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Blockchain Implementation in Cold Supply Chains: A Stackelberg Game Analysis of Perceived Risk and Its Effect on Profitability

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Abstract

This paper analyzes the role of blockchain technology in managing the cold supply chain of deteriorating products. Blockchain, as an innovative technology, has significantly enhanced transparency and traceability. These advantages are particularly critical in the supply chain of deteriorating items, as these products have a limited consumption window and their quality depends on proper handling and transportation. The analytical framework of this study is based on a Stackelberg game model of a manufacturer and a retailer, examining the effects of this technology on demand and supply chain profitability. The customer utility function is modeled by considering the product's value and blockchain-related factors, and the impacts of blockchain technology on perceived risk and customer decision-making are evaluated. The modeling results indicate that, under normal conditions, implementing blockchain improves transparency, increases demand, and consequently enhances the overall profitability of the supply chain. However, when customers' perceived risk increases due to unfavorable or inconsistent information, the profitability of both the retailer and the manufacturer may decline compared to the case without blockchain. These findings highlight that blockchain adoption is not universally beneficial for the supply chain and must be carefully implemented, considering specific market conditions and customers' perceived risks.

Keywords: Cold supply chain, Blockchain technology, Deteriorating products, Game theory.

1 | Introduction

The Cold Supply Chain is a system in which temperature-sensitive products, such as perishable food, pharmaceuticals, and vaccines, are maintained within a specific temperature range throughout all stages of

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transportation and storage to ensure their quality and safety. These supply chains face challenges such as premature deterioration, resource wastage, and a lack of customer trust in product quality. Their primary goal is to prevent product deterioration and reduce waste caused by improper temperature management. An example of a cold supply chain is the dairy product supply chain, where products must be stored at controlled temperatures. From the moment these products are produced in the factory to their transportation, distribution to retail stores, and storage at the point of sale, temperatures must be continuously monitored to prevent deterioration and preserve product freshness. A lack of access to accurate information on storage conditions and the product's history can lead to consumer distrust, quality issues, and high costs associated with quality management and waste. Blockchain technology enables the collection and sharing of accurate, continuous, and immutable information about the temperature and storage conditions of products. This capability can influence consumer decision-making, as customers are more likely to prefer products with better storage conditions over competing options. By increasing consumer confidence in product safety and quality, blockchain becomes particularly significant for highly perishable food products, such as dairy. For a product like milk, which requires precise handling and transportation, the advantages of blockchain technology are undeniable. In the cold milk supply chain, maintaining proper temperature is critical to prevent spoilage. At any point in the chain, if the milk's temperature deviates from the acceptable range, the blockchain immediately records this anomaly and alerts all stakeholders. Such alerts enable companies to take corrective actions promptly, ensuring product integrity.

If any temperature deviation occurs, customers are notified and can decide whether to purchase the product. When the customer, through blockchain, realizes that the product has not been stored under proper conditions and consequently decides not to purchase it, this occurrence, enabled by the increased transparency and trust it provides, will lead to enhanced confidence in the supply chain, ensuring its competitiveness and quality. Given the rapid advancement of blockchain technology and its significance in improving supply chain efficiency, along with modern consumers' increasing demand for accurate and transparent information, research in this field can uncover new and innovative applications. It can also help optimize cold supply chain performance and develop new models for effective temperature and quality management. Additionally, consumers' growing awareness and concerns about product quality and safety, particularly for temperature-sensitive items, underscore the need for advanced, effective solutions.

Therefore, in this paper, we investigate the implementation of blockchain technology by the manufacturer in the cold supply chain (dairy products). The use of this technology not only enhances transparency regarding the temperature conditions under which the product is stored but also introduces perceived risk for customers. In other words, customers may perceive that there is incomplete or inaccurate information about the product or its storage conditions. The cold supply chain examined in this study consists of a manufacturer and a retailer, with the manufacturer as the decision-maker, and the relationship between the members is modeled as a Stackelberg game.

The structure of the paper is as follows. Section 2 reviews the related literature. Section 3 presents the problem formulation and modeling. Section 4 outlines the solution procedure for the model, while Section 5 provides the results of the model solution. Finally, Section 6 concludes the study and offers directions for future research.

2 | Literature Review

In this section, we analyze and review the existing literature on cold supply chain management and the application of blockchain technology in managing deteriorating goods supply chains.

Liu et al. [1] developed a vaccine supply chain model consisting of a vaccine manufacturer, a blockchain-based vaccine tracking platform, and a vaccination unit to discuss pricing and coordination mechanisms. This study analyzes the pricing and coordination of the vaccine supply chain facilitated by blockchain technology. The paper by Kayikci et al. [2] explores the potential of blockchain technology (BT) to support operational excellence in the supply chain of deteriorating products during the COVID-19 pandemic. Liu et al. [3] focused on blockchain implementation by developing a vaccine supply chain game model comprising a vaccine manufacturer and a vaccination unit. The study analyzes the conditions under which blockchain technology can be applied. The vaccine manufacturer and the vaccination unit jointly build the blockchain, sharing a contract that improves vaccine supply chain performance, although it does not optimize total profit to its ideal level. Priyan [4] investigated the impact of digital technologies and carbon emissions on improving supply chain decision-making by integrating fuzzy logic and blockchain technology. In this study, defective items are returned to the supplier after inspection. The objective is to determine optimal strategies for minimizing both carbon emissions and the total system cost. Hamidoglu et al. [5] proposed an IoT-based agricultural supply chain integrated with a cooperative Nash game between telecommunications operators and agricultural companies. The goal of the paper is to establish collaborative decision-making procedures prior to the integration of blockchain technology into the supply chain, which is regulated by a government subsidy policy. Zhang et al. [6] examined the effects of blockchain-based digital transformation in a cold supply chain consisting of a manufacturer, a retailer, and a third-party logistics provider (3PL). In this model, the manufacturer is a fresh product company, while the retailer is a major retail platform. Deterioration occurs during both production and transportation through the third-party logistics provider. Cao et al. [7] analyzed how the adoption of a blockchain-based platform influences the decisions of agricultural supply chain members. Considering a two-tier supply chain, they defined game models with and without the blockchain-based platform. Yadav et al. [8] examined the economic impact of the medical industry during the COVID-19 pandemic on cumulative demand for ramp-type items, accounting for inflation effects and wastewater disposal costs in a two-warehouse system. The study assumes that the economic impact of blockchain on inventory costs is greater in rented warehouses than in owned warehouses. Marchese and Tomarchio [9] presented a comprehensive model for a blockchain-based agricultural food supply chain tracking system and demonstrated its application through a prototype. The primary focus of this system is to leverage blockchain features to allow supply chain members to store and manage product tracking information in a transparent, reliable, and tamper-proof manner. Li et al. [10] considered a fresh agricultural product supply chain consisting of a supplier and a retailer. The retailer is responsible for both wholesale and retail sales of fresh agricultural products, determining the degree of blockchain adoption and advertising efforts. Meanwhile, the supplier determines green investments and efforts to maintain product freshness. Zheng and Zhou [11] developed a sustainable model for integrating agricultural logistics based on blockchain technology and proposed a comprehensive blockchain-enabled smart logistics model for agricultural products. Yuan et al. [12] developed a theoretical game model to analyze the optimization of tracking schemes for low-end fresh products and high-end fresh products within a competitive fresh product supply chain. The study also explored the impact of power structure on tracking schemes, identifying conditions under which one scheme outperforms others. Ma et al. [13] investigated the role of blockchain in mitigating food contamination. The study developed a game model for a two-tier supply chain comprising two suppliers and one retailer to analyze the strategic deployment of the retailer's efforts to minimize contamination while utilizing blockchain technology. Interestingly, for Contamination-Vulnerable Food (CVF), blockchain adoption enhances cooperation between suppliers and retailers, whereas the likelihood of cooperation decreases for Contamination-Resistant Food (CRF). Yang et al. [14] evaluated the use of blockchain technology to address the issue of inaccurate freshness reporting in a two-tier fresh product supply chain consisting of a rural cooperative and a centralized supermarket. Mohan Modak et al. [15] examined a two-tier supply chain involving a retailer and a manufacturer. The manufacturer not only produces and processes fresh agricultural products but also simultaneously operates as an online seller. Jiang et al. [16] analyzed blockchain integration strategies in a three-tier livestock meat supply chain, where consumers prefer trust in product quality. The results reveal how consumer preferences for quality trust influence blockchain integration and transaction decisions among supply chain participants.

Based on the aforementioned studies, the application of blockchain technology in cold supply chains for deteriorating products has not yet been thoroughly analyzed or evaluated. Given the high sensitivity of products such as dairy to temperature fluctuations, the necessity for precise temperature control to maintain quality and prevent deterioration, and the need for product traceability to enhance customer trust and ultimately drive purchasing decisions, examining the adoption of blockchain technology in these supply chains is of significant importance. Therefore, this paper investigates the role of blockchain in improving the performance of the dairy supply chain, considering the Stackelberg relationship among supply chain members and analyzing the conditions under which the manufacturer adopts this technology.

3 | Problem Definition and Model Formulation

The supply chain considered in this study is a two-level structure, with the first level comprising a manufacturer and the second level comprising a retailer. Given the manufacturer's leadership in decision-making, a Stackelberg game is formulated between the manufacturer and the retailer. Due to product deterioration, the manufacturer's decision to adopt blockchain technology aims to enhance customer trust in product quality and optimal storage conditions. However, despite the implementation of blockchain technology and the resulting transparency in product information available to customers at the point of purchase, customers' perceived risk does not entirely dissipate. In the context of cold supply chains and blockchain adoption, this perceived risk may encompass various dimensions that influence customers' purchasing decisions. An increase in perceived risk reduces the utility customers derive from the product. In other words, if customers perceive a high risk associated with purchasing the product (e.g., due to lingering concerns about transparency or potential quality issues), their overall utility decreases. Some customers may continue to harbor doubts about the accuracy and reliability of information provided by blockchain, despite its widespread use. This variation in customer trust levels may lead to residual perceived risk. Therefore, the utility function can be expressed as follows:

$$U = \lambda\vartheta - \beta p - \gamma\theta - R. \quad (1)$$

The problem parameters are presented in *Table 1*. In this paper, it is assumed that $\lambda \geq R$, which ensures that blockchain can be used as an optional technology for the manufacturer.

Table 1. Parameters and decision variables of the problem.

λ	Blockchain-based transparency enhancement regarding product quality, freshness, and temperature storage conditions
ϑ	Product value to the customer
β	Consumer price sensitivity
c	Fixed cost of the manufacturer
R	Perceived risk cost to the consumer due to the use of blockchain
θ	Product deterioration rate
γ	Consumer sensitivity to the deterioration rate
p	Retail price
T	Replenishment cycle
w	Wholesale price

Based on the utility function, the demand function is presented as follows:

$$D = 1 - \frac{\beta p + \gamma\theta + R}{\lambda}. \quad (2)$$

The inventory level of the retailer is given by

$$\frac{dI(t)}{dt} = -D - \theta I(t). \quad (3)$$

Considering the Condition $I(T) = 0$, we have:

$$I(t) = \frac{\left(1 - e^{(T-t)\theta}\right)(\beta p + \gamma\theta + R - \lambda)}{\theta\lambda}. \quad (4)$$

Q=I gives the order quantity(0). Therefore, the profit functions for the retailer and the manufacturer are defined as follows:

$$\pi_R = p\int_0^T D dt - wQ, \tag{5}$$

$$\pi_M = (w - c)Q. \tag{6}$$

4 | Mathematical Model Solution

Due to the leader-follower relationship among supply chain members and the problem modeling as a Stackelberg game, the retailer's optimal decisions are initially determined by solving the system. $\frac{\partial \pi_R}{\partial p} = 0$, $\frac{\partial \pi_R}{\partial T} = 0$. The solution to this system will determine p and T as a function of w.

$$p^* = -\frac{2R - w\beta + 2\gamma\theta - 2\lambda}{3\beta}, \tag{7}$$

$$T^* = -\frac{2(R + w\beta + \gamma\theta - \lambda)}{3w\beta\theta}. \tag{8}$$

Finally, the manufacturer's profit function is updated after the retailer's optimal decisions are determined, and the optimal value of the manufacturer's decision variable is determined.

Theorem 1. The values obtained from *Eqs. (7)* and *(8)* for the retailer's profit function are optimal and unique, maximizing the retailer's profit.

Proof: To prove this theorem, we show that $|H|_{2*2} > 0$.

$$\begin{aligned} |H|_{2*2} &= \frac{-1}{4\lambda^2}[-8Tw\beta\theta(\lambda - \gamma\theta - \beta p - R) + 4(-R - 2\beta p + w\beta + Tw\beta\theta - \gamma\theta + \lambda)^2] \\ &= \frac{-1}{4\lambda^2}\left[-8Tw\beta\theta(\lambda D) + 4\big(D + \beta(w + Tw\theta - p)\big)^2\right]. \end{aligned} \tag{9}$$

It is sufficient to show that the following expression is negative:

$$\left[-8Tw\beta\theta(\lambda D) + 4\big(D + \beta(w + Tw\theta - p)\big)^2\right]. \tag{10}$$

We assume that this expression is negative. Therefore, we have:

$$-8Tw\beta\theta(\lambda D) + 4\big(D + \beta(w + Tw\theta - p)\big)^2 < 0, \tag{11}$$

$$\big(D + \beta(w + Tw\theta - p)\big)^2 < 2Tw\beta\theta(\lambda D), \tag{12}$$

$$|D + \beta(w + Tw\theta - p)| < \sqrt{2Tw\beta\theta(\lambda D)}. \tag{13}$$

Given that the value of the expression $w + Tw\theta - p$ is always zero, the above relationship holds at all times.

Theorem 2. Given the obtained values for the retail price and Replenishment cycle, the manufacturer's profit function is concave, and the optimal wholesale price is unique.

Proof: To prove this, it is sufficient to show that $\frac{\partial^2 \pi_M}{\partial w^2} < 0$.

$$\frac{\partial^2 \pi_M}{\partial w^2} = \frac{4}{27w^4\beta^2\theta\lambda}[w(2w^3\beta^3 - (R + \gamma\theta - \lambda)^3) + 3c(R + \gamma\theta - \lambda)^3], \tag{14}$$

For the concavity of the manufacturer's profit function, the following Condition must hold:

$$w(2w^3\beta^3 - (R + \gamma\theta - \lambda)^3) + 3c(R + \gamma\theta - \lambda)^3 < 0. \tag{15}$$

Therefore, with the above Condition, we have: $\frac{\partial^2 \pi_M}{\partial w^2} < 0$.

Thus, the manufacturer's problem, considering *Condition (15)*, will be formulated as follows:

$$\begin{cases} \text{Max}\ \pi_M, \\ \text{s.t.}\quad w(2w^3\beta^3-(R+\gamma\theta-\lambda)^3)+3c(R+\gamma\theta-\lambda)^3<0. \end{cases} \quad (16)$$

This problem will be solved using the Karush-Kuhn-Tucker conditions, and the optimal wholesale price will be determined.

5 | Solution Results and Interpretation

Based on the parameter values shown in *Table 2*, the initial model results for both scenarios, with and without blockchain technology, are presented in this table. The results indicate a significant improvement in the supply chain's profitability when the manufacturer utilizes blockchain technology.

Table 2. Parameter values and corresponding model solutions.

						Model with blockchain technology	Model without blockchain technology
$\beta=0.4$	$\gamma=1$	$\theta=0.5$	$\lambda=4$	$R=1$	$c=1$	$\pi_R=0.82087, \pi_M=0.71688, T^*=3.56$ $p^*=4.73, w^*=1.7$	$\pi_R=0.00026$ $\pi_M=0.0004$

A question that may arise is whether using blockchain is always recommended, given its numerous advantages. To address this question, we examine the ranges of the parameters λ and R and determine for which values of these parameters the use of blockchain is advisable.

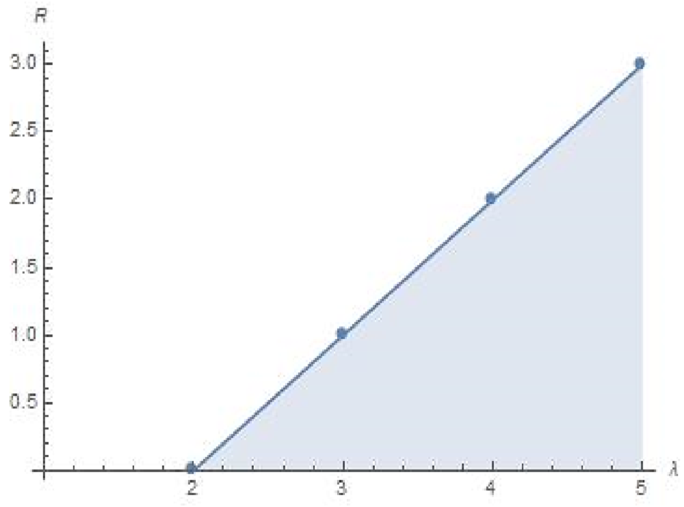

Fig. 1. The range of parameters λ and R for the adoption of blockchain technology.

It is known that when consumers' concerns about product information and storage conditions are low, the manufacturer can achieve higher profits by using blockchain technology than by not using it. On the other hand, when consumers are highly concerned about product information, it is wiser not to use blockchain, as shown in *Fig. 1*.

If the information provided to customers through tracking systems such as blockchain does not align with their expectations or standards, the perceived risk increases. For example, in cold supply chains, such as milk transportation, if the customer notices that the temperature has deviated from the permissible range at certain stages, even if the product is physically safe, they may perceive it as unsafe. Reports of disease outbreaks through dairy products, prolonged product stays in the supply chain without proper management, summer storage conditions in areas with significant temperature fluctuations, and longer transportation times can all increase perceived product quality risk.

In *Fig. 1*, the manufacturer's strategy regarding blockchain adoption is illustrated. As shown, in the dark area, the use of blockchain is recommended for both the manufacturer and the retailer. The more the customer's perceived risk is minimized, the greater the benefits of using blockchain. If customers do not have sufficient confidence in the product's information and storage conditions, using blockchain does not provide greater benefit than not using it, and this holds even as λ increases, as *Fig. 1* confirms.

The reason is that customers believe that transparency in product information provided by blockchain technology increases the product's value beyond the cost, offsetting consumer concerns when the perceived risk is small. It means that blockchain technology is more beneficial for supply chain members than its drawbacks. Therefore, the manufacturer (and the retailer) can achieve higher profits by reducing consumer concerns about perceived risk. Conversely, if consumers are the type who care about product risk due to incomplete or incorrect product information or storage conditions, they focus more on product risk and data security than on transparency in product information. In this case, if the manufacturer does not use blockchain technology, the supply chain members will gain higher profits.

6 | Conclusion

This study investigates the use of blockchain technology in cold supply chains for deteriorating products, specifically dairy products, with a focus on the interaction between the retailer and the manufacturer in a Stackelberg game framework. Using analytical models, the impact of blockchain on customer demand and supply chain profitability under various risk conditions was evaluated. The results of the modeling indicate that using blockchain for temperature management in the cold supply chain of deteriorating goods can, in many cases, reduce customers' perceived risk, thereby increasing demand and profits for supply chain members. However, one key finding of this research is that blockchain cannot always be considered an optimal solution. In situations where perceived risk is very high, the total supply chain profit may be even lower than when blockchain is not implemented.

This result is particularly evident when the costs of blockchain implementation are high or when the information provided by blockchain leads to excessive risk awareness among customers. In such cases, customers may refrain from purchasing the product, leading to reduced demand and, consequently, lower profits for the supply chain. In the Stackelberg game between the retailer and the manufacturer, it was observed that the leader can adjust pricing strategies and the level of blockchain usage to optimize both their own and the retailer’s profits. However, as the results showed, these adjustments must be made carefully, taking into account customers' perceived risk. Ultimately, this study demonstrates that while blockchain can improve efficiency and reduce risk in many cases, excessive use of this technology in high-risk conditions may have the opposite effect, resulting in reduced profits for the supply chain. Therefore, decisions regarding the use of blockchain should be accompanied by careful analysis of market conditions, implementation costs, and customers' perceived risk.

This study focused primarily on the use of blockchain in cold supply chains. One important area for future research is examining the interplay between emerging technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and blockchain to improve cold supply chain management and reduce risk. Future studies could also involve more precise modeling and various scenarios of changes in perceived risk, along with how retailers and manufacturers manage this risk.

Other potential research topics include a more comprehensive analysis of blockchain implementation costs in the supply chain and a comparison with the benefits derived from risk reduction and improved transparency, a more detailed study of consumer behavior in response to information provided by blockchain, the examination of multi-level game models and strategies in the supply chain, especially when more actors are involved, and finally, the investigation of market differences and how this technology impacts each market.

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Data Availability

The data supporting the findings are available from the corresponding author upon reasonable request.

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