Loss-Averse Aviation Enterprises' Procurement Decisions on Spare Parts

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Abstract: As the aviation industry thrives, the market for aviation spare parts is witnessing unprecedented growth. The procurement of aviation spare parts holds paramount importance for the operational and managerial efficacy of aviation enterprises. Ensuring scientific, rational, and precise procurement of these aviation spare parts constitutes a pivotal strategy for aviation enterprises to effectively manage operational costs and enhance efficiency. The formulation of procurement strategies is critically affected by losses experienced in aviation spare parts procurement. Given the substantial variation in loss aversion among different aviation enterprises, studying the decision-making patterns in aviation spare parts procurement under diverse levels of loss aversion assumes considerable theoretical significance. This paper employs prospect theory and considers the scenario where the budget cost aligns with the purchasing cost, serving as the psychological break-even point for aviation spare parts procurement. This paper introduces loss aversion theory into the research on aviation spare parts procurement. This paper investigates the correlation between aviation spare parts procurement quantity and its influencing factors, and conducts a sensitivity analysis of key variables. Based on the analytical results, insights and suggestions for procurement practices are proposed. These innovations are shown to contribute to the development of loss aversion theory and decision-making procurement, thereby offering valuable guidance for aviation spare parts procurement.

Keywords: Loss-Aversion; Procurement; Aviation Spare Parts

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1 Introduction

In the context of the rapidly expanding and highly competitive global aviation industry, procurement decisions for aviation spare parts have become a pivotal element in the operational management strategies of both aviation enterprises and aircraft manufacturers. According to statistical data, the total market value of aviation spare parts has exceeded 50 billion US dollars [5]. In practice, procurement and inventory management are inherently interconnected. With the ongoing advancements in aviation technology and the continuous expansion of fleet sizes, the ability to conduct efficient and precise procurement of spare parts is not only crucial for cost control and profitability within aviation enterprises but also serves as a key metric for evaluating the effectiveness of their supply chain management.

Owing to the sporadic nature of the demand for aircraft maintenance parts, aviation enterprises found it difficult to forecast the demand for parts [6]. Shortage or backlog of

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aviation spare parts can result in financial losses and reduced operational capability. Researchers recognize the significance of investigating the procurement and management of aviation spare parts and have undertaken extensive studies and practical applications in this field over the years.

The forecasting of aviation spare parts demand constitutes a critical component of aviation spare parts procurement management. The traditional methods of spare parts demand forecasting research mainly focus on time series analysis method, regression analysis method and machine learning method.

The time series analysis method aims to forecast the demand for aviation spare parts by utilizing historical time series data on relevant purchases. Willemain et al. used the exponential smoothing method to forecast the demand for aviation spare parts by analyzing the distribution of spare parts life characteristics [22]; Ghobbar and Friend and Regattieri et al. validated the effectiveness of the weighted moving average method for aviation spare parts demand forecasting, demonstrating its reliability through comparative testing of multiple techniques and historical data validation [4, 17].

Regression analysis method is a method of determining the relationship between spare parts consumption and the influencing variables by analyzing the relationship between the demand for aviation spare parts and a number of influencing factors, establishing the relationship between the target input and output variables. Cao et al. demonstrated that the negative binomial regression model is effective for predicting high-priced repairable LRU (HR-LRU) parts [2]. Guo et al. proposed a regression analysis combination method of repairable parts to achieve the spare parts demand forecast [7]; Their results indicated that the model is better than individual forecasting models and direct combination approaches, which to a certain extent proves that the regression model can solve the forecasting problem affected by multiple factors. Yang et al. applied in regression model to predict the consumption of spare parts [26].

The actual demand for spare parts occurs without regularity. Ghobbar and Friend noted that the intermittent demand for aviation spare parts is often characterized by long intervals between demand occurrences, the presence of a high frequency of zero values in the demand data, and the irregularity of demand occurrences [4]. In recent years, with the rise of artificial intelligence, machine learning has become a popular method for demand forecasting research of aviation spare parts. Choi and Suh designed a systematic method incorporating data mining techniques to predict military aviation spare parts requirements more accurately, considering spare parts management characteristics [3]; Their study identified the random forest technique as the most effective. Lee et al. employed machine learning models to enhance the prediction accuracy of aircraft maintenance parts and evaluated their model performance through changes in hit rates [12]. Lucht et al. used data as a basis for forecasting demand for aviation spare parts in conjunction with machine learning [13]. Shafi et al. demonstrated the effectiveness of an artificial neural network model in predicting safety-critical aviation spare parts [19].

Generally, aviation enterprises estimate the demand for spare parts by analyzing data such as aircraft flight hours, aircraft utilization rates, and the lifespan of spare parts to determine the procurement quantities. However, the scope of factors considered in this process is relatively limited. In reality, the demand for aviation spare parts is influenced by a multitude of factors. The expansion of fleet size further increases the number of influencing factors, leading to a decline in the accuracy of demand forecasts. It is precisely due to the high uncertainty in their demand for aviation spare parts that determining the optimal procurement quantity becomes challenging. If the quantity of spare parts ordered exceeds the actual demand, it results in excess inventory and increased holding costs. Conversely, if the quantity procured falls short of the actual demand, it leads to shortage, incurring losses and higher replenishment cost. To minimize rising procurement costs and reduce unnecessary expenditures, it is essential to develop a rational procurement strategy and determine the optimal procurement quantity.

In traditional research on procurement decision-making problems, the assumption of absolute rationality of the procurement entity is a fundamental premise for constructing decision-making models. However, in real-world purchasing decisions, the behavioral preferences of companies also significantly influence the outcomes. Experimental economists have demonstrated that in uncertain environments, decision-makers are seldom neutral toward losses, with many exhibiting a preference for loss aversion [10, 20, 23-25].

This paper investigates how loss aversion preference in aviation enterprises influence their procurement decisions for spare parts. Loss aversion theory was first applied in the fields of psychology and economics. It was not until

2000 that Schweitzer and Cachon first applied the theory of loss aversion to supply chains [18]. Using the newsvendor model, they compared order quantities under loss-averse versus risk-neutral conditions, revealing a systematic decision bias: Actual procurement volumes consistently deviated from the model's theoretical optimum. Different products generate varying profits and costs. Buyers therefore develop purchasing strategies based on product profitability. The interesting thing is that when the product's profit is high, the actual purchase quantity is smaller than the optimal purchase quantity of the ideal newsvendor model, while when the profit is low, the actual purchase quantity is larger than the optimal purchasing quantity of the ideal newsvendor model. In order to explore this 'systematic decision bias', enhance practical relevance and better for the enterprise to provide theoretical guidance, many scholars have conducted a lot of research on this.

Pournader et al. proposed that different procurement subjects have different tolerance for losses, and their degree of loss aversion will have an important impact on procurement strategy [16]. Kahneman and Tversky established that loss-averse individuals prioritize avoiding losses over pursuing equivalent gains [11]; Wang and Webster demonstrated that when the shortage cost is large enough, the retailer's order quantity increases with the degree of loss aversion [20]. Ma et al. revealed that under supply uncertainty, loss-averse decision-makers tend to order larger quantities compared to stable supply conditions [14]. A company's purchasing strategy can be affected by a variety of factors, such as wholesale prices, retail prices, inventory costs, shortage costs, and various other factors. Some scholars have analyzed the factors that may influence procurement. Wang and Webster considered the effect of shortage price on the optimal purchase quantity and found that when the shortage cost is high, loss-averse newspaper vendors would order more newspapers than risk-neutral vendors [20]. The more loss-averse the vendor, the larger the optimal order quantity, and the factors of wholesale price and retail price were also considered in the study. Xu et al. investigated the optimal option purchase decision of loss-averse retailers under emergency replenishment conditions and without shortage costs [24]. Huang et al. found that as the newsboys is loss-averse, he or she prevents potential losses from possible oversupply by reducing order quantities [9]. To the best of our knowledge, there are no papers related to the study of purchasing decisions for aviation spare parts under loss-averse scenarios.

In the daily operational management of aviation enterprises, aviation spare parts procurement is subject to numerous uncertainties-including fluctuations in spot prices and variations in shortage cost-that may incur significant financial risks for aviation enterprises. (1) How does the loss aversion preferences influence aviation spare parts procurement decisions? (2) How should aviation enterprises adapt their strategies optimal procurement decisions? By analyzing procurement decision-making under loss aversion conditions, this paper provides theoretical and managerial insights to help aviation enterprises optimize their procurement strategies.

In addition, to better describe the factors influencing the decision-making behaviors of concerned enterprises, an overview of Kahneman and Tversky's prospect theory is provided. As defined in Kahneman and Tversky [11], the theoretical framework will not be reiterated in this paper.

Kahneman and Tversky pointed out that people's gains or losses are relative to a specific reference point, and changes in the reference point leading to changes in people's preferences [11]. Consider that different decision makers always have a standard of comparison or evaluation in mind when they view a loss. This reference point influences the decision maker's judgement and evaluation, so their view of the same matter may vary depending on the reference point. Wang and Wang investigated loss aversion purchasing strategies using quantity as a reference point [21]. Some scholars have chosen the capital preservation point as the profit reference point to facilitate calculations and analyses [1, 8]. The number and size of reference points have also been studied. Ma found that loss aversion ordering is usually smaller than risk neutrality, except when the profit reference point is large enough, the two order quantities are equal [15]. Zhou explained the decision bias in the newsboy model using two reference points [27].

As stated earlier, actual spare parts requirements are affected by a number of factors. In general, demand forecasting assumes that spare parts are always in 'as good as new' condition, but there are cases where repairable spare parts are reused, and their usage time, quality, and wear and tear are not the same as 'new', which results in an error between demand forecasting and actual demand. Therefore, it is inaccurate to determine the quantity of aviation spare parts to be purchased by forecasting demand.

The procurement process inherently ties up significant capital reserves. Emergency replenishment scenarios or excessive inventory redundancy impose substantial additional costs on airlines, rendering such outcomes counterproductive to operational efficiency. This necessitates the formulation of scientifically grounded procurement policies. In practical operations, procurement decisions demonstrate behavioral heterogeneity influenced by loss-averse preferences. Aviation enterprises exhibiting pronounced aversion to shortage costs may maintain inventory levels exceeding theoretically optimal quantities, while those prioritizing inventory cost might implement sub-optimal procurement strategies to minimize perceived financial losses.

The existing literature shows that buyers' purchase decisions often are different from the optimal procurement decision [18, 20, 23-25]. Therefore, we apply the loss aversion theory in the field of behavioral decision-making to the procurement of spare parts, and study the influence of aviation enterprises' loss avoidance behavior preference on the spare parts procurement strategy, so as to narrow the deviation between theoretical research and practical decision-making, and help aviation enterprise better formulate the procurement strategy of aviation spare parts.

In summary, while the existing literature has yielded extensive findings on loss aversion and procurement decision-making, research on procurement decisions for aviation spare parts under the framework of loss aversion theory remains understudied. In comparison with prior studies, the innovations and contributions of this research lie primarily in the following three aspects:

1) This study introduces loss aversion theory into the research on aviation spare parts procurement. While existing studies on aviation spare parts procurement have not yet explored the role of loss aversion in procurement decision-making, this paper applies loss aversion theory to the aviation procurement process. The aim is to narrow the divergence between theoretical frameworks and actual procurement decisions, thereby assisting aviation enterprises in formulating improved procurement strategies.
2) The relationship between procurement cost and budgeted cost is adopted as the reference point. We define the breakeven point as the procurement quantity at which procurement cost equals the budgeted cost. Scenarios where procurement cost exceeds the budgeted cost are regarded as losses, whereas those where procurement cost falls below the budgeted cost are considered gains. The selection of this reference point aligns with the practical context of aviation spare parts procurement, overcoming the conventional limitation of viewing any increase in procurement cost as a loss, thereby enabling a more precise quantification of losses and gains.
3) This study reveals the correlations among procurement quantity, the loss aversion coefficient, and budgeted cost under the loss aversion theory. The relationship between procurement quantity and the loss aversion coefficient is dynamic, asymmetric, and nonlinear; procurement quantity may either increase or decrease as the loss aversion coefficient rises. A similar complex relationship exists between procurement quantity and budgeted cost.

We believe that these innovations not only contribute to the development of loss aversion theory and procurement decision-making but also offer valuable insights for aviation spare parts procurement.

2 Model Formulation

We consider an aviation enterprise that purchases aviation spare parts from the supplier. The notation used in this paper is summarized in Table 1. Each year, the aviation enterprise will allocate a budget cost I to procure q units of spare parts at a price of w per piece to meet the actual demand for aviation spare parts D. Due to the uncertainty of the demand D, it is not possible to judge whether the purchased procurement volume q will be able to meet its actual demand. The following two scenarios occur:

Case 1: When the aviation spare parts demand D is less than the purchase quantity q, the purchase quantity q can meet the demand. Too much procurement of aviation spare parts will cause redundancy, which will increase the inventory cost. The aviation enterprise will be conditional on each other's borrowing of the aviation spare parts, which generates the price of the handling of the aviation spare parts t.

Case 2: When the demand for the aviation spare parts D is greater than the purchase quantity q, the purchase quantity q is unable to meet the demand. It must be purchased again. In this case, additional costs are incurred, which are collectively referred to as shortage costs s.

Without loss of generality, we make some assumptions regarding the shortage cost per unit s, the purchase price per unit w, the inventory price per unit v and the recycling price per unit t.

Assumption 1. The shortage cost per unit of spare parts is bigger than the sum of the purchase price per unit of spare parts and the inventory price per unit of spare parts, i.e. $s > w + v$.

Assumption 2. The sum of the purchase price per unit of spare parts and the inventory price per unit of spare parts is bigger than the recycling price per unit of spare parts, i.e. $w + v > t$.

Table 1 Basic Parameters in this Paper

Notation	Explanation
x	The random market demand
$f(\cdot)$	The probability density function
$F(\cdot)$	The cumulative distribution function
C	The actual procurement cost
d	The market demand
t	The recycling price per unit of spare parts
w	The purchase price per unit of spare parts
v	The inventory price per unit of spare parts
s	The shortage cost per unit of spare parts
q	The procurement/purchase quantity
β	The loss aversion coefficient
I	The budget cost

Most scholars study the optimal purchasing strategy of purchasers based on the method of expected profit maximization, while the profit of spare parts procurement cannot be directly quantified. This paper adopts the method based on expected cost minimization to study the optimal purchasing strategy.

Purchasing strategy based on traditional expected profit maximization is always different from the actual procurement decisions in reality. Some scholars have found that the reason may come from the loss aversion of the purchaser. In view of this, we integrate loss aversion theory into aviation spare parts procurement model.

For a loss-averse decision maker, it is necessary to determine whether the decision outcome is a gain or a loss based on the psychological reference point. Specifically, when the actual procurement cost is less than the psychological reference point, it is a gain for the aviation enterprises; when the actual procurement cost is greater than the psychological reference point, it is a loss for the aviation enterprises.

Based on the knowledge related to prospect theory, it is assumed that the budgeted cost of aviation enterprises purchases is I, Combining the classical loss aversion function and the aviation spare parts procurement cost function C, the aviation enterprises loss aversion procurement utility function can be defined as follows:

$$U(C(D;q)) = C(D;q) + \beta(C(D;q) - I)^{+} = \begin{cases} C(D;q), & C(D;q) < I \\ (1+\beta)C(D;q) - \beta I, & C(D;q) \geqslant I \end{cases}$$

Let β represent the loss aversion coefficient. Aviation enterprises perceive gains when actual procurement costs fall below budget costs, and losses when costs exceed budget costs. The bigger the loss aversion coefficient is, the more loss-averse the aviation enterprises become. The loss aversion function has been widely used in economics and operations management.

Next, we consider the optimal procurement policy of the loss-averse purchaser.

The purchaser's cost, denoted as $C(D;q)$, is

$$C(D;q) = (w+v)q - t(q-D)^{+} + s\left(D-q\right)^{+} = \begin{cases} C_1(D;q) = (w+v-t)q + tD, & if\ D < q \\ C_2(D;q) = (w+v-s)q + sD, & if\ D \geqslant q \end{cases} \quad (1)$$

Next, we discuss the break-even point of the actual demand realization. Let d denote the actual demand realization.

Case 1 If $d<q$, $C_1(d;q)=(w+v-t)q+td$. Let $C_1(d;q)-I=0$, we get $d_1(q)=[I-(w+v-t)q]/t$. Since $C_1(d;q)-I$ is strictly increasing in d, if $d>d_1$(q), then $C_1(d;q)-I>0$; If $d<d_1(q)$, then $C_1(d;q)-I<0$.

Case 2 If $d \geq q$, $C_2(d;q)=(w+v-s)q+sd$. Let $C_2(d;q)-I=0$, we get $d_2(q)=[I-(w+v-s)q]/s$. Since $C_2(d;q)-I$ is strictly increasing in d, if $d>d_2(q)$, then $C_2(d;q)-I>0$; If $d<d_2(q)$, then $C_2(d;q)-I<0$.

Lemma 3.1 The purchaser has two break-even quantities of realized demand:

$$d_1(q) = \frac{I-(w+v-t)q}{t} \text{ and } d_2(q) = \frac{I-(w+v-s)q}{s}.$$

where if $D>d_1(q)$ or $D>d_2(q)$, the purchaser's realized cost is negative and if $D<d_1(q)$ or $D<d_2(q)$, the purchaser's realized cost is positive.

Lemma 3.1 means that if the amount of demand realized results in a purchase cost that is greater than the budgeted cost ($D>d_1(q)$ or $D>d_2(q)$), the purchaser will face losses, and if the amount of demand realized results in a purchase cost that is less than the budgeted cost ($D<d_1(q)$ or $D<d_2(q)$), the purchaser will face gains.

Therefore, the purchaser's expected utility function, denoted $E[U(C(D;q))]$, can be written as

$$\begin{aligned}E[U(C(D;q))] &= \int_0^{\frac{I-(w+v-t)q}{t}}[(w+v-t)q+tx]f(x)dx+\int_{\frac{I-(w+v-t)q}{t}}^{q}\{(1+\beta)[(w+v-t)q+tx]-\beta I\}f(x)dx \\ &+\int_q^{\frac{I-(w+v-s)q}{s}}[(w+v-s)q+sx]f(x)dx+\int_{\frac{I-(w+v-s)q}{s}}^{\infty}\{(1+\beta)[(w+v-s)q+sx]-\beta I\}f(x)dx\end{aligned} \quad (2)$$

3 Optimal Purchasing Policies

This section systematically analyzes optimal strategies for spare parts procurement. We first derive the loss-neutral optimal procurement policy by minimizing expected costs, identifying critical properties of spare parts demand and inventory dynamics. Building on these findings, we then investigate how loss aversion reshapes procurement patterns for aviation enterprises, providing actionable managerial insights.

3.1 Optimal Procurement Strategy for Loss-Neutral Aviation Enterprises

Theorem 3.1 To minimize expected cost $E[U(C(D;q))]$, the loss-neutral purchaser's optimal procurement quantity q^* can be given as

$$q^* = F^{-1}[(s-w-v)/(s-t)].$$

Proof of Theorem 3.1

Based on the analysis in section 2, a loss-averse purchaser's expected loss aversion utility function of $E[U(C(D;q))]$ can be given as

$$\begin{aligned}E[U(C(D;q))] &= \int_0^{\frac{I-(w+v-t)q}{t}}[(w+v-t)q+tx]f(x)dx+\int_{\frac{I-(w+v-t)q}{t}}^{q}\{(1+\beta)[(w+v-t)q+tx]-\beta I\}f(x)dx \\ &+\int_q^{\frac{I-(w+v-s)q}{s}}[(w+v-s)q+sx]f(x)dx+\int_{\frac{I-(w+v-s)q}{s}}^{\infty}\{(1+\beta)[(w+v-s)q+sx]-\beta I\}f(x)dx\end{aligned}$$

It follows that

$$\begin{aligned}\frac{\partial E[U(C(D;q))]}{\partial q} &= F(q)[(1+\beta)(w+v-t)-(w+v-s)]-\beta F(d_1)(w+v-t) \\ &-\beta F(d_2)(w+v-s)+(1+\beta)(w+v-s)\end{aligned}$$

It further follows that

$$\frac{\partial^2 E[U(C(D;q))]}{\partial q^2} = \beta f(d_1)\frac{(w+v-t)^2}{t}+f(q)[(1+\beta)(w+v-t)-(w+v-s)]+\beta f(d_2)\frac{(w+v-s)^2}{s}.$$

Obviously, $\frac{\partial^2 E[U(C(D;q))]}{\partial q^2}>0$, which could imply that $E[U(C(D;q))]$ is concave.

In such a case, it follows from the concavity of $E[U(C(D;q))]$ and the first-order condition that a loss-averse purchaser's optimal ordering quantity q^* solves

$$\begin{aligned}&F(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+F(d_1^*)(w+v-t)(-\beta) \\ &+F(d_2^*)(w+v-s)(-\beta)+(1+\beta)(w+v-s)=0\end{aligned}.$$

Because the purchaser is loss-neutral (*β=0*), we can get optimal procurement quantity q^* that satisfies $F(q^*)(s-t)+(w+v-s)=0$. That is

$$q^* = F^{-1}[(s-w-v)/(s-t)].$$

It completes the proof.

Corollary 3.1 To minimize $E[U(C(D;q))]$, there are following results on the optimal purchasing decision q^* for a loss-neutral purchaser:

(1) q^* decreases when the purchase price w increases.

(2) q^* decreases when the inventory price v increases.

(3) q^* increases when the shortage cost s increases.

(4) q^* increases when the recycling price t increases.

Proof of Corollary 3.1

Theorem 3.1 indicates that

$q^* = F^{-1}[(s-w-v)/(s-t)]$ and it holds that

$$\frac{dq^*}{dw} = \frac{1}{f(q^*)}\frac{d}{dw}(\frac{s-w-v}{s-t}) = \frac{-1}{f(q^*)(s-t)} < 0,$$

$$\frac{dq^*}{dv} = \frac{1}{f(q^*)}\frac{d}{dv}(\frac{s-w-v}{s-t}) = \frac{-1}{f(q^*)(s-t)} < 0,$$

$$\frac{dq^*}{ds} = \frac{1}{f(q^*)}\frac{d}{ds}(\frac{s-w-v}{s-t}) = \frac{w+v-t}{f(q^*)(s-t)^2} > 0,$$

$$\frac{dq^*}{dt} = \frac{1}{f(q^*)}\frac{d}{dt}(\frac{s-w-v}{s-t}) = \frac{s-w-v}{f(q^*)(s-t)^2} > 0.$$

It completes the proof.

For the optimal procurement decision of loss-neutral aviation enterprises' spare parts, Corollary 3.1 reveals the dynamic relationships among factors influencing the optimal procurement quantity. The scenario described in Corollary 3.1 aligns with real-world operational principles and provides a clear interpretation, which can be elucidated as follows. Under standard operational management conditions, if the purchase price w increases, it indicates that the procurement cost is too high and the continued procurement may outweigh the losses. The aviation enterprises may strategically reduce the frequency of purchases or purchase spare parts in bulk after weighing the cost of procurement with the risk of shortage.

If the inventory price v rises (e.g., inventory fees increase or inventory turnover decreases), the optimal procurement quantity q^* decreases, it implies that the inventory cost v has exceeded the loss of shortage, and the aviation enterprises should significantly reduce the inventory, reduce the purchase quantity, or even accept the shortage-as maintaining excess inventory becomes economically inefficient.

When the price of shortage s increases, it means that the loss in the case of shortage is much greater than the procurement cost and the inventory cost of spare parts, and the aviation enterprises will prioritize increasing the purchase quantity of spare parts to reduce the probability of shortage in order to prevent the occurrence of shortage of spare parts. Although this elevates inventory expenses, the resultant reduction in shortage costs substantially outweighs additional inventory costs, yielding net operational savings.

When the recycling price t increases, it means that the cost can be partially offset by the recycling of residual value, even if the inventory is overstocked. The aviation enterprises can accept higher levels of spare parts inventory as the cost of excess inventory is mitigated by recycling value.

3.2 Optimal Procurement Strategy for Loss-Aversion Aviation Enterprises

In section 3.1, we derive the optimal spare parts procurement strategy to minimize aviation enterprises' expected costs. However, relevant studies have shown that in real life, buyers' purchase decisions often deviate from the optimal procurement decision [10, 18, 23-25]. The empirical studies demonstrate that buyers' loss-averse behavior affects their decisions, and the loss aversion effect provides a possible explanation for the actual and theoretical decision biases. To reconcile this gap, we integrate loss aversion into aviation spare parts procurement modeling. Our framework quantifies how loss-averse preferences distort procurement volumes under potential financial losses, providing a behavioral explanation for observed decision biases.

Theorem 3.2 $E[U(C(D;q))]$ is concave in q and there is a unique optimal order quantity q^* that minimizes the loss-averse purchaser's expected utility and satisfies the following condition:

$$\begin{aligned} &F(q^*)[(1+\beta)(w+v-t)-(w+v-s)] + F(d_1^*)(w+v-t)(-\beta) \\ &+F(d_2^*)(w+v-s)(-\beta) + (1+\beta)(w+v-s) = 0 \end{aligned}. \tag{3}$$

The proof of Theorem 3.2 is similar to the Proof of Theorem 3.1, which is omitted.

From this, we can obtain the break-even point at the two optimal purchase volumes:

$$d_1(q^*) = \frac{I-(w+v-t)q^*}{t} \text{ and}$$

$$d_2(q^*) = \frac{I-(w+v-s)q^*}{s}.$$

To better describe the relationship between expected cost utility $E[U(C(D;q))]$ and purchase volume q, an example is given below.

Example 3.1 Consider a loss-averse purchaser with an option purchase decision. Suppose the market demand D is subject to a uniform distribution on [0,1000]. The operation parameters are given as w=6, v=2, t=1, s=15, I=700 and β=5. We compute the loss-averse purchaser's expected utility $E[U(C(D;q))]$ from an option purchase quantity q.

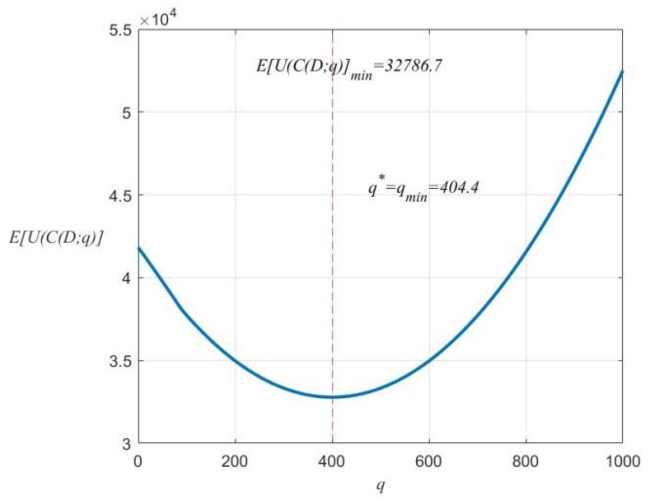

Figure 1 Expected utility $E[U(C(D;q))]$ under different procurement quantity q

In the initial stage of procurement, when the procurement quantity is small, the probability that the actual demand exceeds the procurement quantity is high, resulting in frequent shortage. During this phase, aviation enterprises need to bear high shortage costs (e.g., emergency purchase premiums, loss of flight delays, damage of reputation, etc.) and low risk of inventory overstocking, limited inventory and handling costs. With the slight increase in the procurement quantity, the probability of shortage is significantly reduced, and the reduction of shortage costs is much greater than the increase in inventory costs, and the total cost is gradually decreasing.

When the procurement quantity reaches a certain critical value, the marginal effect of the shortage cost and the inventory cost are equal. At this time, the probability of shortage and the probability of inventory redundancy reach the optimal balance, the total cost is minimal, and the procurement quantity at this time is the optimal purchase quantity.

When the purchase volume far exceeds the actual demand, the probability of inventory overstock increases significantly, resulting in a significant increase in inventory costs (such as inventory costs, capital occupation interest, spare parts depreciation or scrap losses), although the probability of shortage is extremely low, the marginal reduction in shortage cost can no longer offset the increase in inventory costs. The growth rate of inventory costs outpaces the decline in shortage costs, and the total cost gradually increased.

Next, we analyze the sensitivity of several influencing factors that affect the optimal procurement quantity of spare parts:

Corollary 3.2

If $(w+v-t)[F(d_1^*)-F(q^*)]+(w+v-s)[F(d_2^*)-1]>0$, then $\dfrac{dq^*}{d\beta}>0$;

If $(w+v-t)[F(d_1^*)-F(q^*)]+(w+v-s)[F(d_2^*)-1]<0$, then $\dfrac{dq^*}{d\beta}<0$.

Corollary 3.2 shows that when $(w+v-t)[F(d_1^*)-F(q^*)]+(w+v-s)[F(d_2^*)-1]>0$, as the loss aversion coefficient β increases, the optimal procurement quantity q^* rises. At this time, the aviation enterprises couldn't bear the high cost caused by the loss, in order to reduce the investment of the shortage cost as much as possible. Aviation enterprises may choose to increase the procurement quantity of spare parts to reduce the shortage loss.

If $(w+v-t)[F(d_1^*)-F(q^*)]+(w+v-s)[F(d_2^*)-1]<0$, the optimal order quantity q^* decreases with the increase of the loss aversion coefficient β.

In this case, we have the following explanation: The aviation enterprises believe that the possibility of shortage in the actual situation is very small. At this time, they can bear the cost of loss and the shortage cost is less than the cost of the previous purchase. In order to save the cost of the early purchase, the aviation enterprises will reduce the purchase of spare parts.

Proof of Corollary 3.2

With the optimal procurement quantity q^*, we can derive the optimal solution for the two break-even points:

$$d_1^*=\frac{I-(w+v-t)q^*}{t} \quad \text{and} \quad d_2^*=\frac{I-(w+v-s)q^*}{s}.$$

At this time,

$$\begin{aligned}&F(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+F(d_1^*)(w+v-t)(-\beta)\\&+F(d_2^*)(w+v-s)(-\beta)+(1+\beta)(w+v-s)=0\end{aligned}.$$

Then, we perform an implicit function derivation of the function

$$\frac{dq^*}{d\beta}=\frac{(w+v-t)[F(d_1^*)-F(q^*)]+(w+v-s)[F(d_2^*)-1]}{f(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+f(d_1^*)\dfrac{\beta(w+v-t)^2}{t}+f(d_2^*)\dfrac{\beta(w+v-s)^2}{s}}.$$

When $(w+v-t)[F(d_1^*)-F(q^*)]+(w+v-s)[F(d_2^*)-1]>0$, the optimal procurement quantity q^* increase with the increase of the loss aversion coefficient β.

When $(w+v-t)[F(d_1^*)-F(q^*)]+(w+v-s)[F(d_2^*)-1]<0$, the optimal procurement quantity q^* decrease with the decrease of the loss aversion coefficient β. It completes the proof.

Example 3.2 Different purchasers have different tolerance of losses, so we analyze the relationship between the optimal procurement quantity q^* and the loss aversion coefficient β. We suppose the market demand D is subject to a uniform distribution on [0,1000] and the operational parameters are given as: w=6, v=2, t=1, s=15 and I=700. We plot the optimal order quantity as a function of different loss aversion coefficients.

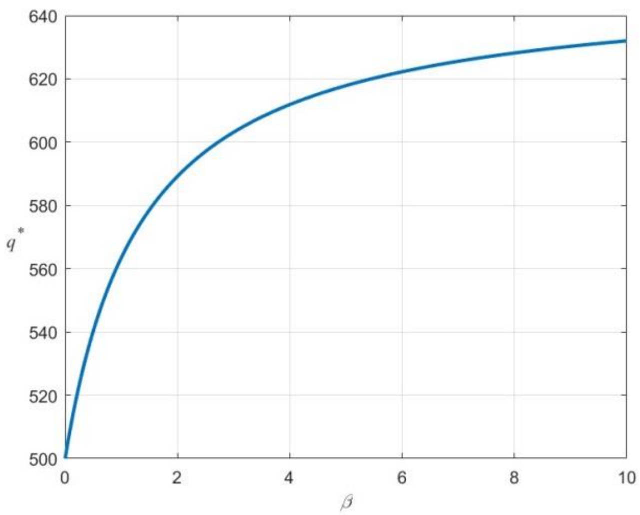

Figure 2 The optimal procurement quantity q^* under different loss aversion coefficient β

Figure 2 conforms to: $(w+v-t)[F(d_1^*)-F(q^*)]+(w+v-s)[F(d_2^*)-1]>0$ situation. The higher the aviation enterprises' aversion to loss, the much spare parts will be purchased. The optimal procurement quantity q^* increases with the increase of loss aversion coefficient β.

This trend aligns with real-world observations that loss-averse aviation enterprises prioritize mitigating risks associated with inventory shortage. When aviation enterprises exhibit stronger loss-averse tendencies, they demonstrate heightened motivation to avoid financial losses stemming from shortage scenarios, including premium costs for urgent procurement, operational disruptions, and reputational damage. To mitigate such risks, aviation enterprises tend to increase procurement quantity, thereby reducing the probability of shortage occurrences through enhanced inventory buffer levels. The intensified loss-averse orientation essentially amplifies the perceived utility of shortage consequences. This strategically incentivizes aviation enterprises to adopt more conservative inventory policies.

Corollary 3.3 For a loss-averse retailer with shortage cost s, the optimal procurement quantity q^* is increasing in the shortage cost s.

Corollary 3.3 shows that when the market demand exceeds the procurement quantity or the number of spare parts in stock is not high, a larger shortage cost means a greater under-purchasing loss. This phenomenon is similar to that in the newsvendor model when the shortage cost is considered.

Due to the inability to accurately predict the demand for spare parts, and because of the high value of consumable parts, redundant spare parts will occupy more budget costs. It leads to an increase in inventory costs. Aviation enterprises are caught in the contradiction of high shortage losses and large capital occupation. Therefore, as shortage cost increases, the optimal procurement quantity of spare parts will increase accordingly. If an aviation enterprise is loss-averse, the same amount of loss will have a greater impact on the loss-averse aviation enterprise. In other words, a loss-averse aviation enterprise needs to invest a certain amount of budget money to protect itself from potential losses. The more loss-averse the aviation enterprise, the much budget money need to be invested.

Proof of Corollary 3.3

When the optimal purchase quantity q^* exists,

$$\begin{array}{l} F(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+F(d_1^*)(w+v-t)(-\beta) \\ +F(d_2^*)(w+v-s)(-\beta)+(1+\beta)(w+v-s)=0 \end{array}.$$

We perform an implicit function derivation of the function

$$\frac{dq^*}{ds}=\frac{1-F(q^*)+\beta[1-F(d_2^*)]+\beta(w+v-s)f(d_2^*)\dfrac{(w+v)q^*-I}{s^2}}{f(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+\dfrac{\beta(w+v-t)^2}{t}f(d_1^*)+\dfrac{s\beta(w+v-s)^2}{s^2}f(d_2^*)}.$$

Combined with equation $d_2(q^*)=\dfrac{I-(w+v-s)q^*}{s}$, we can conclude that $(w+v)q^*-I>0$. Then $1-F(q^*)+\beta[1-F(d_2^*)]+\beta(w+v-s)f(d_2^*)\dfrac{(w+v)q^*-I}{s^2}>0$.

It follows that $\dfrac{dq^*}{ds}>0$, the optimal purchase quantity q^* increase with the increase of the shortage cost per unit *s*. It completes the proof.

Example 3.3 For explaining the above conclusions more intuitively, we assume the market demand *D* is subject to a uniform distribution on [0,1000] and the operation parameters are given as w=6, v=2, t=1, β=1 and I=700. One of the most important points we have to make is that the shortage cost $s\in[8,50]$.

Figure 3 illustrates that when the shortage cost is lower, aviation enterprises face fewer potential losses from shortage. In this scenario, even a marginal increase in the procurement quantity can significantly reduce the probability of shortage, and the marginal reduction of the shortage cost is larger, which drives the rapid growth of the procurement quantity. When the cost of shortage is already at a high level, the baseline procurement quantity is large, and the marginal effect of further increasing the procurement quantity in reducing the probability of shortage is weakened, and the growth of the procurement quantity tends to be flat. And the increase in procurement quantity directly leads to a linear increase in inventory costs (such as inventory fees, capital occupation, depreciation). When the cost of shortage is high, although the aviation enterprises tend to increase purchases to avoid shortage losses, the accumulation of inventory costs will gradually offset the benefits of the reduction of shortage cost. Real-world aviation enterprises inventory space or budget caps can be hard constraints. When the shortage cost is extremely high, aviation enterprises theoretically need to purchase more spare parts, but due to practical conditions (such as full warehouses), the growth of procurement volume is forced to slow.

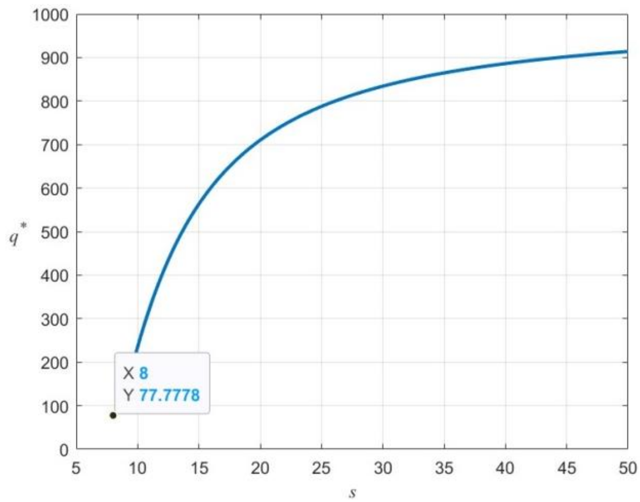

Figure 3 The optimal procurement quantity q^* under different shortage cost per unit *s*

Corollary 3.4 For a loss-averse retailer with shortage cost, the optimal option purchase quantity q^* is increasing in the recycling price *t*.

Proof of Corollary 3.4

When the optimal procurement quantity q^* exists,

$$\begin{array}{l} F(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+F(d_1^*)(w+v-t)(-\beta) \\ +F(d_2^*)(w+v-s)(-\beta)+(1+\beta)(w+v-s)=0 \end{array}.$$

We perform an implicit function derivation of the function

$$\frac{dq^*}{dt}=\frac{(1+\beta)F(q^*)-\beta F(d_1^*)+\beta(w+v-t)f(d_1^*)\dfrac{(w+v)q^*-I}{t^2}}{f(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+\dfrac{\beta(w+v-t)^2 f(d_1^*)}{t}+\dfrac{\beta f(d_2^*)(w+v-s)^2}{s}}.$$

Because $d_1(q^*)=\dfrac{I-(w+v-t)q^*}{t}$ and $d_1<q$, we can get

$$(1+\beta)F(q^*)-\beta F(d_1^*)+\beta(w+v-t)f(d_1^*)\frac{(w+v)q^*-I}{t^2}>0.$$

It completes the proof.

Corollary 3.4 demonstrates that the optimal procurement quantity of spare parts increases with the unit recycling price of these spare parts, which aligns with market dynamics. Specifically, when the procurement quantity falls short of market demand, the recycling price per unit remains zero. In such cases, aviation enterprises must increase their procurement quantities to mitigate shortage losses. Conversely, when the procurement quantity exceeds market demand, a higher unit recycling price leads to reduced losses for aviation enterprises. Consequently, as the unit recycling price of spare parts rises, aviation enterprises will increase their procurement quantities to optimize cost efficiency.

The recycling price in this article not only refers to the recycling price of spare parts, but also includes the sharing of spare parts and residual value between aviation enterprises. Spare parts sharing generally refers to the joint support and maintenance of spare parts in the inventory. Multiple aviation enterprises, spare parts investors and spare parts maintenance units can build a ‘pool’ to reduce inventory costs by sharing spare parts and play their part to meet the needs of the airline fleet, thereby improving management efficiency. Aviation enterprises can reduce their resource investment through spare parts sharing, especially the cost of capital, space and time, and reduce their own inventory costs and capital occupation by handling some redundant aviation spare parts.

Example 3.4 We suppose the market demand D is subject to a uniform distribution on [0,1000] and the operation parameters are given as w=6, v=2, β=1, $t\in$[8,50], s=15 and I=700. We plot the optimal procurement quantity q^* as a function of different the recycling price per unit of spare parts t.

Figure 4 indicates that as the price of spare parts recycling increases, the optimal procurement quantity of spare parts increases. The rise in spare parts recycling prices can be analyzed from two aspects.

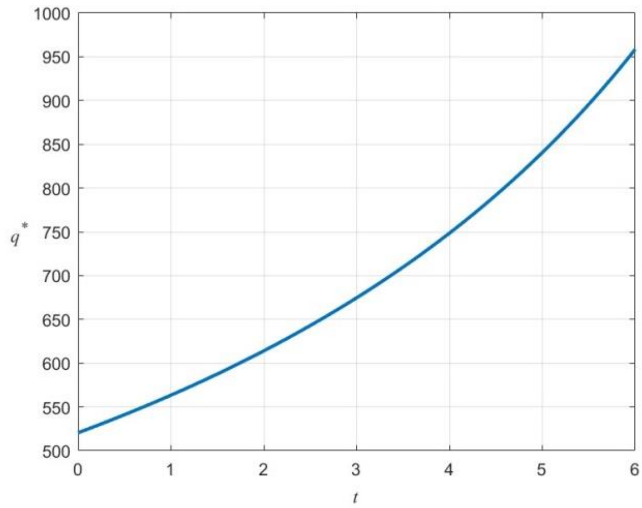

Figure 4 The optimal procurement quantity q^* under different the recycling price per unit t

On the one hand, due to the increase in asset valuation or the rise in income when sharing spare parts, aviation enterprises have more potential funds to purchase additional spare parts to avoid shortage, even though inventory costs may increase. However, the increase in the value of stored spare parts can offset potential losses. At the same time, it is also important to optimize inventory strategies, such as whether to retain more spare parts to secure higher residual value returns.

On the other hand, one must consider whether the rise in spare parts recycling prices conceals the risk of shortage. For example, aviation spare parts are typically expensive and have long procurement cycles; Recycling prices may reflect the stability of the supply chain. Fluctuations in market demand can cause a rapid increase in recycling prices, leading aviation enterprises to consider the potential losses from shortage situations, thus slightly increasing their procurement quantity.

Corollary 3.5

If $s\beta f(d_1^*)(w+v-t)+t\beta f(d_2^*)(w+v-s)>0$, then $\dfrac{dq^*}{dI}>0$;

If $s\beta f(d_1^*)(w+v-t)+t\beta f(d_2^*)(w+v-s)<0$, then $\dfrac{dq^*}{dI}<0$.

Corollary 3.5 shows that as the budget cost s increases, the optimal procurement quantity may increase or decrease. For loss-averse aviation enterprises, demand distribution, the recycling price per unit of spare parts, and the shortage cost per unit of spare parts are all important factors affecting optimal procurement quantity.

Proof of Corollary 3.5

When the optimal procurement quantity q^* exists,

$$\begin{aligned}&F(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+F(d_1^*)(w+v-t)(-\beta)\\&+F(d_2^*)(w+v-s)(-\beta)+(1+\beta)(w+v-s)=0\end{aligned}.$$

We perform an implicit function derivation of the function

$$\begin{aligned}\frac{dq^*}{dI}&=\frac{\dfrac{\beta f(d_1^*)(w+v-t)}{t}+\dfrac{\beta f(d_2^*)(w+v-s)}{s}}{f(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+\dfrac{\beta f(d_1^*)(w+v-t)^2}{t}+\dfrac{\beta f(d_2^*)(w+v-s)^2}{s}}\\&=\frac{s\beta f(d_1^*)(w+v-t)+t\beta f(d_2^*)(w+v-s)}{stf(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+s\beta f(d_1^*)(w+v-t)^2+t\beta f(d_2^*)(w+v-s)^2}\end{aligned}.$$

Then we can find

$$stf(q^*)[(1+\beta)(w+v-t)-(w+v-s)]+s\beta f(d_1^*)(w+v-t)^2+t\beta f(d_2^*)(w+v-s)^2>0.$$

If $s\beta f(d_1^*)(w+v-t)+t\beta f(d_2^*)(w+v-s)>0$, $\dfrac{dq^*}{dI}>0$;

If $s\beta f(d_1^*)(w+v-t)+t\beta f(d_2^*)(w+v-s)<0$, $\dfrac{dq^*}{dI}<0$.

It completes the proof.

For Corollary 3.5, We give the following two explanations:

The first aspect is that the dynamic adjustment of the reference point. In the loss aversion model, the budget cost is set as the psychological break-even point (reference point). When the budget increases, the reference point moves up, and the aviation enterprises' perception of loss changes: if the actual procurement cost exceeds the new budget, the aviation enterprises become more sensitive to the 'relative loss'. To avoid the risk of exceeding budgets, aviation enterprises may reduce procurement quantity; If the increased budget increases the aviation enterprises' ability to respond to risk, the company may increase the procurement quantity to reduce shortage risks.

The other aspect is that when the shortage cost is significantly higher than the cost of purchasing and inventory, aviation enterprises tend to increase procurement quantity to avoid shortage losses. If budget increases ease financial constraints, aviation enterprises may further increase their procurement quantity to meet more demand. When inventory costs or purchase prices are high, an increase in budgets may motivate businesses to reduce procurement quantity, as higher budgets cannot offset the direct cost pressures of inventory and procurement, and aviation enterprises are more inclined to prevent waste through inventory control.

Example 3.5 We give an example: suppose the market demand D is subject to a uniform distribution on [0,1000] and the operation parameters are given as w=6, v=2, s=15 and t=1.

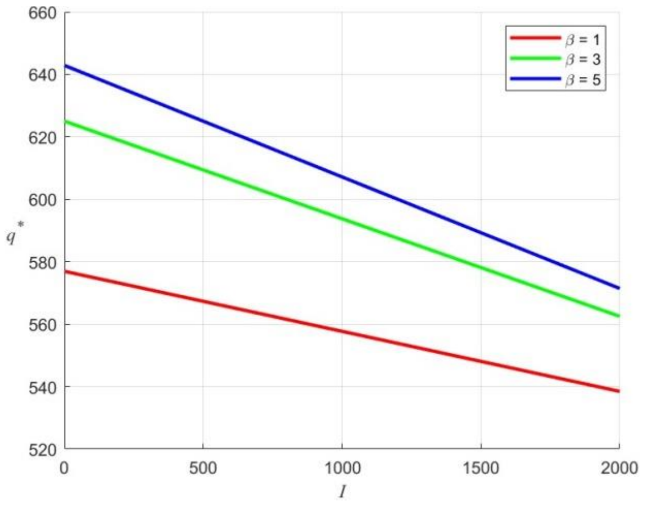

Figure 5 The optimal procurement quantity q^* under different budget cost I

Figure 5 conforms to $s\beta f(d_1^*)(w+v-t)+t\beta f(d_2^*)(w+v-s)<0$. In Figure 5, we could clearly find that the optimal procurement quantity under different loss aversion coefficients decreases with the increase of the budgeted cost.

In considering the attitude of aviation enterprises towards losses, specifically, with the increase of the coefficient of loss aversion and the budget costs, the speed of reduction of the optimal purchase of aviation spare parts is greater. This occurs because in budget costs may come from the rises in procurement costs and inventory costs, and higher budgets cannot offset the direct cost pressure of inventory and procurement. Aviation enterprises are more inclined to avoid waste by controlling inventory, which also shows that aviation enterprises are more sensitive to 'relative loss', and in order to avoid the risk of exceeding the new budget, enterprises may reduce procurement quantity.

4 Conclusions

Aviation spare parts, which encompass consumables and components required for routine aircraft maintenance and repair, play a critical role in airline operational management. Consequently, the procurement of these parts has become a pivotal strategy for aviation enterprises to reduce costs and improve operational efficiency.

The traditional newsvendor model research show that buyers' procurement decisions often are different from the optimal procurement decision. In the aviation industry, there often exists a discrepancy between the actual procurement quantity of aviation spare parts and the theoretically optimal procurement decisions. This observed phenomenon has prompted our research interest, leading us to conduct a comprehensive study series on procurement decision-making for aviation spare parts.

This paper investigates the optimal aviation spare parts procurement decisions for loss-averse aviation enterprises in the context of considering shortage cost. Utilizing Prospect Theory, we introduce a loss-averse utility function, with budget costs serving as the psychological break-even point, to quantify the loss aversion effect in aviation spare parts procurement. Through mathematical derivation, we obtain the optimal procurement quantity that minimizes the expected loss-averse utility. Subsequently, we conduct a sensitivity analysis of various factors within the model, discussing their relationships with the optimal procurement quantity one by one. Numerical simulations are provided to validate the theoretical conclusions.

In the context of significant shortage cost arising from aviation spare parts shortage, this study provides theoretical insights into determining optimal procurement quantities for loss-averse aviation enterprises. For instance, under the premise of minimizing expected utility costs, the optimal procurement quantity of aviation spare parts may increase or decrease with the increase in loss aversion coefficient, procurement price, inventory holding cost, and budgeted procurement cost. Conversely, the procurement quantity increases with the rise in unit shortage cost and unit recycling value.

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