UDC 658.511 **doi: 10.20998/2078-7405.2026.104.03**

# INVENTORY PLANNING FOR 3D-PRINTED SPARE PARTS UNDER UNCERTAIN DEMAND

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**Received: 25 March 2026 / Revised: 10 April 2026 / Accepted: 25 April 2026 / Published: 15 May 2026**

**Abstract.** *In recent years, additive manufacturing technologies have increasingly appeared in industrial spare parts logistics systems. Instead of maintaining large inventories of finished components, companies can increasingly rely on digital inventories and produce spare parts on demand using 3D printing. This shift creates new decision-making challenges related to the management of raw printing materials and the planning of production under uncertain demand. This paper proposes a two-echelon newsvendor model for inventory planning in additive manufacturing-based spare parts supply systems. In the proposed framework, the first decision stage determines the quantity of raw printing material to be stocked before demand realization, while the second stage determines the number of spare parts produced in response to stochastic customer demand. The model captures the trade-offs between material procurement cost, inventory holding cost, and shortage penalties. The mathematical formulation is developed as a two-stage stochastic optimization problem. Numerical experiments are conducted to analyze the relationship between raw material inventory levels and expected system cost. The results show that the cost function exhibits a well-defined minimum and that the optimal material inventory level strongly depends on shortage cost parameters. Sensitivity analysis further demonstrates how shortage penalties influence optimal inventory decisions. The findings highlight the strategic role of raw material inventory in additive manufacturing supply systems and provide practical insights for companies adopting 3D printing technologies in spare parts logistics.*

**Keywords:** *additive manufacturing; spare parts logistics; two-echelon newsvendor model; inventory planning; stochastic demand; supply chain optimization.*

## 1. Introduction

Efficient spare parts management is a critical component of modern industrial logistics. Industries such as aerospace, automotive manufacturing, and heavy machinery rely heavily on the availability of spare parts to maintain system reliability and minimize downtime. However, spare parts demand is often highly uncertain and intermittent, which makes traditional inventory management approaches costly and inefficient. Maintaining large inventories to ensure availability can lead to high holding costs, while insufficient stock may result in service delays or production disruptions.

For several decades, the Institute of Logistics at the University of Miskolc has been actively engaged in the analysis and design of logistics systems [1–4]. This research direction has played an important role not only in education but also in industrial research and development activities. One of the strategic objectives of this research field is to continuously explore new application areas where modern optimization methods can support practical logistics decision-making. In this context, additive manufacturing and the supply chains associated with 3D printing represent a promising and emerging field of application [5, 6].

In several industrial projects related to spare parts logistics, it can be observed that many companies still rely primarily on traditional stocking strategies, even when new manufacturing technologies could offer alternative solutions. This practical observation highlights that the integration of new technologies into logistics decision-making frameworks often lags behind technological development itself.

From the author's perspective, additive manufacturing may fundamentally reshape the traditional logic of spare parts logistics. While classical supply chains were designed around centralized production and long-term storage of physical products, 3D printing enables a more flexible, decentralized, and demand-driven production approach. Instead of storing large quantities of finished products, companies may increasingly rely on digital inventories and produce components only when they are required.

Although additive manufacturing is frequently described as a disruptive technology, its practical integration into analytical logistics models remains relatively limited. In particular, the interaction between raw material stocking decisions and on-demand production planning has received only limited attention in the operations research literature. This raises an interesting research question: how can classical stochastic inventory models [7,8] be adapted to capture the decision-making challenges arising in additive manufacturing environments?

This observation motivates the development of analytical models that combine established inventory theory with emerging manufacturing technologies. One of the most widely used stochastic inventory models is the newsvendor model, which determines the optimal order quantity for a single period under uncertain demand. While the classical newsvendor model considers only a single decision point, many real-world supply systems involve multiple sequential decision stages.

In additive manufacturing-based spare parts logistics, two key decision stages can be identified. The first stage corresponds to the stocking of printing materials, while the second stage represents the production of spare parts in response to uncertain customer demand. These two stages are inherently connected, since the number of parts that can be produced is limited by the available raw material.

In the author's view, the integration of additive manufacturing technologies with established operations research models offers an interesting opportunity to bridge theoretical modeling and practical industrial challenges. Exploring such hybrid manufacturing–logistics systems may contribute both to the academic literature and to practical decision support in modern supply chains.

This paper therefore proposes a two-echelon newsvendor framework for modeling inventory decisions in a 3D printing-based spare parts supply system. In the proposed system, the first stage represents the stocking decision for printing material, while the second stage determines the number of parts produced to meet uncertain customer demand. The model captures the trade-offs between material procurement costs, inventory holding costs, and shortage penalties resulting from unmet demand.

The main objective of this study is to develop a stochastic optimization model that supports decision-making in additive manufacturing spare parts logistics under demand uncertainty. By integrating raw material inventory decisions with production planning, the proposed model provides a structured approach to balancing supply chain costs and service levels in additive manufacturing environments.

The remainder of the paper is organized as follows. Section 2 describes the problem setting and system structure. Section 3 presents the mathematical formulation of the proposed model. Section 4 discusses the numerical analysis. Finally, Section 5 concludes the paper and outlines potential directions for future research.

## 2. Problem description

This study considers a spare parts supply system supported by additive manufacturing technology. The system is designed to provide spare components under uncertain demand conditions while maintaining a balance between inventory costs and service level requirements. In contrast to traditional spare parts logistics, where finished products are stored in advance, the considered system relies on the storage of printing materials and the possibility of producing parts on demand using 3D printing technology (see Figure 1).

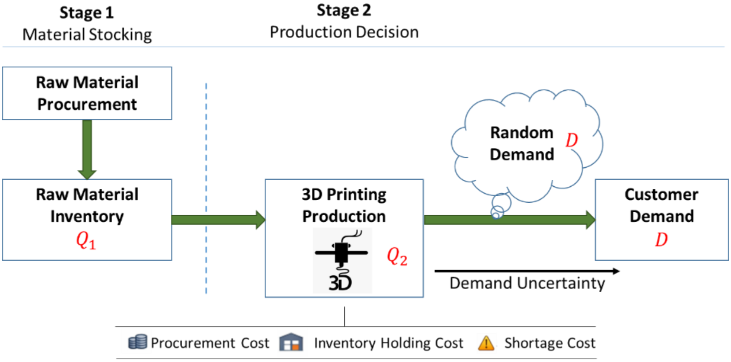

Figure 1 – Two-stage structure of additive manufacturing spare parts supply system [own elaboration].

The proposed system consists of two sequential decision stages. The first stage corresponds to the inventory decision related to the raw material required for additive manufacturing. The second stage represents the production decision, where spare parts are produced in response to realized demand. These two stages form a two-echelon decision structure, since the production of spare parts is directly constrained by the availability of printing material.

At the beginning of the planning period, the decision-maker determines the quantity of raw material to be stocked. This decision must be made before the actual demand for spare parts becomes known. The stocked material represents the available capacity for future production, and therefore it plays a critical role in determining the responsiveness of the system.

After the demand for spare parts is realized, the second decision stage takes place. At this point, the decision-maker determines how many spare parts should be produced using the available material. Since the production quantity cannot exceed the available raw material, the production decision is constrained by the initial stocking decision. If the produced quantity is insufficient to meet demand, shortage costs may occur, representing lost sales, delayed service, or other operational penalties.

The demand for spare parts is assumed to be stochastic and is represented by a random variable. This reflects the typical characteristics of spare parts demand, which is often irregular and difficult to predict. The objective of the decision-maker is to determine the optimal raw material stocking level and production quantity that minimize the expected total cost of the system.

The total cost of the system may include several components. First, there is a procurement cost associated with purchasing the raw printing material. Second, inventory holding costs may arise if part of the material remains unused after the production decision. Third, holding costs may also occur if produced spare parts exceed realized demand. Finally, shortage costs are incurred when the realized demand exceeds the available produced quantity.

The decision structure of the system can therefore be interpreted as a two-stage stochastic decision problem. The first-stage decision determines the raw material inventory level, while the second-stage decision determines the production quantity after the uncertainty in demand has been revealed. This structure naturally leads to a two-echelon newsvendor-type model, where the first echelon represents material stocking and the second echelon represents spare part production.

From a practical standpoint, such a system can be observed in modern spare parts supply chains where additive manufacturing technologies are used to complement or partially replace traditional inventory-based strategies. Instead of storing large numbers of finished components, companies may maintain a stock of printing material and produce parts only when they are required.

The decision process considered in this study can be conceptually illustrated as a two-stage supply chain structure. In the first stage, printing material is procured and stored, while in the second stage spare parts are produced using the available material to satisfy uncertain customer demand.

To formally describe the decision problem, several key elements are considered in the model. Let $Q_1$ denote the quantity of printing material stocked at the beginning of the planning period, and let $Q_2$ denote the number of spare parts produced after demand realization. The demand for spare parts is represented by a random variable $D$. The model considers material procurement cost, inventory holding costs, and shortage penalties associated with unmet demand. The following section presents the mathematical formulation of the proposed optimization model.

## 3. Mathematical Model of the Two-Echelon Inventory System

This section presents the mathematical formulation of the proposed two-echelon newsvendor model for additive manufacturing-based spare parts supply under demand uncertainty. The model describes the sequential relationship between raw material stocking and spare part production while capturing the main cost components of the system.

The planning horizon is assumed to consist of a single decision period. During this period the demand for spare parts is uncertain and is represented by a random variable. The decision process therefore takes place in two stages. In the first stage the decision-maker determines the quantity of raw material required for additive manufacturing. This decision must be made before the actual demand becomes known. After the realization of demand, the second stage begins, where the number of spare parts to be produced is determined based on the available raw material.

Let $D$ denote the stochastic demand for spare parts. The first-stage decision variable is $Q_1$ which represents the quantity of raw printing material stocked before demand realization. After demand becomes known, the second-stage decision variable $Q_2(D)$ determines the number of spare parts produced in response to the realized demand. Since spare parts can only be produced from available material, the production quantity cannot exceed the available raw material inventory.

The cost structure of the system includes several components. First, a procurement cost arises when raw printing material is purchased. In addition, holding costs may occur if part of the raw material remains unused after the production decision. Further holding costs may also appear when the produced number of spare parts exceeds the realized demand.

Finally, shortage costs are incurred if demand exceeds the available production quantity. In order to describe the inventory dynamics of the system, three quantities are introduced. The first quantity corresponds to the unused raw material that remains after production.

This quantity can be written as

$$I_1 = Q_1 - Q_2(D)$$

where $I_1$ denotes the remaining raw material inventory.

The second quantity represents the surplus finished spare parts that remain after demand has been satisfied. This situation occurs when the production quantity exceeds the realized demand. The surplus inventory can therefore be expressed as

$$I_2 = (Q_2(D) - D)^+$$

where the operator $(x)^+ = \max(x, 0)$ denotes the positive part of a value.

The third quantity corresponds to the shortage that occurs when the realized demand exceeds the produced quantity. The shortage amount can therefore be written as

$$B = (D - Q_2(D))^+$$

These expressions allow both surplus inventory and unmet demand to be represented in a compact mathematical form.

Based on these quantities, the total cost of the system can be defined. The overall cost consists of four components: the procurement cost of raw material, the holding cost of unused material, the holding cost of surplus finished spare parts, and the shortage cost resulting from unmet demand. The objective of the decision-maker is therefore to determine the decision variables that minimize the expected total cost of the system. The expected cost function of the system can be written as

$$\min_{Q_1, Q_2(D)} \left[c \cdot Q_1 + \mathbb{E}(h_1 \cdot \left(Q_1 - Q_2(D)\right) + h_2 \cdot (Q_2(D) - D)^+ + p \cdot (D - Q_2(D))^+)\right]$$

subject to the material availability constraint

$$0 \leq Q_2(D) \leq Q_1$$

and the non-negativity condition

$$Q_1 \geq 0.$$

The operator $\mathbb{E}(\cdot)$ denotes the expected value with respect to the stochastic demand. The first term of the objective function represents the procurement cost of raw material. The remaining terms describe the expected holding costs of unused material, the holding costs of surplus finished spare parts, and the penalty associated with unmet demand.

The structure of the model can also be interpreted within the framework of two-stage stochastic programming. In this interpretation the first-stage decision determines the raw material inventory level, while the second-stage decision determines the production quantity after the realization of demand. This structure reflects the operational flexibility offered by additive manufacturing systems, where production decisions can adapt to realized demand within the limits imposed by the available raw material.

## 4. Numerical results and sensitivity analysis

This section presents the numerical results obtained for the proposed model in the context of additive manufacturing-based spare parts supply. The objective of the analysis is to illustrate how the raw material inventory level influences the expected operational cost of a spare parts system where components are produced on demand using 3D printing technology.

The numerical experiments also reflect the two-stage decision structure introduced in the mathematical model. In the first stage, the decision-maker determines the raw material inventory level $Q_1$, representing the available printing material. In the second stage, after the realization of demand $D$, spare parts are produced using additive manufacturing technology up to the limit imposed by the available material inventory.

### Numerical Input Data

For the numerical experiments, the model parameters were specified based on a simplified spare parts demand scenario. The demand for the considered spare part was represented by three discrete demand scenarios in order to illustrate the stochastic nature of spare parts demand. The demand levels were assumed to be $d_1 = 80, d_2 = 100, d_3 = 120$ units with corresponding probabilities 0.30, 0.50, and 0.20 respectively.

The cost parameters of the system were defined as follows. The procurement cost of raw printing material was set to $\mathrm{c} = 5$ cost units per unit. The holding cost of unused raw material was assumed to be $h_1 = 1$ cost unit per unit, while the holding cost of surplus finished spare parts was $h_2 = 2$ cost units per unit. The shortage cost associated with unmet demand was assumed to be $\mathrm{p} = 10$ cost units per unit.

In the numerical analysis, the candidate raw material inventory level $Q_1$ was evaluated within the interval $0 \leq \mathrm{Q}_1 \leq 160$. For each possible value of $Q_1$, the production decision was determined according to the available raw material and the realized demand scenario. Accordingly, the production quantity in scenario $s$ was defined as

$$Q_{2s} = min(Q_1, d_s),$$

which reflects the assumption that spare parts are produced on demand, but the production quantity cannot exceed the available raw material inventory.

Based on these parameters, the expected total cost of the system was calculated for each inventory level, and the optimal raw material inventory level was determined. The numerical calculations and graphical illustrations presented in this section were generated using MATLAB.

### Expected Total Cost and Optimal Inventory Level

Figure 2 illustrates the relationship between the raw material inventory level $Q_1$ and the expected total cost of the system. When the available material inventory is very low, the system frequently experiences shortages because insufficient printing material is available to produce the required spare parts. For example, when

$Q_1 = 0$, the expected total cost is approximately 980 cost units, mainly driven by shortage penalties.

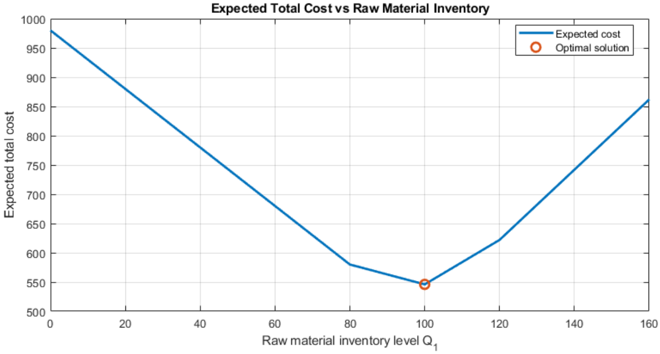

Figure 2 – Expected total cost vs. raw material inventory [own elaboration].

As the inventory level increases, the expected cost decreases significantly because the system gains greater production flexibility. When the inventory level reaches $Q_1 = 80$ units, the expected cost decreases to 580 cost units.

The minimum expected cost occurs at $Q_1^* = 100$, where the expected total cost is approximately $C(Q_1^*) = 550$.

This value represents the optimal balance between shortage costs and inventory-related costs. If the material inventory increases further, the expected cost begins to rise again. For example, at $Q_1 = 160$ the expected cost increases to 860 cost units, mainly due to increasing procurement and holding costs.

### Analysis of Cost Components

Figure 3 decomposes the total cost into procurement cost, raw material holding cost, finished goods holding cost, and shortage cost.

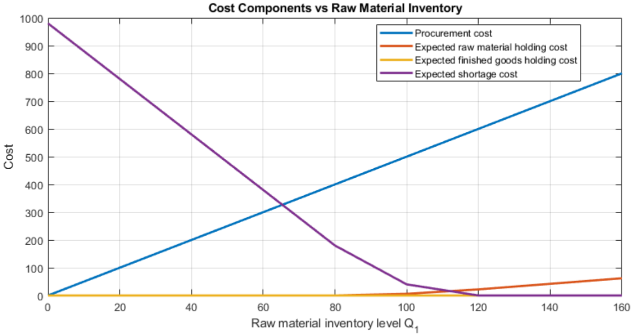

Figure 3 – Cost components vs. raw material inventory [own elaboration].

The procurement cost increases linearly with the inventory level according to $c \cdot Q_1$, which reflects the cost of acquiring printing material used in the additive manufacturing process.

In contrast, the expected shortage cost decreases rapidly as the inventory level increases. When no printing material is available, the system cannot produce spare parts and shortages occur in every demand scenario, resulting in an expected shortage cost of 980 cost units. As the inventory level increases, the additive manufacturing system becomes capable of responding to demand more effectively, significantly reducing shortage penalties. Around $Q_1 = 100$ the expected shortage cost becomes very small and above 120 units it is almost negligible.

The expected holding cost of raw material gradually increases as the inventory level grows, because larger inventories increase the probability that part of the material remains unused during the planning period. At $Q_1 = 160$ the expected raw material holding cost reaches 60 cost units.

The holding cost of finished spare parts remains minimal across most of the examined range. This reflects one of the main advantages of additive manufacturing: spare parts are produced only when demand occurs, reducing the need for storing finished goods.

## Sensitivity Analysis with Respect to Shortage Cost

Figure 4 presents the sensitivity of the optimal raw material inventory level to changes in the shortage cost parameter $p$.

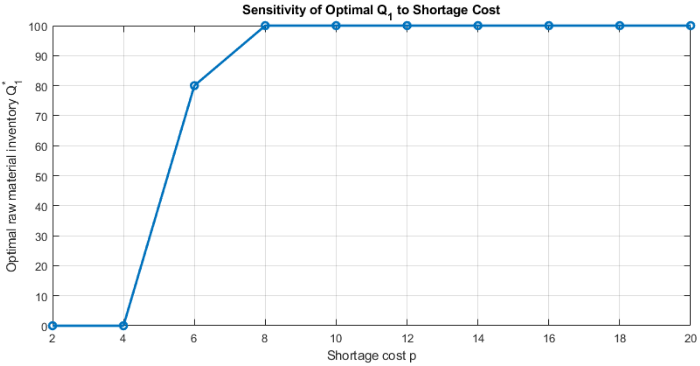

Figure 4 – Sensitivity of optimal $Q_1$ to shortage cost [own elaboration].

When shortage costs are very low ($p = 2$ or $p = 4$), the optimal inventory level is essentially zero, indicating that maintaining raw material inventory is not economically justified. When the shortage cost increases to $p = 6$, the optimal inventory level rises sharply to $Q_1 = 80$ units.

For shortage cost values above $p = 8$, the optimal inventory level stabilizes around $Q_1^* = 100$, which approximately corresponds to the most probable demand level.

## Sensitivity of the Minimum Expected Cost

Figure 5 illustrates how the minimum expected total cost changes as a function of the shortage cost parameter. As expected, higher shortage penalties increase the overall expected system cost.

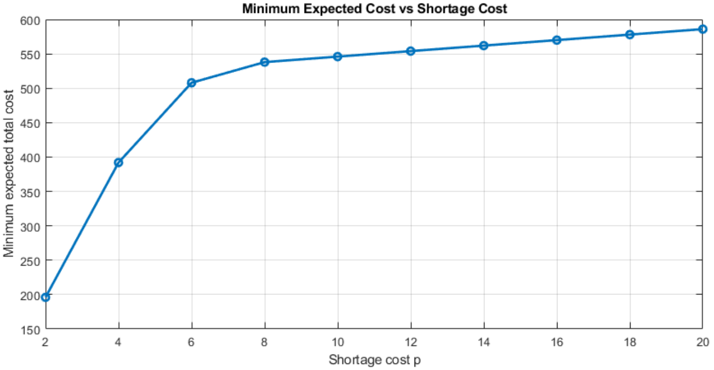

Figure 5 – Minimum expected cost vs. shortage cost [own elaboration].

When $p = 2$, the minimum expected cost is approximately 200 cost units. When the shortage cost increases to $p = 10$, the minimum expected cost rises to 550 cost units. For higher shortage cost values the expected cost increases gradually, reaching 590 cost units when $p = 20$.

## Managerial Implications

The numerical results provide several insights for supply chain managers implementing additive manufacturing technologies. First, raw printing material inventory plays a critical role in ensuring the responsiveness of 3D printing-based spare parts supply systems. Maintaining an adequate level of printing material allows companies to exploit the flexibility of additive manufacturing and produce spare parts on demand.

Second, the optimal inventory level strongly depends on the economic consequences of shortages. In industries where equipment downtime is costly, maintaining higher levels of printing material inventory becomes economically justified.

Finally, the analysis demonstrates that additive manufacturing can reduce the need for storing finished spare parts. Instead of maintaining large finished goods inventories, companies may rely on raw material inventory combined with digital spare parts models, producing components only when actual demand occurs.

## 5. Discussion and Conclusions

The results of this study demonstrate how classical inventory theory can be adapted to emerging manufacturing technologies such as additive manufacturing. By extending the traditional newsvendor framework to a two-echelon decision structure, the proposed model captures the interaction between raw material stocking decisions and on-demand production enabled by 3D printing. The numerical analysis confirms that the optimal raw material inventory level is determined by a trade-off between shortage penalties and inventory-related costs. When raw material inventory is insufficient, the system experiences frequent shortages, leading to high penalty costs. Conversely, excessive material inventory increases procurement and holding costs. The optimal solution therefore emerges at the point where these opposing cost components are balanced.

An important insight of the study is the strategic role of raw material inventory in additive manufacturing environments. Unlike traditional spare parts supply chains that rely on storing finished products, additive manufacturing enables a more flexible production approach where raw material inventory effectively represents production capacity. Maintaining an appropriate level of printing material allows companies to respond to uncertain demand while avoiding excessive finished goods inventory. The sensitivity analysis also highlights the strong influence of shortage cost parameters on the optimal inventory decision. In industries where equipment downtime is costly, maintaining higher levels of printing material inventory may be economically justified in order to ensure service availability.

From a practical perspective, the proposed model provides a structured analytical framework for supporting inventory decisions in additive manufacturing-based spare parts logistics. The model can assist decision-makers in determining appropriate raw material stocking levels while considering demand uncertainty and cost trade-offs. Future research may extend the proposed framework in several directions. Possible extensions include multi-period decision models, multiple spare parts types, capacity constraints of additive manufacturing systems, and the integration of distributed 3D printing networks within spare parts supply chains.

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# ПЛАНУВАННЯ ЗАПАСІВ 3D-ДРУКОВАНИХ ЗАПЧАСТИН ЗА НЕВИЗНАЧЕНОГО ПОПИТУ

**Анотація.** *Останніми роками технології адитивного виробництва дедалі частіше з'являються в логістичних системах промислових запасних частин. Замість того, щоб підтримувати великі запаси готових компонентів, компанії дедалі більше покладаються на цифрові запаси та виготовляють запчастини за запитом за допомогою 3D-друку. Ця зміна створює нові виклики для прийняття рішень, пов'язані з управлінням сировиною для друку та плануванням виробництва за умов невизначеного попиту. У цій статті пропонується модель продавця новин на два рівні для планування запасів у системах постачання запасних частин на основі адитивного виробництва. У запропонованій структурі перший етап прийняття рішення визначає кількість сировини для друку до реалізації попиту, тоді як другий етап визначає кількість запасних частин, виготовлених у відповідь на стохастичний попит клієнтів. Модель відображає компроміси між витратами на закупівлю матеріалів, витратами на зберігання запасів і штрафами за дефіцит. Математичне формулювання розроблено як двоетапна задача стохастичної оптимізації. Проводяться чисельні експерименти для аналізу взаємозв'язку між рівнем запасів сировини та очікуваною вартістю системи. Результати показують, що функція витрат має чітко визначений мінімум, а оптимальний рівень запасів матеріалів значною мірою залежить від параметрів дефіциту витрат. Аналіз чутливості додатково демонструє, як штрафи за дефіцит впливають на оптимальні рішення щодо запасів. Результати підкреслюють стратегічну роль запасів сировини в системах постачання адитивного виробництва та дають практичні інсайти для компаній, які впроваджують технології 3D-друку в логістиці запасних частин.*

**Ключові слова:** *адитивне виробництво; логістика запасних частин; модель продавця газет, яка має дворівневу структуру; планування запасів; стохастичний попит; оптимізація ланцюга постачання.*