either inventory overstock or stockout losses. Fuzzy Set Theory provides a direct mathematical apparatus for transcending this limitation. By introducing membership functions, this theory quantifies fuzzy demand rates and cost parameters as possibility distributions, thereby constructing EOQ extension models based on fuzzy numbers. This methodological approach effectively addresses data volatility and imprecision in e-commerce contexts, offering a more adaptable scientific basis for inventory management scenarios characterized by complexity and dynamic variability in electronic commerce.

F. When W. Harris explored how cash flow is maintained in 1915, he proposed the famous Economic Order Quantity (EOQ) model based on this, which was improved by Wilson in 1934. Feng J et al. proposed a demand prediction method based on SSA (the sparrow search algorithm) - BPNN (back-propagation neural network) to study the inventory management of a cross-border e-commerce company [1]. Maity et al. further extended the existing economic order quantity model and considered the inventory decision-making problem that needs to be addressed under fuzzy premise conditions [2]. Matteo et al. believe that inventory turnover refers to the ratio between a company's sales cost and average inventory cost over a certain period of time [3]. This theory refers to the seller's requirements for the turnover speed of their inventory products. This prompts every enterprise producing goods to improve the efficiency of resource utilization, thereby further enhancing the management level of the enterprise and the response speed to the commodity market. Inventory turnover rate is of great significance to every enterprise, as it demonstrates comprehensive indicators such as a company's cash collection ability. Muhammad et al. found through field visits that employees have clear job responsibilities and are aware of their real-time situation and performance [4]. It can enhance employees' work enthusiasm and improve the inventory control management level. Dellino et al. used the ARIMA model to predict future demand, and comprehensively considered its prediction results with other influencing factors such as price, inventory, stockout possibility, product quality, etc. They proposed a supply chain decision support system suitable for fresh and perishable products. After testing, the results showed that the system developed feasible procurement plans within a reasonable and acceptable prediction error range [5]. During the operation of enterprises, high inventory will increase storage costs, occupy a large amount of working capital, and reduce the efficiency of capital utilization; If the inventory is too low, it is easy to experience stockouts, which in turn reduces customer satisfaction and affects overall service quality. For N outdoor e-commerce enterprises, how to scientifically manage inventory during the sales process, maintain inventory within a reasonable range, and quickly respond to and meet customer needs is a key issue that they must address and solve at this stage [6-9]. However, in many cases, due to the lack of sufficient information in inventory control of e-commerce enterprises, coupled with the complex and volatile production process, it is difficult to accurately predict the demand quantity using probability theory, and one can only have a vague understanding of possible demand changes. In summary, fuzzy mathematics can effectively express inventory control problems for various possibilities presented in uncertain environments. However, inventory management in e-commerce enterprises has its own uniqueness. Based on this, fuzzy set theory is adopted to explore inventory control problems in e-commerce enterprises in uncertain environments, in order to establish a fuzzy parameter inventory model and optimize its solution.

2 Fuzzy Set Theory

2.1 Fuzzy Set Mathematical Expression

In the inventory management of e-commerce enterprises, the enormous quantities and wide variety of required materials, together with the intrinsic complexity of inventory control, significant spatial–temporal disparities, machine breakdowns, order cancellations, and a host of other uncertain factors, jointly amplify the ambiguity inherent in decision-making under uncertainty[10-13]. This ambiguity becomes especially pronounced when firms forecast next year's demand at the end of the fiscal year. For instance, the projected demand for a particular item may be stated as "about 200 units." Here, 200 is a fuzzy number: it might be 190 or 210, with a minimum plausible value of 150 and a maximum of 250. The corresponding range can be represented by the interval [150, 250]. Such a fuzzy demand implies that the interval itself constitutes a fuzzy set, denoted by D. Any value within this set is a potential realization of future demand, but the associated degrees of credibility differ; values near the center are more plausible, whereas those at the extremes are less so. To quantify these likelihoods, we introduce a mapping. $\phi_x : D \to [0,\ 1]$, where $x \in [L,\ U] = D\ (L < U)$ and $\phi_x \in [0,\ 1]$. For every element in D, this mapping assigns a unique value in [0, 1], thereby defining a fuzzy subset ϕ_x of D, referred to as the membership function of D, or equivalently, the membership grade of x in D. A membership value $\phi_x = 0.8$ indicates an 80 % possibility, whereas φ(x) $\phi_x = 0.5$ indicates a 50 % possibility. In inventory-control optimization, the membership function is commonly represented by a trapezoidal distribution, which is classified into three types: left-skewed, right-skewed, and middle-shaped. The present study adopts the middle-shaped trapezoidal distribution, whose membership function is formulated as follows:

$$\phi_x = \begin{cases} 0, & x < a \\ (x-a)/(b-a), & a \le x < b \\ 1, & b \le x < c \\ (d-x)/(d-c), & c \le x < d \\ 0, & x \ge d \end{cases}$$

The image is shown in Figure 1.

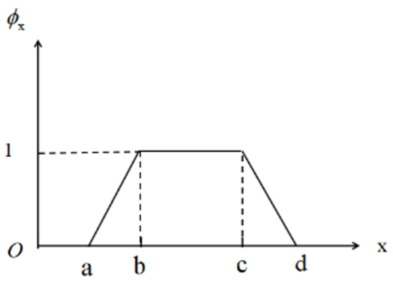

Fig. 1. Graph of trapezoidal distribution membership function

Once the trapezoidal fuzzy number $D = [a,b,c,d]$ has been specified, any comparison of fuzzy magnitudes requires a defuzzification procedure that establishes an unambiguous ordering. This paper adopts the graded mean integration representation (GMIR) method for this purpose [14]. For a trapezoidal fuzzy number $D = [a,b,c,d]$, the GMIR defuzzied value is expressed as

$$P(x)=\int_0^1 h\left[\frac{a+d+(b-a-d+c)}{2}\right]dh/\int_0^1 hdh \\ =(a+2b+2c+d)/6 \tag{1}$$

Among them, h represents the membership degree at any level, with a value range of $h \in (0,\ 1]$.

2.2 Fuzzy Operation Rule

Trapezoidal fuzzy numbers support the four fundamental arithmetic operations. Let two trapezoidal fuzzy numbers be $D_1=[x_1,x_2,x_3,x_4]$, $D_2=[y_1,y_2,y_3,y_4]$.

Their operational rules are defined as follows:

1) Fuzzy Addition: $D_1+D_2=[x_1+y_1,\ x_2+y_2,\ x_3+y_3,\ x_4+y_4]$;

2) Fuzzy multiplication: $D_1 \times D_2=[c_1,c_2,c_3,c_4]$, where $c_1=Min\{x_i y_j\}(i,\ j=1,4)$, $c_2=Min\{x_i y_j\}(i,j=2,3)$, $c_3=Max\{x_i y_j\}(i,j=2,3)$, $c_4=Max\{x_i y_j\}(i,j=1,4)$. When $x_i \geq 0$ and $y_j \geq 0$ for all $i,j \in \{1,2,3,4\}$, the operation simplifies to $D_1 \times D_2=[x_1y_1,\ x_2y_2,\ x_3y_3,\ x_4y_4]$

3) Fuzzy subtraction: $D_1 - D_2=[x_1-y_4,x_2-y_3,x_3-y_2,x_4-y_1]$;

4) Fuzzy division: $D_1/D_2=[d_1,\ d_2,d_3,\ d_4]$, where $d_1=Min\{x_i/y_j\}(i,j=1,4)$, $d_2=Min\{x_i/y_j\}(i,j=2,3)$, $d_3=Max\{x_i/y_j\}(i,j=2,3)$, $d_4=Max\{x_i/y_j\}(i,j=1,4)$. When $x_i \geq 0$ and $y_j \geq 0$ for all $i,j \in \{1,2,3,4\}$, the operation reduces to $D_1/D_2=[x_1/y_4,\ x_2/y_3,\ x_3/y_2,\ x_4/y_1]$;

5) Let $\alpha \in R$, When $\alpha \geq 0$, define $\alpha \times D=[\alpha x_1,\alpha x_2,\alpha x_3,\alpha x_4]$;

When $\alpha < 0$, define $\alpha \times D=[\alpha x_4,\alpha x_3,\alpha x_2,\alpha x_1]$.

3 Optimization Model for Inventory Control in E-Commerce Enterprises

3.1 Problem Statement

Taking the inventory management of a certain type of material in an e-commerce enterprise as an example, it was found through research that the e-commerce enterprise had the highest number of materials with a capital occupation of less than $10000, accounting for more than 80% of the total amount of materials in the e-commerce enterprise. This type of material procurement is relatively easy, but the demand for materials is great, and the demand quantity is unstable, which is a fuzzy number. At the same time, it is assumed that the ordering cost and storage cost are also fuzzy numbers. This article explores the use of fuzzy set theory to establish a multi-fuzzy mathematical inventory model in the case of uncertain demand quantity, ordering cost, and storage cost, in order to optimize the inventory control problem of certain materials in e-commerce enterprises.

Make the following assumptions:

1) Orders arrive instantly and replenish inventory.

2) The consumption situation is directly proportional to the quantity of a certain type of material.

3.2 Establishment and Optimization of Multi-Fuzzy Inventory Model

Regarding the inventory issue of materials in e-commerce enterprises, the following symbols are agreed upon:

D : Denotes the quantity of products required for inventory, i.e., $D=[d_1,d_2,d_3,d_4]$.

C^o : Denotes the unit ordering cost of materials, i.e., $C^o=[c_1^o,c_2^o,c_3^o,c_4^o,]$.

C^h : Denotes the unit holding cost of materials, i.e., $C^h=[c_1^h,c_2^h,c_3^h,c_4^h,]$.

Q : Denotes the order quantity, generally a deterministic value.

M : Denotes the transportation cost per shipment, generally a deterministic value.

In summary, the total cost of inventory includes three expenses: ordering fees, storage fees, and transportation fees. namely

$$C=C^oD/Q+C^hQ/2+MD/Q \tag{2}$$

In the expression, the first term represents the ordering cost, defined as the product of the unit ordering cost C^o and the number of orders D/Q ; the middle term is the holding cost, defined as the product of the unit holding cost C^h and the average inventory level $Q/2$ (This paper adopts $Q/2$ to denote the average inventory); the last term is the transportation cost, defined as the product of the fixed transportation cost M and the number of orders D/Q .

By substituting the aforementioned parameters $D=[d_1,d_2,d_3,d_4]$, $C^o=[c_1^o,c_2^o,c_3^o,c_4^o,]$ and $C^h=[c_1^h,c_2^h,c_3^h,c_4^h,]$ into Equation (2) and employing the rules of fuzzy arithmetic, the total inventory cost can be derived as:

$$C=\left[\frac{c_1^od_1}{Q}+\frac{c_1^hQ}{2}+\frac{Md_1}{Q},\ \frac{c_2^od_2}{Q}+\frac{c_2^hQ}{2}+\frac{Md_2}{Q},\frac{c_3^od_3}{Q}+\frac{c_3^hQ}{2}+\frac{Md_3}{Q},\ \frac{c_4^od_4}{Q}+\frac{c_4^hQ}{2}+\frac{Md_4}{Q}\right] \tag{3}$$

Defuzzifying Eq. (3) by means of Eq. (1) yields the crisp total inventory cost

$$P(C)=\frac{1}{6}\left[\frac{c_1^od_1}{Q}+\frac{c_1^hQ}{2}+\frac{Md_1}{Q}+2\left(\frac{c_2^od_2}{Q}+\frac{c_2^hQ}{2}+\frac{Md_2}{Q}\right)+2\left(\frac{c_3^od_3}{Q}+\frac{c_3^hQ}{2}+\frac{Md_3}{Q}\right)+\frac{c_4^od_4}{Q}+\frac{c_4^hQ}{2}+\frac{Md_4}{Q}\right] \tag{4}$$

To determine the optimal economic order quantity Q^* under the premise of minimizing the total cost, we set the partial derivative of the cost function with respect to Q to zero: $\frac{\partial P(C)}{\partial Q} = 0$.

Solving this equation yields the optimal economic order quantity Q^*, namely:

$$Q^* = \left[\frac{2\left(c_1^o d_1 + 2c_2^o d_2 + 2c_3^o d_3 + c_4^o d_4\right) + 2M\left(d_1 + 2d_2 + 2d_3 + d_4\right)}{c_1^h + 2c_2^h + 2c_3^h + c_4^h} \right]^{1/2} \tag{5}$$

4 Case Analysis

A Chinese e-commerce company A focuses on the operation of small household goods, with its headquarters located in Yiwu City, Zhejiang Province. The company was founded in 2003 and has undergone more than ten years of continuous development, successfully transforming it from a workshop-style production factory to a medium-sized enterprise with an annual turnover of 100 million US dollars. At present, the company has direct offline stores in Qingdao, Nanjing, and Hangzhou, and has two small-scale production factories in Yiwu and Xuzhou. The enterprise has established a full chain independent operation system from product design to market promotion and belongs to a typical self-produced and self-sold household goods enterprise. In the past three years, the company's average annual sales have remained stable at $100 million, placing it in a leading position in the domestic home small commodity industry. In terms of marketing channel construction, the company has a clear online business layout, not only opening an official flagship store on the Tmall platform, but also relying on the Alibaba platform to carry out small commodity wholesale business, selling self-produced finished products in bulk to downstream retailers. Wholesale business is also a core component of the company's annual sales revenue. From the perspective of product structure, the company's main business focuses on three categories of products, namely storage boxes, water bottles, and hand warmers. In the past three years, the annual sales of these three core products have accounted for over 90% of the company's total annual sales, making them the main pillars of the company's revenue. In recent years, with the sustained strong market demand for new rechargeable hand warmers, multifunctional storage boxes, and other products, coupled with the company's high emphasis on product quality management and continuous improvement of product quality control level, its product market share has significantly increased. The three main products of the company belong to mature categories with stable market demand. However, due to the characteristics of the enterprise's business model, the company uses online stores as its core customer source channel, and the geographical distribution of customers is extremely wide. In addition, factors such as the reputation level of e-commerce platform stores and historical customer evaluations have a significant impact on product sales volume, resulting in significant fluctuations in the company's product sales volume. Further analysis shows that business managers lack systematic and scientific methods to support customer demand forecasting. They simply calculate the average value based on previous sales data provided by e-commerce platforms as the basis for demand forecasting and production planning. This extensive forecasting method often leads to excessive production inventory or insufficient inventory supply in enterprises, resulting in significant economic losses annually due to imbalanced inventory management. It can be seen that the accuracy of demand forecasting is directly related to the rationality and effectiveness of inventory management in enterprises, and has a crucial impact on the operational efficiency of enterprises.

To verify the feasibility of the multi-fuzzy parameter inventory model, validation was conducted based on the data of water cup material inbound and outbound from e-commerce company A. After investigation, it was found that these water cup materials have been stored for a long time, and the bulk of the material procurement is large. The inconsistency between material procurement and the production department's demand has led to a large backlog of inventory. From January 1, 2025, to October 31, 2025, the incoming quantity is 5012 pieces, and the outgoing quantity (production demand quantity) is 4425 pieces. Assuming a one-time purchase is completed. Assuming that the order placement fee is approximately $300 per time, the unit storage cost is about $12 per month, and the transportation cost is a fixed value, which is $880 per time.

Therefore, the actual expenses of the e-commerce enterprise can be calculated as follows:

Ordering cost: 300

Average inventory level: 5012/2=2506

Holding cost: 2506×12=30072

Transportation cost: 880

Total cost: 300+30072+880=31252

The fuzzy mathematical inventory model is then applied for optimization and solution. Based on the reasonable forecast from the production department at the end of 2024, we can define:

$D = [4200,\ 4300,\ 4350,\ 4600]$, $C^{o} = [295, 300, 305, 310]$,

$C^{h} = [11.5,\ 12.0,\ 12.5,\ 13.0]$,

Substituting these values into Equation (5), we obtain $Q^{*} \approx 998$, which means the optimal economic order quantity is 998 units. The optimized costs under this quantity are as follows:

Number of procurement orders: 4425÷998≈4.43 times, which is rounded up to 5 times.

Ordering cost: 300×5=1500

Holding cost: 998/2×12=5988

Transportation cost: 880×5=4400

Total cost: 1500+5988+4410=11898

The total cost calculated by the optimized fuzzy inventory model is 19354 lower than the actual cost, by 31252-11898. Although the ordering and transportation costs have increased, the inventory storage cost has significantly decreased, from 30072 to 5988, a decrease of 80.09%. The total inventory cost has decreased from 31252 to 11898, a decrease of 61.93%.

If the demand quantity is fuzzy while the unit ordering cost and unit holding cost are deterministic, i.e., $D=[4200,\ 4300,\ 4350,\ 4600]$, $C^{o}=300$, $C^{h}=12$, $M=880$ Substituting these values into Equation (5) yields $Q^{*}\approx 992$.

If all conditions are deterministic, i.e., D=4425, $C^{o}=300$, $C^{h}=12$, and M=880, substituting these values into Equation (5) yields $Q^{*}\approx 989$. This indicates that any change in the fuzzy parameters will affect the optimal economic order quantity.

5 Conclusions

Due to the complexity and variability of e-commerce enterprises, this article applies mathematical fuzzy set theory to handle inventory management. Taking water cup materials as an example, a trapezoidal fuzzy inventory model is constructed. Studied the ordering quantity problem under fuzzy environment with fixed transportation costs, including demand quantity, unit ordering cost, and unit storage cost. This article studies the inventory control problem of e-commerce enterprises with multiple fuzzy parameters. If a certain parameter has sufficient conditions to clarify its value, then it is a definite value. If all conditions are sufficient, then all parameters belong to deterministic values, and this becomes the ordering quantity problem under deterministic conditions. Although the actual environment for inventory control in e-commerce enterprises is vague, the ultimate decision is to determine the optimal one. The example calculation results show that applying trapezoidal fuzzy set mathematical theory to solve inventory management problems in e-commerce enterprises is reasonable and feasible, and can effectively control funds and reduce inventory costs.

Inventory control is a very broad field, and due to my limited knowledge and energy, there are still many areas that need further research in the future.In the next research, it can be proposed to combine the fuzzy model with machine learning for dynamic parameter estimation or to extend it to multi-level inventory systems. Due to incomplete historical data of e-commerce company A, sufficient supporting evidence cannot be provided. Currently, only comparative analysis can be used to determine a prediction plan that is suitable for the current scenario, and continuous optimization of demand forecasting and ordering management methods is needed in subsequent research. Inventory control work involves multiple links and dimensions. In the future, it is necessary to continuously strengthen professional knowledge learning, actively explore various methods and means of inventory control, make up for the shortcomings of our own work, and thus improve the overall level of inventory control in e-commerce enterprises, providing strong guarantees for the stable operation of the enterprise.

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