

Optimal Decisions for the Perishable Food Supply Chain by Applying Blockchain Technology

S. Abedi and S.W. Yoon

Department of Systems Science and Industrial Engineering
State University of New York at Binghamton,
Binghamton, NY, USA

Corresponding author's Email: sabedi1@binghamton.edu

Abstract: Due to increasing concerns over food safety, the level of customer's awareness of the products has been considered significantly during the recent years. In this study, the application of the Blockchain technology and its impact on perishable food supply chain is examined. Blockchain can help to eliminate the costly delays and waste the products due to its traceable, secure and distributed structure. Perishable food nature of quality deterioration over time, inefficient quality control during the transportation and food contamination incidents lead to a need for more detailed information on food production. Besides, asymmetric information at the situation that parties are not equally informed about the details of the products causes marketing failures such as last minute order cancellations, late payments and retroactive changes to contracts. In this study, a decision making mechanism is developed based on the quality, price, safety, and degree of information exposure parameters by applying Blockchain technology in the perishable food supply chain management.

Keywords: Blockchain Technology, Perishable Food, Dynamic Pricing, Food Traceability

1. Introduction

Recently, consumer's increasing concern and awareness to the safety and quality of food products specially the perishable food, has motivated the food industry to improve the traceability, and the control of perishable food supply chain. Perishable food nature of quality deterioration over time, inefficient quality control during the transportation and food contamination incidents lead to a need for more detailed information on food production. Besides, asymmetric information at the situation that parties are not equally informed about the details of the products causes marketing failures such as last minute order cancellations, late payments and retroactive changes to contracts. Generally, a trusted third party as a centralized trading system can lead to exist of asymmetric and tampered information among food supply chain participants (Amorim et al., 2012). Radio Frequency Identification (RFID) is one of the technological advancement that works based on radio waves between a tag attached to products. The trade-off between RFID advantages, its considerable investment costs, and the exist challenges of consumer's privacy, provides a need of more efficient traceability system among all parties of the supply chain.

In the last few years, distributed ledger and Blockchain technology has gained a lot of interest from the researchers and industrial domains because of its potential in decentralizing the supply chain management which provides traceable, transparent, and secure environment in food trading. The Blockchain technology is a peer to peer distributed ledger composed from linked blocks includes a list of hash pointers. The transaction records among the users are encrypted and uploaded to the new block that linked to the previous blocks as digital assets and creates a chain. The chain is appended only data structure and registering a new transaction needs a consensus of all users to verify and validate (Ghasemi et al., 2017). This technology could transform the food industry by increasing transparency, efficiency, and collaboration across the entire food system. For example, consumers could trace the source of the products, a retailer would verify if a carton of egg is really cage-free, a shipper would realize if a truck is full before scheduling a delivery, and health administrations could easily find out a particular product is come from which harvest and on which farm, to reach the source of contaminated products. Blockchain empowers all levels of a supply chain to be more responsive to any food safety calamity (Tse et al., 2017). Currently, most of the compliance data is modified by a third party and recorded in a centralized database that are so vulnerable to intentional information errors, high operation costs, and hacking (Su and Zhang, 2009). Moreover, this technology could promote faster and fairer payment through smart contract applications. Smart contract can be considered as a set of digital promises and terms of the agreement between disparate, anonymous users without applying a central third party authority or external enforcement mechanism (Amorim et al., 2012). In food supply chain, quality and the delivery time are two important obligation conditions in the contract which is monitored during the process (Gao and You, 2018). In this study, it is tried to develop the decision mechanisms by applying

Blockchain technology for a decentralized system. The remaining of this paper is structured as follows. Section 2 shows related work in the area of perishable food supply chain and Blockchain technology adaption. Section 3 describes the problem and proposed mathematical model. Section 4 conducts a numerical example to provide some managerial insights and section 5 concludes the paper and presents future work.

2. Literature Review

During the last decade, traceability systems have been given significant attention in perishable food supply chain. (Zhu and Lee, 2018), conducted an economic analysis for a perishable food supply chain by considering RFID traceability system through decentralized optimization model and concluded dynamic pricing policy which supported by the traceability system, could significantly reduce food waste and improve the retailer's performance. (Yang et al., 2017), by applying mixed integer linear programming showed that flexible promotion, replenishment policy, increasing the variety of products, and corresponding shelf space can increase the total expected profit for the perishable food supply chain. (Hertog et al, 2014), tried to optimize the perishable goods flow and minimize economic losses by considering shelf life and product quality in the cost function. In the previous studies, different technologies such as Internet of Things (IoT), Business Information Systems, RFID and Electron Spin Resonance are increasingly applied with the goal of collecting and managing information from different level of food supply chain and increasing the consumer support for the product traceability, food inspection, and standards.

Despite all advantages of the mentioned technologies in this area, there are some drawbacks such as centralization of data storage and the ambiguity of the transactions that leads tampering, information asymmetry and high privacy risk (Sandhu et al., 2010). During the last years, by introducing Blockchain the privacy protection and transparency of transactions are guaranteed between supply chain parties. (Chang et al., 2018), applied generic stochastic model to show that Blockchain can help to reduce order quantities, selling prices, and target inventory levels. (Westerkamp et al., 2018), generated transparency along the supply chain and provided comprehensible production information through applying smart contract and Ethereum virtual machine implementation. (Casado et al., 2018), examined the improvement of current agriculture supply chain by proposing a new model combination of Blockchain, smart contract and a multi-agent supply chain system. (Pop et al., 2018), proposed a decentralized solution to provide a balance between energy demand and production by applying Blockchain and associated smart contract. (Gao and You, 2018), studied the optimization problem of decentralized supply chains considering multiple stakeholders under uncertainty through applying stochastic mixed-integer bilevel nonlinear program. They showed that stakeholders tend to choose more conservative strategies when considering uncertainties in decentralized supply chain. (Terelius et al., 2011), analyzed a decentralized optimization algorithm based on the dual decomposition technique and proved that dual algorithm converges faster and has less communication with a decentralized primal algorithm. Blockchain basically prepares a platform that allows supply chain parties to access reliable, secure, and protected information in an efficiently. Currently, there is few research practice subjects to the Blockchain technology effect and corresponding design and application issues from perspective of perishable food supply chain management. Blockchain can help solve the interoperability challenges of IoT devices and act as a uniform method to securely share data among the users.

3. Model Description

This study aims to show optimal decisions mechanism for a two level distribution network of perishable products including a supplier and a retailer by considering the advantages of the Blockchain technology. The retailer orders one type of fresh food from the supplier who is responsible for transportation and protecting the quality of the products from origin to destination. The Blockchain degree of adoption indicates percentage information of the supply chain parties and procedures that are represented onto the Blockchain ledger. It is assumed that the adoption degree quantifies the information exposure (Chang et al., 2018). Increasing β , reflects higher adoption of Blockchain leveraged and complexity of managing the whole system. The adoption cost includes the set up charge of the Blockchain infrastructure, maintenance, managing users and database to the system, etc. Customers are sensitive to quality, price, and β . The major notation is summarized in Table 1.

Table 1. Notation Summary

| <i>Parameters</i> | |
|---------------------------|---|
| α | nonnegative price elasticity of demand |
| c | purchasing cost per item in the selling period T |
| D | demand in T |
| δ | value deterioration parameter |
| i | number of price markdown, $i = 0, 1, \dots, n$ |
| γ | compensation rate for late delivery |
| M | nonnegative constant parameters of market potential |
| μ | nonnegative food value elasticity of demand |
| p_0^r | initial retail price |
| q_0 | initial quality at the supplier warehouse |
| t | selling period in the retail store, $0 \leq t \leq T$ |
| t_0 | committed delivery time |
| t^r | delivery time from the supplier to the retailer |
| W^r | retailer's expected profit |
| W^s | supplier's expected profit |
| ψ^r | investment parameter for Blockchain technology for retailer |
| ψ^s | investment parameter for Blockchain technology for supplier |
| ξ | demand expansion effectiveness to β |
| <i>Decision Variables</i> | |
| β | Blockchain adoption degree |
| η | price markdown rate of the retailer |
| N | order quantity of the retailer |
| P_0 | initial wholesale price per item before delivery |
| P | actual wholesale price per item for the delivered food |

The quality of fresh food such as fruit and vegetable decreases linearly through their shelf life (Zhu and Lee, 2018). Therefore, the quality deterioration equation of the food when reaches to the retailer can be presented as

$$q^r = q_0 - \delta q t^r \quad (1)$$

where q_0 is initial quality at the supplier location before transportation, q^r is the quality of the food at the retailer location and δ is the deterioration rate of the perishable food. In each period t , the demand function is defined as

$$f(D_t) = M - \alpha p(t) + \mu q(t) + \xi \beta \quad (2)$$

that representing nonnegative constant parameters of market scale M , price elasticity α , demand sensitivity to quality μ , and demand growth to Blockchain adoption degree ξ . Since the delivery time is not stable because of various random factors such as weather conditions and traffic congestion, the purchased perishable products are at the risk of deterioration during the transportation. Therefore, two stage problem is defined to study the decision making of the supplier and retailer, respectively. In the first stage, the supplier determines the initial wholesale price P_0 based on the order quantity of the retailer, Blockchain cost and committed delivery time t_0 , before the transportation. In the second stage, the actual wholesale price P of the delivered foods is determined based on the realized delivery time t_r as

$$P(t^r) = P_0 - \gamma(t^r - t_0) \quad (3)$$

In case of delay in delivery time, γ is considered as compensation rate for deterioration of the perishable products to the retailer. Since customers are so sensitive to the freshness and quality of the perishable food, dynamic pricing and price discount are significantly considered in this industry. Retailer decreases the price when the food approaches its expiration date to minimize the spoilage waste. The markdown could be happened several times to optimize the retailer's profit. Following the optimal decisions for the retailer and the supplier are determined in a decentralized supply chain by applying Blockchain.

3.1 Optimal Decisions for the Retailer

The retailer needs to decide optimal order quantity in the first stage before the transportation and then determines the optimal markdown rate in the second stage when the goods are delivered. It is assumed that retailer applied the same markdown rate for all n times of price markdown

$$\eta_i = 1 - i\eta \quad (4)$$

the i^{th} markdown price based on the given initial retail price p_0^r can be expressed as

$$p_i^r = p_0^r(1 - i\eta) \quad (5)$$

the corresponding demand function after the transportation becomes

$$f(D_i) = M - \alpha p_i^r + \mu(q^r - \delta t^r) + \xi\beta \quad (6)$$

for $t \in [T_{i+1}, T_i]$, where $T_0 = 0$ and $T_{n+1} = T$, the demand in the i^{th} price markdown period can be derived as

$$D_i = \int_{T_i}^{T_{i+1}} f(D_t) dt = (T_{i+1} - T_i) [M - \alpha p_0^r(1 - i\eta) + \mu(q^r - \frac{1}{2}\delta(T_{i+1} + T_i)) + \xi\beta] \quad (7)$$

Therefore, the demand over period T can be indicated as

$$\sum_{i=0}^n D_i = \sum_{i=0}^n (T_{i+1} - T_i) [M - \alpha p_0^r(1 - i\eta) + \mu(q^r - \frac{1}{2}\delta(T_{i+1} + T_i)) + \xi\beta] = N \quad (8)$$

Substituting q^r from Eq. (1) in Eq. (8) and then the optimal markdown rate of retailer for any given N , P_0 , β , and n times price markdown is determined as

$$\eta^*(N|t_r) = \frac{N - T(M - \alpha p_0^r + \mu q_0 + \xi\beta) + \mu\delta T(t^r + \frac{1}{2}T)}{\alpha p_0^r \sum_{i=0}^n i(T_{i+1} - T_i)} \quad (9)$$

Regarding the Blockchain technology, $\psi\beta$ can also show the cost of overexposure of information which causes to lose competitive advantages, by displaying more information to the competitors in the network. Therefore, in this study, the $\psi\beta$ is expressed as a convex and quadratic investment function $\psi\beta^2$ by supply chain parties to indicate the decreasing returns of investment in the Blockchain technology in case of overexposure of information. By considering Eq. (5), for any given initial wholesale P_0 and the cost of investing in Blockchain technology, the expected profit of the retailer is indicated as

$$\begin{aligned} W^r(N|P, \beta) &= E_{t^r} \{ (\sum_{i=0}^n p_i^r D_i) - PN - \psi^r \beta^2 \} = \sum_{i=0}^n [(p_0^r - p_0^r i\eta) (\int_{T_i}^{T_{i+1}} f(D_t) dt)] - PN - \psi^r \beta^2 \\ &= p_0^r \eta A_1 (2\alpha p_0^r - A_3) + \frac{1}{2} p_0^r \eta \mu \delta A_2 + p_0^r T (A_3 - \alpha p_0^r - \frac{1}{2} \mu \delta T) - \alpha (p_0^r)^2 \eta^2 A_1 \sum_{i=0}^n i - PN - \psi^r \beta^2 \end{aligned} \quad (10)$$

where $A_1 = \sum_{i=0}^n i(T_{i+1} - T_i)$, $A_2 = \sum_{i=0}^n i(T_{i+1}^2 - T_i^2)$, and $A_3 = M + \mu q_0 - \mu \delta t^r + \xi\beta$.

By substituting optimal markdown rate from Eq. (9), the first and second derivatives of $W^r(N)$ with respect to N are indicated in Eqs. (12) and (13), respectively as

$$\frac{\partial W^r(N|P, \beta)}{\partial N} = \frac{1}{2\alpha A_1} [\delta \mu A_2 - \sum_{i=0}^n i(2N + \delta \mu T^2 - 2TA_3 + 2T\alpha p_0^r) - 2A_1(A_3 - 2\alpha p_0^r)] - P \quad (11)$$

$$\frac{\partial W^r(N|P, \beta)}{\partial N^2} = -\frac{\sum_{i=0}^n i}{\alpha A_1} < 0 \quad (12)$$

It is shown that expected profit function of retailer is strictly concave in N , and the maximum point of this function which indicates the optimal order quantity of the retailer is determined as

$$N^*(P, \beta) = \frac{2A_1(2\alpha p_0^r - \alpha P - A_3) + \delta\mu A_2 + T \sum_{i=0}^n i(2A_3 - \delta\mu T - 2\alpha p_0^r)}{2 \sum_{i=0}^n i} \quad (13)$$

3.2 Optimal Decisions for the Supplier

The supplier determines the initial and actual wholesale prices based on the committed and actual delivery time, respectively. By considering expected profit of the supplier in Eq. (14) and substituting N^* from Eq. (13), the optimal P and β can be derived through the first and second order derivative of $W^s(N|P, \beta)$ as

$$W^s(N|P, \beta) = E_{t_0}\{(P - c)N^*(P, \beta) - \psi^s \beta^2\} \quad (14)$$

$$\frac{\partial W^s(P, \beta)}{\partial P} = \frac{1}{2 \sum_{i=0}^n i} [2A_1 \alpha (c - 2P + 2p_0^r) - 2A_1 A_3 + \delta\mu A_2 - T \sum_{i=0}^n i (\delta\mu T - 2A_3 + 2\alpha p_0^r)] \quad (15)$$

$$\frac{\partial W^s(P, \beta)}{\partial \beta} = \frac{\xi(P-c)(T \sum_{i=0}^n i - A_1)}{\sum_{i=0}^n i} - 2\psi^s \beta \quad (16)$$

$$H_{W^s(N|P, \beta)} = \begin{bmatrix} \frac{-2A_1 \alpha}{\sum_{i=0}^n i} & \frac{\xi(T \sum_{i=0}^n i - A_1)}{\sum_{i=0}^n i} \\ \frac{\xi(T \sum_{i=0}^n i - A_1)}{\sum_{i=0}^n i} & -2\psi^s \end{bmatrix} \quad (17)$$

Further, the determinant of Hessian matrix is determined as

$$\det_{H_{W^s(N|P, \beta)}} = \frac{4\alpha\psi^s A_1 \sum_{i=0}^n i - \xi^2 (T \sum_{i=0}^n i + A_1)^2}{(\sum_{i=0}^n i)^2} \quad (18)$$

For any $\psi^s > \frac{\xi^2 (T \sum_{i=0}^n i + A_1)^2}{4\alpha A_1 \sum_{i=0}^n i}$, H_{W^s} is negative definite and then profit function of the supplier will be concave. By considering Eqs. (15 and 16) = 0, the maximum parameter of P and β can be determined as

$$P(\beta) = \frac{T \sum_{i=0}^n i (2A_3 - \delta\mu T - 2\alpha p_0^r) + 2A_1 (c\alpha - A_3 + 2\alpha p_0^r) + \delta\mu A_2}{4\alpha A_1} \quad (19)$$

$$\beta(P) = \frac{\xi(P-c)(T \sum_{i=0}^n i - A_1)}{2\psi^s \sum_{i=0}^n i} \quad (20)$$

Then, optimal β^* , P^* , and P_0^* are determined by substituting Eqs. (19 and 20) in each other and considering Eq. (3) as

$$\beta^* = \frac{\xi(A_1 - T \sum_{i=0}^n i) [2A_1 (A_4 + \alpha(c - 2p_0^r)) - \delta\mu A_2 + T \sum_{i=0}^n i (\delta\mu T - 2A_4 + 2\alpha p_0^r)]}{8\alpha\psi^s A_1 \sum_{i=0}^n i} \quad (21)$$

$$P^* = \frac{\delta\mu(A_2 - T^2 \sum_{i=0}^n i) + 2T \sum_{i=0}^n i (A_4 - \alpha p_0^r) - 2A_1 (A_4 - c\alpha - 2\alpha p_0^r)}{4\alpha A_1} \quad (22)$$

$$P_0^* = \frac{\delta\mu(A_2 - T^2 \sum_{i=0}^n i) + 2T \sum_{i=0}^n i (A_4 - \alpha p_0^r) - 2A_1 (A_4 - c\alpha - 2\alpha p_0^r)}{4\alpha A_1} + \gamma(t^r - t_0) \quad (23)$$

where $A_4 = M + \mu q_0 - \delta\mu t^r + \frac{\xi^2 (P-c)(T \sum_{i=0}^n i - A_1)}{2\psi^s \sum_{i=0}^n i}$.

4. Numerical Example

The summary of conducted numerical example to show the positive effect of applying Blockchain technology in a perishable food supply chain, is shown in the Table 2. The generated input parameters for 168 hours selling period are set as $M = 50$, $\delta = 0.02$, $\alpha = 5$, $\psi^r = 3.5$, $\psi^s = 3.5$, $\mu = 4$, $\gamma = 0.05$, $q_0 = 2$, $p_0^r = 10$, $c = 5$, $t_0 = 8$, and $t^r = 10$ in appropriate unit and the example is executed using Mathematica. It is assumed that during the 168 hours product lifecycle, retailer would conduct two times of markdowns at $T_1 = 96$ and $T_2 = 144$. According to the obtained results, the retailer's profit increases with conducting two times markdown price compare with no discount scenario.

Table 2. Markdown Price Performance

| Scenarios | Selling Period T | Markdown Time | | Optimal Markdown Rate η^* % | Demand Difference D_t % | Profit Difference W^r % |
|----------------|--------------------|---------------|-------|----------------------------------|---------------------------|---------------------------|
| | | T_1 | T_2 | | | |
| No Discount | 168 | - | - | - | - | - |
| Once Markdown | 168 | 96 | - | 25.57 | 24.29 | 13.06 |
| Twice Markdown | 168 | 96 | 144 | 30.54 | 40.02 | 15.81 |

By reaching to the expiration date of the products, the retailer takes advantage of dynamic pricing and markdown to decrease the lost. Besides, access to the information across the supply chain would increase the awareness of the safety and traceability of the perishable food that leads to increase the demand and retailer's profit as illustrated in Figure 1. As shown in Table 3, applying the optimal level of β , will increase the order quantity, wholesale price and supplier's profit accordingly.

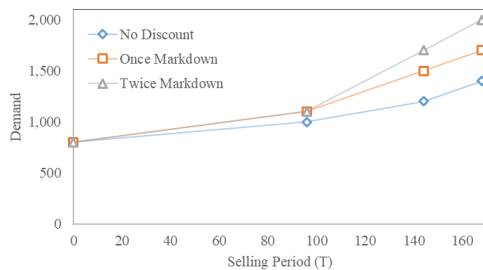


Figure 1. Demand Based on Dynamic Pricing

Table 3. Blockchain Adoption Degree Performance

| β | N | P | W^s % |
|---------|------|-------|---------|
| 2.8 | 820 | 9.06 | 17.26 |
| 3.2 | 873 | 9.43 | 18.06 |
| 3.6 | 926 | 9.84 | 18.53 |
| 4.1 | 932 | 10.07 | 19.59 |
| 4.8 | 1022 | 11.27 | 20.81 |

5. Conclusions and Future Work

Based on the developed decision making mechanism by considering the Blockchain technology in a perishable food supply chain, from supplier's perspective, this technology can guarantee the security of the products information about the quality and safety without considering the third party. From retailer's perspective, benefiting the advantages of the Blockchain would help them in applying dynamic pricing during product's cyclelife information and moreover, the increase of adoption degree would let retailer to make markdown price at the appropriate times that would decrease the cost of waste and preserve the probability demand of the customers before the expiration date of the products. From customer's perspective, access to the product information, would guarantee the safety and quality of the products, and provide fair prices accordingly. So it is significant for decision makers to examine the balance between Blockchain benefits and corresponding investment costs. Therefore, when customers and different parties of a perishable food supply chain have access to more information of the procedures and the products, then they can cooperate with each other efficiently and make more profit. As a future work, the effect of smart contract in perishable food supply chain and optimal Blockchain adoption degree can be examined.

6. References

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