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Supply chain model for deteriorating products with advanced preservation policy

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Abstract

This study presents a two-echelon supply chain model for short life deteriorating products with an application of preservation technology. Various preservation policies have been defined to improve the lifetime of deteriorating products. The recent innovations in this regards include several types of preservation technologies to reduce the deterioration rate. Use of such technologies increases the supply chain profit of such fixed lifetime products. Unlike several researchers, who proposed a continuous reduction in rates of deterioration with investment in the preservation technology, this study focuses on more real circumstances by proposing model of such a preservation policy that improves lifetime of a product and minimizes the effects of deterioration in such a way that magnitude of decrease in deterioration reduces for additional investment in the preservation technology. The model is validated with numerical example. The implication of investment in preservation technology is illustrated by evaluating increasing value in product's lifetime and the profit which authenticates the proposed model.

Keywords

Supply chain, Deterioration, Advanced preservation policy, Nonlinear programming

1. Background and motivation

Most of the food products, for examples bakery items, fruits, and vegetables start deteriorating as soon as they are produced. Due to deterioration, quality of the food products is either reduced or these products become perishable after a certain period of time, thus making them unfit for human consumption. At retail stores, such food products are usually discarded, when they are no longer fresh because they will not catch customers' attention and will just create inventory costs. Such disposals not only create an economic loss but also affect the environment and natural resources. In United States, approximately 15% of the food products expire due to deterioration before reaching their consumers. It is reported that, throughout the world, 1.3 billion tons of food products are discarded every year, which is approximately 33% of all the food produced for human consumption. The focus of this study is to minimize these losses by providing preservation policies for such food products.

Product's deterioration (PD) has been discussed in literature by many researchers. First model for deteriorating inventory was proposed by Ghare and Schrader (1963). Sachan (1984) developed an Economic Order Quantity (EOQ) model with shortages and time dependent product demand where inventory items deteriorate at a constant rate. Chang and Dye (1999) improved the model by considering backlogged shortages. This research dimension was further explored by Skouri *et al.* (2009) and they proposed an inventory model with time dependent rate of deterioration and ramp type demand rate considering partial backlogging. Theory of stochasticity for the rate of PD was introduced by Sarkar (2013). He proposed an Economic Production Quantity (EPQ) model considering three probabilistic (uniform, triangular, beta) deterioration rates to find the optimum lot size and number of deliveries. Chen and Teng (2014) developed an EOQ model with deteriorating items having maximum life time and permissible delay in payments to minimize the total cost on optimal value of retailer's replenishment cycle. Goel *et al.* (2015) considered variable quadratic rate of PD in a deterministic inventory model and they proposed a supply chain model considering supplier, manufacturer and a retailer with stock dependent demand and partial backlogging. In their model they considered "critical time at which inventory goes zero" as decision variable. Sarkar *et al.* (2015) studied a two echelon supply chain system focusing on setup cost, system reliability and PD. They concluded that setup cost is directly and deterioration rate is inversely proportional to the system reliability. Lin *et al.* (2016) studied an inventory system considering PD that depends upon product maximum life time and the product price is demand dependent. They solved the problem by maximizing profit on optimal values of preservation cost and replenishment cycle.

Solution of the PD comes with PT. Deterioration can be controlled either by adding preservatives to the product which stops or modifies the chemical reactions which cause PD or by controlling those ambient conditions which cause initiate or accelerate the deterioration. For the last decade, many researchers explored the application of PT for deteriorating products. Hsu *et al.* (2010) considered a basic inventory system for deteriorating products with application of PT and maximized profit by finding optimal values of PT cost investment, replenishment cycle, shortage period, and order quantity. Dye and Hsieh (2012) proposed an EOQ model with time varying rate of deterioration and application of PT. They discussed that the rate of deterioration can be reduced through investment in PT. Dye (2013) also studied an inventory system with non-instantaneous deteriorating items to observe inventory behavior under PT investment. They concluded that there is an increase in customer service by adopting PT in a relevant system. Idea of seasonal deteriorating products with application of PT was put forward by He and Huang (2013). They minimized the total inventory cost on optimal values of ordering frequency, PT cost investment, market price and ordering quantity. Dye and Hsieh (2013) studied the effect of PT investment on deterioration rate reduction under two-level trade credit. They proposed a deterministic retailer EOQ model with time varying demand and solved by Particle Swarm Optimization (PSO) algorithm to maximize total profit on optimal values of PT cost, trade credit policy, number of replenishments and time scheduling. (Shah *et al.*, 2016) modeled manufacturer-buyer two echelon supply chain with time varying rate of deterioration which can be reduced at retailer with investment in preservation technology. They assumed that reduced rate of deterioration is a continuous increasing function of investment in preservation technology. In their model, trade credit policy is adopted by manufacturer and buyer both. Tsao (2016) supposed that PD is non-instantaneous and that deterioration will decrease by increasing investment in PT. He modeled joint location, inventory and PT problem and proposed an algorithm to maximize the total system profit. (Jawla and Singh, 2016) suggested a RL model considering learning, time dependent deterioration, preservation technology, inflation, and holding cost as continuous function of time.

This research considers short life time deteriorating products which are preserved for longer time by the application of PT, the effect of which reduces with additional investment. Moreover, this model introduces a variable component of selling-price, which depends on maximum lifetime of the product. Objective of this research is to best plan the cycle time and investment in PT such that the total profit per unit time is maximized.

2. Problem definition

This study considers a supply chain management system having a manufacturer and a retailer for deteriorating product. Manufacturer produces and delivers the product to the retailer. Transportation cost is considered within setup cost of the manufacturer. Other costs at manufacturer include material cost, cost of special preservation materials, production cost, and inventory holding cost. The product under consideration is deteriorating in nature and it starts deteriorating when delivered to the retailer. In order to reduce the effects of deterioration, preservation technology is used in form of cold storage, humidity, sanitation, etc. Though the rate of deterioration is reduced by the application of preservation technology, still some products deteriorate during the cycle. Therefore, retailer demands from manufacturer the amount of product which fulfills customers' demand and compensates the deteriorated quantity during planned cycle. Thus, manufacturer's demand is the sum of retailer's demand and the deteriorated quantity. Manufacturer purchases raw material and produces exactly the same number of items as are demanded by the retailer, thus having no shortages. Manufacturer plans its production in a way that the rate of production depends on rate of demand. As the rate of demand remains constant, therefore the rate of production also remains constant during the production cycle. Manufacturer supplies the finished product to the retailer. The cycle time of manufacturer is synchronized with that of the retailer. The costs at retailer include ordering cost, purchasing cost, inventory holding cost, and the cost of preservation technology. As the system is considered to be a centralized supply chain, therefore, purchasing cost of retailer is the same as the selling-price of the manufacturer. Selling-price at the retailer is variable and depends on maximum lifetime of the product. Figure 1 illustrates the structure of the supply chain system under consideration.

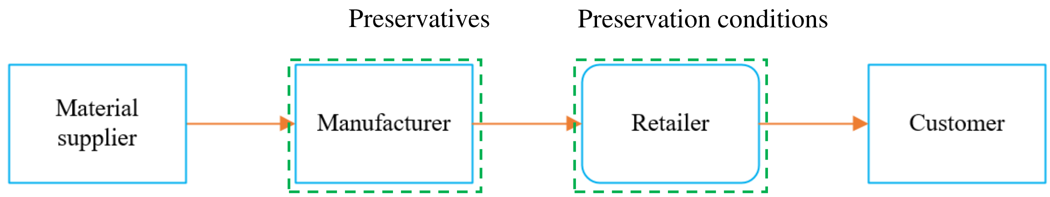

Figure 1. Process flow

3. Model formulation

3.1 Model Notation

3.1.1 Variables

T cycle time (time units)

p_a cost of preservation technology for preservation conditions at retailer (\$/unit/unit time)

p_b cost of preservatives at manufacturer (\$/unit)

3.1.2 Parameters

d_R customer's demand per unit time (units/unit time)

D_R customer's demand per cycle (units/cycle)

N_D number of items deteriorated per cycle at retailer (units/cycle)

PQ_R purchasing quantity per cycle (units/cycle)

I_R^o on-hand inventory at any time t, $0 \le t \le T$ (units)

I_R total inventory carried during one cycle (units/cycle)

A_R ordering cost (\$/order)

PC_R purchasing cost per unit (\$/unit)

h_R inventory holding cost per unit per unit time (\$/unit/unit time)

TC_R total cost per unit time (\$/unit time)

SP_R selling-price per unit (\$/unit)

SR_R sales revenue per unit time (\$/unit time)

TP_R total profit per unit time (\$/unit time)

TP total profit per unit time of the supply chain as a centralized system (\$/unit time)

L maximum lifetime of the product (time units)

θ rate of deterioration

α degree of vulnerability to deterioration

d_M demand per unit time (units/unit time)

D_M demand per cycle (units/cycle)

P rate of production (units/unit time)

I_M^a on-hand inventory at any time t, $0 \le t \le t_1$ (units)

I_M^b on-hand inventory at any time t, $t_1 \le t \le T$ (units)

I_M total inventory carried during one cycle at manufacturer (units/cycle)

N_P number of items produced per cycle (units/cycle)

C_{SET} setup cost per setup (\$/setup)

C_{MT} material cost per unit (\$/unit)

C_P production cost per unit (\$/unit)

h_M inventory holding cost per unit per unit time (\$/unit/unit time)

TC_M total cost per unit time (\$/unit time)

SP_M selling-price per unit (\$/unit)

SR_M sales revenue per unit time (\$/unit time)

TP_M total profit per unit time (\$/unit time)

η degree of effectiveness of preservation cost

k proportionality constant within production and demand at manufacturer

3.2 Model Assumptions

1. A supply chain system consisting of a manufacturer and a retailer for a single product is considered.

2. Customer demand at the retailer d_R is known and constant.
3. Product under consideration is deteriorating in nature, which deteriorates at a variable rate θ. Practically, the product does not deteriorate at manufacturer and starts deteriorating when delivered to retailer. This fact is considered in this research.
4. The rate of deterioration is controllable through preservation techniques which are applied in the form of preservatives and preservation conditions. The magnitude of decrease in deterioration decreases with additional investment in preservation technology.
5. Short-lifetime product is sold at higher price when it is preserved and has longer expiration time. Therefore, this research assumes that the variable component of the product's selling-price is a function of its maximum lifetime $\nu = \delta L$ i.e., a product with a longer time to expire is sold at a higher price compared to the same product with a shorter expiration time.
6. The rate of production depends on and is higher than the rate of demand (Qin and Liu, 2014) i.e. $P = kd_M$, where P is the rate of production and d_M is the rate of demand at manufacturer, and $k > 1$.
7. Shortages are not allowed and demand at the retailer is fulfilled during planning horizon.
8. The supply chain is vertically integrated, such that optimal value of profit of the supply chain is obtained as a centralized system.
9. A food product, once expired, cannot be repaired to recover for the same consumption. Therefore, deteriorated items are considered non-repairable, thus removed from inventory and disposed.

3.3 Model Development

The deterioration is a function of lifetime of the products, therefore the rate of deterioration varies with variation in lifetime when preservation technology is applied. The decreased rate of deterioration of a product is exhibited in following equation.

$$\hat{\theta} = \frac{\alpha}{1+\left(1+\eta p^{\gamma}\right)L}$$

Value of γ is proposed to be less than one to represent the effect of preservation on lifetime and deterioration in real cases. In contrast to many researchers, who proposed the effect of investment in preservation technology on deterioration in a conventional way, this study suggests that magnitude of decrease in deterioration keeps decreasing with additional investment in preservation technology and after a specific amount of investment, the decrease in deterioration will be negligible, no matter how much preservation cost is invested.

3.3.1 Retailer's model

The proposed system considers a retailer, who receives the finished product from a manufacturer. The rate of demand of the product at retailer is d_R number of items per unit time and the rate of deterioration is $\hat{\theta}$. Figure 2 shows the behavior of inventory level at retailer. The governing differential equation for the inventory of the product at retailer is as given below, which shows that the rate of change of inventory from 0 to T is the negative rate of its demand and deterioration, as the items are taken out of inventory.

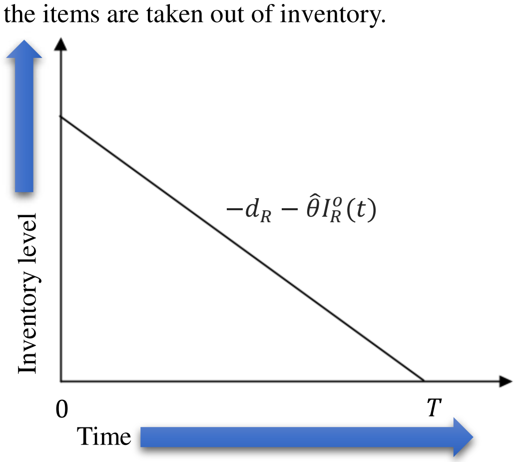

Figure 2. Behavior of inventory level at retailer

$$\frac{dI_R^o(t)}{dt} = -d_R - \hat{\theta} I_R^o,\ 0 \le t \le T$$

The above expression is the slope of the function of on-hand inventory at retailer. The value of the function $I_R^o(t)$, at any time t, is calculated from the given slope by using the inventory condition $I_R^o(t) = 0$ at $t = T$, as

$$I_R^o(t) = \frac{d_R}{\hat{\theta}}\left(e^{\hat{\theta}(T-t)} - 1\right),\ 0 \le t \le T$$

Several costs, which are considered at retailers' level, are explained and calculated below.

Ordering cost

The ordering cost per cycle at the retailer is given as in below equation.

$$\text{Ordering cost per cycle} = A_R$$

Purchasing cost

The ordering/purchasing quantity per cycle of the retailer is the sum of customer demand per cycle and the number of items that would deteriorate in a cycle. In order to calculate the purchasing quantity per cycle, the demand that the retailer faces per cycle is calculated in the following equation.

$$D_R = \int_0^T d_R dt = d_R T$$

Similarly, the number of items that deteriorate at the retailer during one cycle of inventory are computed and given as under.

$$N_D = \hat{\theta}\int_0^T I_R^o(t)dt = \frac{d_R}{\hat{\theta}}\left(e^{\hat{\theta}T} - \hat{\theta}T - 1\right)$$

Therefore, purchasing quantity of the retailer is as given below.

$$PQ_R = D_R + N_D$$

Thus, the purchasing cost of product per cycle for the retailer is calculated and expressed in following equation.

$$\text{Purchasing cost per cycle} = PC_R PQ_R$$

Inventory holding cost

The stock of product's inventory that is carried by the retailer during one cycle $[0,T]$, on which the inventory holding cost is considered, is calculated and expressed in below equation.

$$I_R = \int_0^T I_R^o(t)dt = \frac{d_R}{\hat{\theta}^2}\left(e^{\hat{\theta}T} - \hat{\theta}T - 1\right)$$

Using above expression, inventory holding cost of the retailer for one cycle is calculated and expressed in following equation.

$$\text{Inventory holding cost per cycle} = h_R I_R$$

Preservation cost

The preservation cost p is divided into two categories i.e. the cost for preservation conditions p_a and cost of preservatives p_b, such that $p_a + p_b = p$. By using the preservation cost per unit per unit time and the total inventory carried per cycle, the investment per cycle in preservation technology at the retailer is calculated in the equation as under.

$$\text{Investment in preservation technology per cycle} = p_a I_R$$

Total cost per unit time

The total cost at the retailer is the sum of its ordering cost, purchasing cost, inventory holding cost, and preservation cost, which is given per unit time in below equation.

$$\text{Total cost}\left(TC_R\right)=\frac{1}{T}\left(A_R+PC_R PQ_R+h_R I_R+p_a I_R\right)$$

Sales revenue per unit time

The variable component of selling-price v depend on the maximum lifetime of the product, and is expressed as follows.

$$v=\delta\hat{L}\,.$$

By using fixed and variable components, the selling-price of one item is calculated below.

$$\text{Selling-price per unit }\left(SP_R\right)=\varepsilon+v=\varepsilon+\delta\hat{L}$$

Sales revenue per unit time of the retailer is computed by using its selling-price per unit and demand per unit time, as is expressed in the below equation.

$$SR_R=SP_R d_R$$

Retailer's profit per unit time

The retailer earns profit by selling its product during planning horizon. The profit per unit time of the retailer is calculated by using the sales revenue per unit time and the total cost per unit time, and is given in following equation.

$$TP_R=SR_R-TC_R \tag{1}$$

3.3.2 Manufacturer's model

The manufacturer's demand per cycle is given below.

$$\text{Manufacturer's demand }\left(D_M\right)=PQ_R=D_R+N_D$$

By using the demand per cycle and its cycle time, the rate of demand per unit time at manufacturer is as given below.

$$d_M=\frac{D_M}{T}=\frac{D_R+N_D}{T}$$

Manufacturer produces the products as per demand and the rate of production is proportional to the rate of demand, which is expressed in below equation.

$$P=kd_M=k\frac{D_R+N_D}{T}$$

The governing differential equations of current inventory at manufacturer are expressed below. The cumulative effect of production and demand on the rate of change of inventory level is positive because production rate is higher as compared to the rate of demand. Therefore, inventory stock is replenished during production time. The inventory stock starts depleting when production time is over.

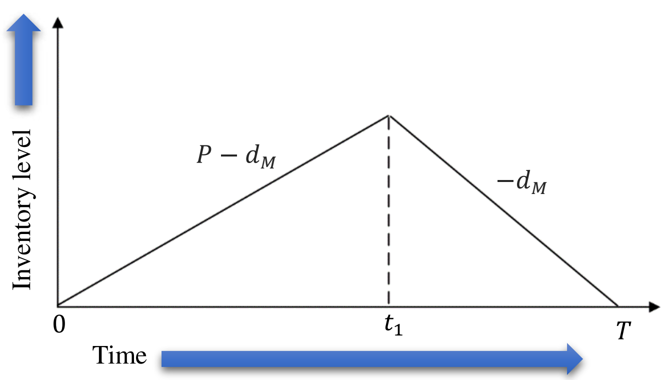

Figure 3. Behavior of inventory level at manufacturer

$$\frac{dI_M^a(t)}{dt}=P-d_M=(k-1)d_M\,,\;0\le t\le t_1$$

$$\frac{dI_M^b(t)}{dt} = -d_M,\ t_1 \le t \le T$$

The value of the functions $I_M^a(t)$ and $I_M^b(t)$, at any time t, is calculated by using following inventory conditions.

$$I_M^a(t) = 0 \text{ at } t = 0$$
$$I_M^b(t) = 0 \text{ at } t = T$$

$$I_M^a(t) = (k-1)d_M t,\ 0 \le t \le t_1$$
$$I_M^b(t) = d_M(T-t),\ t_1 \le t \le T$$

From Figure 3, it can be observed that, for an instant, the level of inventory for both the intervals is same when $t = t_1$. Equating these equations at the point t_1, one can get.

$$(k-1)d_M t_1 = d_M(T-t_1)$$
$$\Rightarrow \qquad t_1 = \frac{T}{k}$$

The usual operations, which are carried out at manufacturer that incur some cost include; purchasing of raw material, production setup, manufacturing/production process, and inventory holding of the finished product. Several costs, which are considered by manufacturer are explained and calculated below.

Setup cost

The setup cost at manufacturer per cycle is given below.

$$\text{Setup cost per manufacturer's cycle} = C_{SET}$$

Material purchasing cost

Material cost per manufacturer's cycle is calculated and expressed in below equation.

$$\text{Material purchasing cost per manufacturer's cycle} = (C_{MT} + p_b)N_P,$$

where N_p is the number of items produced per manufacturer's cycle and is expressed below.

$$N_P = \int_0^{t_1} P dt = D_R + N_D$$

According to world health organization, there is a maximum limit of adding the preservatives in food products. This implication has been considered by applying a maximum limit to the cost of preservatives, as exhibited below.

$$p_b \le M,$$

where M is the maximum investment for the cost of preservatives per unit.

Production cost

Production cost per cycle is computed by using the quantity produced per cycle and production cost per unit, as given below.

$$\text{Production cost per manufacturer's cycle} \quad = C_P N_P,$$

Inventory holding cost

The inventory carried by the manufacturer for one cycle I_m, which incurs inventory holding cost, is expressed below.

$$I_M = \int_0^{t_1} I_M^a(t)\, dt + \int_{t_1}^{T} I_M^b(t)\, dt = \frac{(k-1)d_M T^2}{2k}$$

Total inventory holding cost per manufacturer's cycle is provided below.

$$\text{Inventory holding cost per manufacturer's cycle} \quad = h_M I_M$$

Total cost per unit time

Total cost per unit time at manufacturer is calculated and expressed in below equation.

$$\text{Manufacturer's total cost per unit time}\left(TC_M\right)=\frac{1}{T}\left(C_{SET}+\left(C_{MT}+p_b+C_P\right)N_P+h_M I_M\right)$$

Sales revenue per unit time

Sales revenue of the manufacturer per unit time is calculated as following.

$$SR_M = SP_M d_M$$

As the manufacturer sells its product to the retailer, the selling-price of manufacture is same as the purchasing cost of the retailers. Therefore,

$$SP_M = PC_R .$$

Manufacturer's profit per unit time

The total profit per unit time of manufacturer TP_M is calculated by using sales revenue per unit time and the cost per unit time, which is expressed in the equation below.

$$TP_M = SR_M - TC_M$$

(2)

Total profit per unit time of the supply chain

Adding Equation 1 and 2, and simplifying the results, one can obtain the following expression for total supply chain profit per unit time.

$$TP\left(p_a,p_b,T\right)=TP_R+TP_M=SR_R-\frac{1}{T}\left(A_R+h_R I_R+p_a I_R+C_{SET}+\left(C_{MT}+p_b+C_P\right)N_P+h_M I_M\right)$$

$$=\left\{\varepsilon+\delta\left(1+\eta p^{\gamma}\right)L\right\}d_R$$

$$-\frac{1}{T}\left[\begin{array}{l} A_R+C_{SET}+\left(h_R+p\right)\dfrac{d_R}{\hat{\theta}^2}\left(e^{\hat{\theta}T}-\hat{\theta}T-1\right)+\left(C_{MT}+p_b+C_P\right)\left\{d_R T+\dfrac{d_R}{\hat{\theta}}\left(e^{\hat{\theta}T}-\hat{\theta}T-1\right)\right\} \\ +h_M\dfrac{\left(k-1\right)\left(e^{\hat{\theta}T}-1\right)Td_R}{2k\hat{\theta}} \end{array}\right]$$

(3)

where $\hat{\theta}=\dfrac{\alpha}{1+\left(1+\eta p^{\gamma}\right)L}$ and $p=p_a+p_b$.

Objective function

Objective of this study is to maximize the total profit per unit time TP by finding optimal values of T (retailer's cycle time), p_a (cost of preservation per unit per unit time for preservation conditions at retailer) and p_b (cost per unit of preservatives). The objective is defined mathematically and demonstrated below.

Maximize $TP\left(p_a,p_b,T\right)$

subject to

$p_a, p_b, T \geq 0$,

$p_b \leq M$

4. Computational experiments

4.1 Numerical example

To exhibit application of the proposed model, numerical study is done. Input parameters are taken in appropriate units as explained below.

Table 1. Input parameters

$A_R = \$300$ /cycle	$L = 1.5$ months	$\varepsilon = \$50$ /unit	$k = 4$
$C_{SET} = \$2400$ /cycle	$h_R = \$0.8$ /unit/month	$\alpha = 0.1$	$\gamma = 0.4$
$C_{MT} = \$10$ /unit	$h_M = \$0.5$ /unit/month	$\eta = 1.2$	$M = \$2$
$C_P = \$4$ /unit	$d_R = 2000$ units/month	$\delta = 1$	

Results

Optimum values of the cycle time and preservation investment are computed. By using the optimal results, value of total profit per unit time is calculated. The optimum results are exhibited in Table 2.

Table 2. Optimal results

$TP^* = \$73647$/month	$T^* = 0.80$ month	p_a^*=\$2.75/unit/month	$p_b^* = \$1\text{x}10^{-9}$ /unit

From the optimal value of preservation cost/unit/unit time, the investment in preservation technology per cycle of the proposed setup is calculated and provided below.

Optimal investment in preservation technology per cycle $= p_a^* I_R = \$1761$.

Comparative analysis of the results with and without preservation technology

The results of the comparative analysis are exhibited below in Table 3.

Table 3. Comparative analysis

Parameters	Without preservation	With preservation	Percent improvement
Lifetime (month/s)	1.50	4.20	180.00
Rate of deterioration	0.04	0.019	-52.50
Profit (\$/month)	70631	73647	4.27

Comparative analysis of optimal results with and without application of preservation technology show that the application of preservation technology increases lifetime of the product and total profit per unit time of the proposed supply chain system, while the rate of deterioration is reduced. These variations are illustrated in Figure 4.

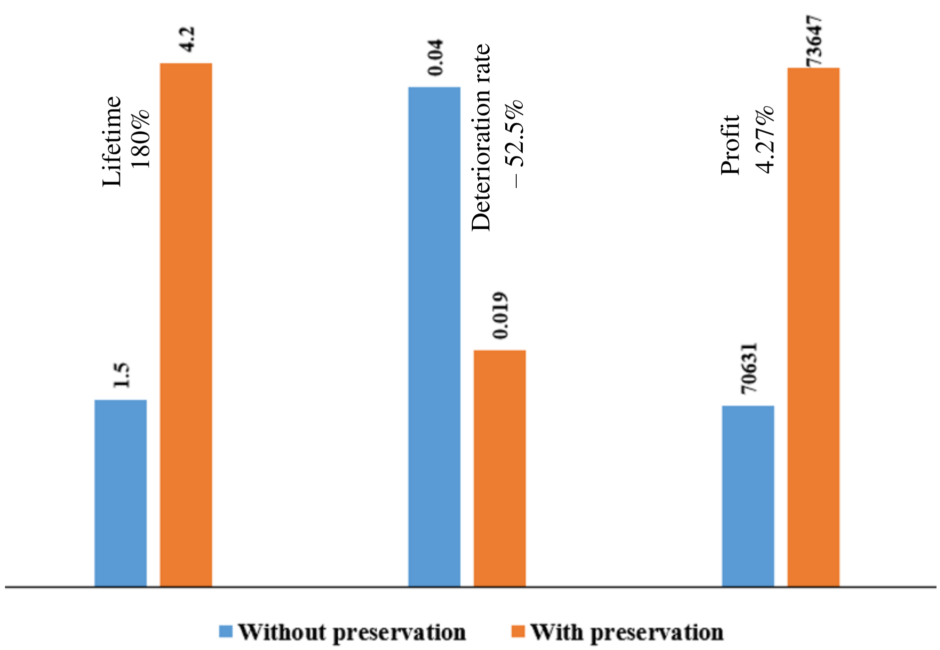

Figure 4. Comparative analysis

5. Concluding remarks

This paper discussed a supply chain system in which preservation technology is used to increase life time of short life deteriorating products and proposed a model to find optimal value of investment in preservation technology. The proposed model suggested that life time of a deteriorating product is increased significantly by applying preservation technology and consequently the rate of deterioration is decreased. The authors also recommended that product having longer time to expire is sold at higher price and it contributes to increase the profit. The hypothesis was verified through the results of numerical illustrations that shows a remarkable increase in the profit of the supply chain when preservation technology was applied. Moreover, it was proved that the investment for preservation conditional is more significant than the investment for preservatives. This research can further be continued to study on how the investment in preservation technology affects the maximum life time of the product. Moreover, it can be investigated that how the variable component of product selling price is affected by maximum life time of the product for a deteriorating product system.

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Biographies

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