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EOQ Based Inventory Optimization with Partial Backordering and Demand Uncertainty in Manufacturing

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Abstract: Inventory management is one of the important aspects in manufacturing systems, especially in the face of demand uncertainty and lead time variability. The classic Economic Order Quantity (EOQ) model is often assumed with constant demand and fixed lead times that do not always reflect the complexity of the real world. This research develops a more adaptive EOQ-Partial Backordering model by integrating a dynamic demand response mechanism as well as a lead time-based ordering strategy, in order to improve the resilience of inventory systems in manufacturing systems. The proposed model is designed to minimize the total inventory cost, by considering the balance between holding cost, backordering cost, and ordering cost. In contrast to previous models, this approach systematically measures between immediate demand fulfillment and delayed fulfillment, thus enabling more flexible inventory decisions. The evaluation of the model was conducted using sensitivity analysis and Monte Carlo simulation, by testing different scenarios of demand volatility and variations in the proportion of backorders. The results show that considering partial backordering in the EOQ framework will result in a better inventory policy, reduce excess stock and improve cost effectiveness. On the other hand, this study also considers the impact of demand fluctuations on the optimal ordering quantity and provides practical knowledge and can be a strategic reference for inventory managers in the manufacturing industry. The main contribution of this research in inventory theory is to bridge the gap between deterministic EOQ models and stochastic demand dynamics in the real world, while offering an applicable decision-making tool for more efficient inventory management and better supply chain resilience.

Keywords: Inventory optimization, EOQ model, Partial backordering, Demand uncertainty, Manufacturing systems

Introduction

The manufacturing industry faces great challenges in optimizing inventory management to ensure efficient production continuity. Imbalances in parts availability can lead to costly production downtime, while excessive inventory can increase holding costs and reduce operational efficiency. Therefore, inventory management strategies are an important aspect in the supply chain of the manufacturing industry. One of the basic methods used in inventory optimization is the Economic Order Quantity (EOQ) model first introduced by Harris (1913). This model aims to determine the optimal order quantity to minimize total inventory costs, which include ordering costs and holding costs. However, in practice, the classic EOQ assumptions of deterministic demand and instant order fulfillment are often incompatible with real conditions in the manufacturing industry.

To increase the relevance of the EOQ model in an increasingly complex manufacturing environment, various studies have developed variations of the classic EOQ model. One widely researched approach is EOQ with Partial Backordering, which allows a portion of demand that cannot be fulfilled immediately to be postponed at a certain cost. Based on Goyal & Giri's (2019) research, considering the backordering aspect in EOQ can reduce the total cost of the inventory system and improve supply chain efficiency. In addition, this model offers greater flexibility in the face of demand fluctuations and lead time uncertainty.

A number of other studies have also tried to accommodate uncertainty in EOQ by considering probabilistic distributions on demand and lead time. For example, Lee & Park's (2018) research developed a stochastic model with variable lead time and partial ordering, which showed that flexibility in ordering policy can significantly reduce the total inventory cost. Meanwhile, Zhou & Yang (2017) proposed an inventory optimization model for perishable products with stochastic demand and partial ordering, which proved that an optimal ordering policy can improve service levels as well as cost efficiency. However, previous research still has some limitations. Goyal & Giri (2019) developed an EOQ model with Partial Backordering in a deterministic context, which assumes that all parameters such as demand and lead time are known with certainty. This is incompatible with the real conditions in the manufacturing industry that often face uncertainties in the supply chain. In addition, previous models often result in complicated calculation procedures, making it difficult to apply to industrial systems with high variability. To overcome these limitations, this study aims to explore the impact of parameter variability in the EOQ with Partial Backordering model on the total cost of inventory systems in the manufacturing industry. By integrating the stochastic approach and Monte Carlo simulation, this research is expected to provide more accurate and applicable recommendations in inventory management. The results obtained are not only expected to provide theoretical contributions in the development of a more realistic EOQ model, but also provide practical benefits for companies in optimizing their inventory management strategies.

Methods

This research method aims to develop an Economic Order Quantity (EOQ) model with Partial Backordering in the context of a manufacturing industry facing demand uncertainty. This model is developed based on a deterministic approach by considering the aspect of partial backordering, where some demand that cannot be fulfilled immediately can be postponed at a certain cost. This section will explain the mathematical formulation of the EOQ model used, the selection of demand distribution, the developed model algorithm, and the Monte Carlo simulation technique to evaluate the model's performance in various demand scenarios.

EOQ Model Formulation with Partial Backordering

In the classical EOQ model, the main assumption is that demand is constant and always met. However, in practice, the manufacturing industry often faces delays in stock fulfillment, so that some demand cannot be met immediately and is postponed to the next period. Therefore, the EOQ model is extended by considering partial backordering, with the following formula:

Optimal Order Quantity

The optimal order quantity Q^* in the EOQ model with Partial Backordering can be calculated using the formula:

$$Q^* = \sqrt{\frac{2C_oE[D]}{C_h} \times \frac{C_b}{C_h + C_b}}$$

With:
Q^* = optimal order quantity
C_o = ordering cost per order
C_h = holding cost per unit per year
C_b = backordering cost per unit per year
$E[D]$ = expected annual demand

Maximum Backordering Amount

The number of units that can be backordered is calculated by:

$$B^* = Q^* \times \frac{C_h}{C_h + C_b}$$

Order Cycle Length

The length of the order cycle is calculated by:

$$T^* = \frac{Q^*}{E[D]}$$

Total Inventory Cost

The total cost of the inventory system, which includes ordering costs, holding costs, and backordering costs, is calculated by:

$$TC = \frac{C_o E[D]}{Q^*} + \frac{C_h}{2} Q^*(1-\beta) + \frac{C_b}{2} B^*$$

Where β is the fraction of demand that can be ordered in advance.

Selection of Demand Distribution

To ensure that the EOQ model with Partial Backordering can be applied in real manufacturing conditions, it is necessary to choose the most appropriate demand distribution. In this study, three main stochastic distributions are used:

1) *Normal Distribution*

If demand fluctuates steadily with small variations around the average.

$$D \sim \mathcal{N}(\mu, \sigma^2)$$

Demand expecatation:

$$E[D] = \mu$$

2) *Poisson Distribution*

If demand occurs discretely and in batch orders, such as ordering products in fixed quantities.

$$D \sim Poisson(\lambda)$$

Demand expectation:

$$E[D] = \lambda$$

3) *Exponential Distribution*

If demand is sporadic and irregular, as in the spare parts industry.

$$D \sim Exponential\ (\lambda)$$

Demand expectation:

$$E[D] = \frac{1}{\lambda}$$

The selection of demand distribution is based on the characteristics of the industry being studied, so that the model can provide more realistic results.

EOQ Model Algorithm with Partial Backordering

To calculate the optimal order quantity and evaluate its impact on total inventory costs, the following algorithm is used:

1) Parameter Initialization

- Define the ordering cost C_o, holding cost C_h, backordering cost C_b and expected annual demand $E[D]$
- Select the appropriate demand distribution (Normal, Poisson, or Exponential)

2) Calculate Optimal Order Quantity Q^*

Use equation:

$$Q^* = \sqrt{\frac{2C_oE[D]}{C_h} \times \frac{C_b}{C_h + C_b}}$$

3) Calculate the Number of Backordering B^*

Use equation:

$$B^* = Q^* \times \frac{C_h}{C_h + C_b}$$

4) Calculate Total Inventory Cost TC

- Calculate ordering cost:

$$TC_{order} = \frac{C_oE[D]}{Q^*}$$

- Calculate holding cost:

$$TC_{holding} = \frac{C_h}{2}Q^*(1-\beta)$$

- Calculate ordering cost:

$$TC_{backorder} = \frac{C_b}{2}B^*$$

- Total inventory cost:

$$TC = TC_{order} + TC_{holding} + TC_{backorder}$$

5) Model Validation with Monte Carlo Simulation

- Perform demand sampling using the selected distribution.
- Calculate Q^* and B^* for each demand scenario.
- Evaluate total cost TC to determine the optimal inventory strategy.

6) Perform Sensitivity Analysis

- Test changes in parameters $C_o, C_h, C_b, E[D]$ to see how these factors affect total inventory costs.

- Identify conditions under which Partial Backordering is more profitable than full fulfillment of demand.

Monte Carlo Simulation for Model Evaluation

To test the EOQ model with Partial Backordering under conditions of demand uncertainty, a Monte Carlo simulation is conducted with the following procedure:
(1) Determine the demand scenario using the selected probabilistic distribution.
(2) Conduct a simulation with 10,000 iterations to see how demand fluctuations affect the optimal order quantity and total inventory cost.
(3) Analyze the simulation results to determine the best strategy in inventory management.

Results and Discussion

Uncertain demand is an important factor affecting inventory policy in manufacturing industry. The classical EOQ model assumes deterministic demand, but in real conditions, demand can fluctuate stochastically. Therefore, this study examines the impact of demand uncertainty on optimal order quantity (Q^*) and total inventory cost (TC) using Monte Carlo simulation based on three types of demand distributions: Normal, Poisson, and Exponential. The simulation was run for 10,000 iterations considering the variation of holding cost (C_h) backordering cost (C_b), ordering cost (C_o) and lead time uncertainty.

Simulation Assumptions and Parameters

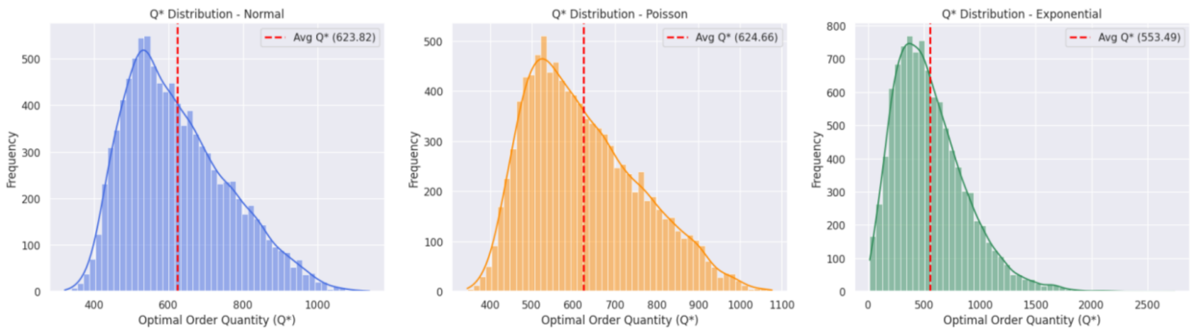
To ensure that the simulation model reflects real conditions, this study uses the following assumptions:

1) Demand is stochastic, following one of three distributions: Normal, Poisson, or Exponential.
2) The holding cost (C_h) and backordering cost (C_b) are not constant but vary within a certain range.
3) Ordering costs (C_o) also vary, reflecting dynamic operational conditions.
4) Lead time is not fixed, ranging from 80% to 120% of the average expected value.
5) The ordering cycle is repeated up to 10,000 iterations, to ensure a stable distribution of results.

The cost parameters used in the simulation are:

Ordering cost (C_o)	: varies between Rp 4,000 - Rp 6,000.
Holding cost (C_h)	: varies between Rp 10 - Rp 30 per unit per year.
Backordering cost (C_b)	: varies between Rp 30 - Rp 80 per unit per year.
Expected annual demand (E[D])	: 1,000 units/year.
Lead time variation	: 80% - 120% of the average.

Impact of Demand Uncertainty on Optimal Order Quantity (Q^*)



Figures 1. Monte Carlo simulation: Distribution of optimal order quantity (Q) for different demand models

The simulation results show that the optimal order quantity (Q^*) varies based on the demand distribution
- Normal Distribution ($Q^* = 624,10$): Relatively stable demand results in a more consistent ordering policy centered around the mean.

- Poisson Distribution ($Q^* = 625{,}18$): Similar results to the Normal distribution, but with a slightly wider spread due to its discrete nature.
- Exponential Distribution ($Q^* = 552{,}49$): More frequent small-volume demand results in a lower optimal order quantity, to avoid overstocking.

Figure 1 illustrates the distribution of optimal order quantities for each demand distribution. In a manufacturing environment facing high uncertainty, the optimal order quantity must be adjusted to the prevailing demand distribution pattern.

Impact of Demand Uncertainty on Total Inventory Cost (TC)

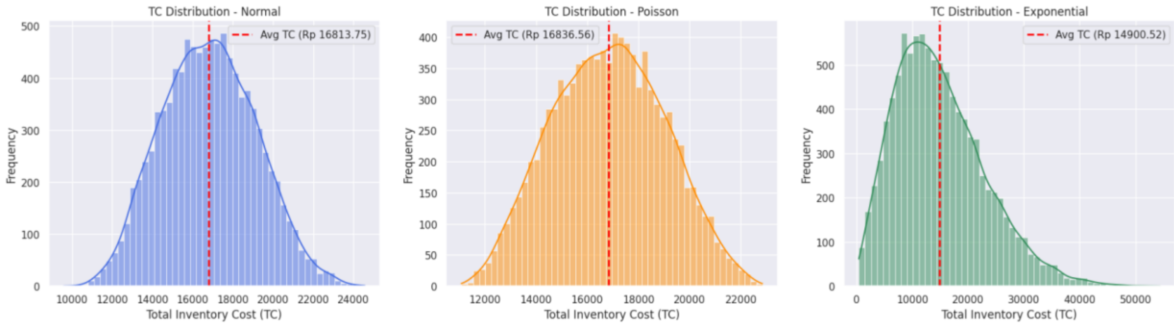


Figure 2. Monte Carlo simulation: Distribution of total ınventory cost (TC) for different demand models

The distribution of inventory cost (TC) also shows significant differences between the three demand scenarios. The Normal distribution ($TC = Rp16{,}837.56$) and Poisson ($TC = Rp16{,}866.62$) have similar cost distribution patterns. The Exponential distribution ($TC = Rp14{,}921.49$) results in lower inventory costs, as less stock is kept to accommodate more sporadic demand patterns. Figures 2 show the distribution of total inventory costs for each type of demand. Thus, under conditions of high demand uncertainty, the EOQ model with Partial Backordering can reduce inventory costs by adjusting the order quantity and holding policy.

Managerial Implications

The results of this study provide several important insights for supply chain management:
If demand is stable as in Normal or Poisson distribution, the company can maintain a larger order quantity to improve inventory efficiency. On the other hand, if demand is unstable as in Exponential distribution, the company should be more flexible in its holding and ordering policies and rely on backordering strategy to avoid high holding costs. In addition, fluctuations in holding costs, back ordering costs, and inconsistent lead times have different effects on inventory decisions, so a dynamic stock strategy is more advisable.

Conclusion

This study explores the effect of demand uncertainty in the EOQ model with Partial Backordering using Monte Carlo simulation. The results of the analysis show that demand distribution, cost variation, and lead time uncertainty have a significant impact on the optimal order quantity and total inventory cost. The following are the main conclusions of this study:

(1) The Effect of Demand Uncertainty on EOQ with Partial Backordering
The simulation results show that the optimal order quantity and total inventory cost are highly dependent on the demand distribution pattern used. Demand that follows the Normal and Poisson distributions produces a more stable order quantity compared to the Exponential distribution, where the order quantity tends to be smaller to avoid the risk of excess stock.

(2) Variation of Cost and Lead Time Parameters
Variation of holding costs and backordering costs have a significant impact on ordering decisions. When holding costs are high, the order quantity is smaller to avoid stock accumulation, while when backordering costs are high, the ordering policy tends to avoid stockouts by increasing the order quantity. In addition,

variable lead times cause fluctuations in the optimal order quantity, where longer lead times increase backordering costs and require a more adaptive ordering strategy.

(3) Impact of Demand Distribution on Total Inventory Cost
The simulation results show that demand distribution affects total inventory cost. In Normal and Poisson distributions, inventory cost is higher because the order quantity is larger to maintain stock availability. Meanwhile, in Exponential distribution, total inventory cost is lower because the order quantity is smaller, reflecting a more flexible stock strategy in dealing with irregular demand.

(4) Implications for Inventory Management in Manufacturing Industry
The EOQ model with Partial Backordering developed in this study can help companies determine more flexible inventory policies based on changing demand patterns and costs. By considering variations in holding costs, backordering costs, and lead time uncertainty, stock management strategies can be optimized to balance between optimal order quantities and total inventory costs.

The EOQ model with Partial Backordering that considers demand uncertainty can optimize inventory policies and reduce costs. This research can be further developed by considering external factors such as price fluctuations and seasonal demand to be more relevant in industrial practice.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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