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DESIGN OF AN INVENTORY MANAGEMENT SYSTEM IN AN AGRICULTURAL SUPPLY CHAIN CONSIDERING THE DETERIORATION OF THE PRODUCT: THE CASE OF SMALL CITRUS PRODUCERS IN A DEVELOPING COUNTRY

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Inventory management along the agrifood supply chain is a subject of great interest due to the constraints related with the perishable condition of product. Significant problems like demand forecasting, inventory management and transportation was evidenced within the supply chain studied. Additionally, the management of perishables and their lifecycle are the most frequently issue in this kind of supply chain.An inventory management policy is defined taking in consideration the optimal quantity for an order and the time for ordering so as to ward off costs related with understock or overstock. This paper presents a mathematical model for inventory management in agricultural supply chains considering perishability. The supply chain studied involves a retailer, a producer and a supplier. The advantages of integrating inventory management along the supply chain are discussed and finally some recommendations and research opportunities set forth.

Key words: Inventory management; Perishable product; Fruit supply chain; Integration in supply chain

INTRODUCTION

Around 2,500 million people work part-time or full-time in 500 million small farms around the world. However, although the land is occupied by these producers, it only represents 12% of all agricultural land covering more than 80% of the worldwide food demand [01]. The contribution by family farmers and small farmers to the millennium goal related to food security, poverty reduction and sustainable development recognized by the General Assembly of the United Nations. For this reason, the need to count with new methodologies that enable greater efficiency and competitiveness in the supply chain of small agricultural producers looms up.

Agricultural supply chains are a subject of great interest, where an effort in the coordination of the actors, activities and resources is required in order to meet the requirements of thecustomers [02], in this sense [03] affirm that in order to improve the customer satisfaction and reduce the cost, the cooperative relationship between the companies must be built, especially in perishables supply chain. However, due to the conditions in which these chains operate, different problems come into view. Among the most important issueslie demand forecasting, inventory management and transport [04]. There are other factors such as margins of intermediation, infrastructure and geographical conditions that can have serious repercussions in terms of post-harvest losses, which affect the economy of the members of the chain.

Literature related to the performance of fruit supply chains confirms that inventory management is a topic of increasing interest because of the restriction that the perishable condition of the product implies. Considering this constraint, it is important to determine the inventory's frequency of revision so that the product's deterioration cycle is lower than the revision cycle, with the purpose of avoiding product losses caused by an inadequate inventory policy. This policy must also consider the optimal quantity of orders and the time products should be ordered to prevent costs due to "understock" or "overstocking" [05, 06, 07]. In this sense [08] developed a multi-echelon inventory model for a deteriorating item from an integrated perspective and determine the optimal delivery quantities for each echelon. On the other hand, authors such as [09] have shown the benefits of integration in the supply chain thanks to the sharing of information, which enables coordinated decisionmaking therein.

In this regard, [10] define four supply chain archetypes described as the traditional supply chain, shared-information supply chain, supplier supply chain (managed by the supplier) and synchronized supply. The latter represents a scenario where information is transmitted in real time among the members of the chain, such as their levels of inventory, product in transit and sales, achieving the best management amongst the archetypes presented. In this case, the structure of the chain is centralized and its performance significantly improved thanks to information sharing. Nevertheless, not all chains are centralized, so it is necessary to create collaboration mechanisms in decentralized chains to achieve some level of integration. Authors such [11] have defined integration as a necessary strategy for getting into new markets. In this respect[12]validate the importance of information in decisionmaking in the chain by putting forward a classifica

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tion of integration mechanisms in decentralized chains where they include information technologies, shared information, joint decision making and contract models.

This paper aims to approach the management of inventories in the framework of an agricultural supply chain through a mathematical model that considers the deterioration of the product over time and demonstrates the advantages of integrating of its echelons. The characteristics of the chain under study are presented, then the mathematical model used to determine the inventory policy is described, subsequently the results are laid out and a sensitivity analysis is carried out by varying some parameters. Finally,conclusions, recommendations and opportunities for new studies are developed.

PROBLEM STATEMENT

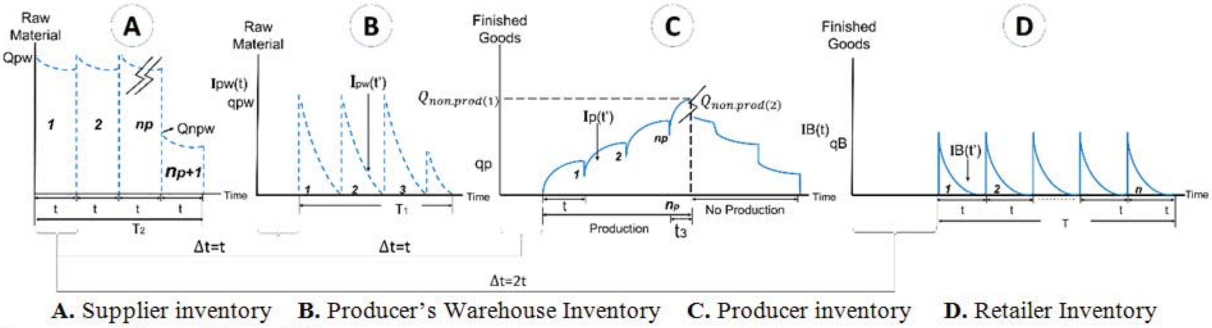
As described above, the study of agricultural supply chains is of great interest mainly due to coordination problems in the chain that affect, among other aspects, the financial results that reflect in the form of low incomefor the case of small farmers. There are some determining factors for the appropriate performance of the chain set forth by [13], such as the variability of demand and prices; the availability of workers; the yield of the crop; labor costs and those associated with the recollection of products; the use of means of transportation that balance out the time it takes to reach the market and the cost; post-harvest management of crops; the degree of maturity of the product; the maximum time for delivery; the availability of products; transportation time and delivery costs. Other authors such as [14], assure that the handling of perishable products and their life cycle are the most differentiating factors of this type of chain. On the other hand, authors how [15], present fruits and vegetables as products that have features of freshness, perishability [16], timeliness, logistics performance [17]. This makes agrifood supply chains constantly-varying complex systems that involve several echelons such as suppliers, distributors, marketers, wholesalers and retailers, among others, which makes it behave as a multidisciplinary system that attempts to satisfy the demands of the final customer through effective coordination of information flows, products and financial resources [18]. A problem of great interest, identified in the literature related to the performance of agricultural supply chains, especially fruit chains, is the management of inventories along the chain, due to the restriction involved in the product's lifecycle. Due to the aforementioned reasons, inventory management becomes a critical issue when dealing with perishable products such as fruits, which require compliance with strict quality requisites. These demands cannot be satisfied only with the desire of small producers to do it, it is also necessary to synchronize from suppliers' supply times, to producers and intermediaries, and from intermediaries to retailers, in order to achieve an adequate estimation of amounts, consumption times in each echelon and eventually the best performance in the chain. The model presented below seeks to represent the behavior of these relationships in a decentralized fruit supply chain, assuming a scenario where information is shared for decision making regarding the inventory along the chain.

MATERIALS AND METHODS

Development of mathematical model

a. **Interaction between supply chain echelons under study**

The chain under study consists of three echelons, namely: a single supplier, a producer and a retailer, as shown in Figure 1. The supplier is responsible for starting the flow of the product to the other echelons, below. The next member of the chain is the producer, who has a warehouse for raw materials and another warehouse to store the finished product. Finally, facing the consumer is the retail echelon, in charge of directly satisfying his demand; the former is also the one that initiates the flow of information, sharing the expected demand with the other actors in the supply chain. The interaction in the supply chain begins at the time the retailer makes an order that attempts to satisfy the demand during a planning period T. This information about the demand is shared with the other echelons and sent to the next supply chain actor (the producer) through an order. The latter must satisfy this order by means of deliveries, at fixed intervals of time, placed in retailer warehouse. Upon receipt of the order, the producer initiates a value-adding process on the raw material in order to generate the finishedproduct



Source: Adapted from [8]

Figure 1: Supply Chain Inventory Management for each echelon

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for the agrifood supply chain under study.

As shown in Figure 1, there is an inversely proportional relationship between the inventories held by the producer, since the raw material inventory is reduced over time when the value-adding process starts, while that of finished product increases. Since the production rate is higher than the demand's, the producer accumulates the inventory of finished product for deliveries carried out in a period after the time of production. In this case, it is assumed that the accumulated inventory is enough to meet the number of remaining deliveries taking into consideration the amount of product that suffers deterioration.

To start off his productive process, the producer requires raw material, which is provided by the supplier. This echelon must perform the supplying of inputs from an external supplier (not considered in this case study), with the objective of maintaining good quality raw material for the producer. The supplier is responsible for providing the raw material required by the producer for itsprocessing. This is achieved by delivering equal quantities at fixed time intervals.

b. Assumptions

- Mathematical inventory model for a single perishable product in an integrated supply chain.
- The aim is to determine the optimal number of deliveries and lot sizes that minimize the total cost of the supply chain.
- Demand and constant production over time.
- The demand rate is lower than the production rate.
- The planning period is known.
- The Lead Time is zero, shortage is not allowed.
- One item is only considered.
- The parameters that represents the deterioration rates are constant and deterministic.
- An order is satisfied through multiple deliveries.
- The supplier delivers the same amount of raw material to the producer.

c. Variables and parameters

Table 1: Notation used in the Mathematical Model

SYMBOL	DESCRIPTION
T	Planning time
T_1	Production time used by the producer $T_1 = n_p t + t_3$
T_2	Cycle time used by the provider $T_2 = (n_p + 1)t$
N	Number of deliveries received by the retailer from the producer for each planning time T
n_p	Number of deliveries received by the retailer from the producer during T_1
t_3	Production time from the point n_p to the end of production
q_B	Lot-size per delivery from the producer to retailer of finished goods
Q_B	Total order quantity of finished goods for retailer per planning time T.
q_p	Finished goods quantity produced in time t.
q_{PW}	Quantity of raw material per delivery received in the producer's warehouse from the supplier.
q_{nPW}	Quantity of raw material delivery received in the producer's warehouse from supplier in last delivery.
Q_S	Supplier's total order quantity of raw materials for period T_2
Q_{PW}	Quantity of raw material harvested by the supplier per delivery
Q_{nPW}	Quantity of raw material harvested by the supplier in last delivery
A_p	Total finished goods inventory for producer in T.
$I_B(t)$	Retailer's finished goods inventory level at time t.
$I_{PI}(t)$	Producer's finished goods inventory level at time t.
$I_{PW}(t)$	Producer's warehouse raw materials inventory level at time t.
$I_S(t)$	Supplier's Raw materials inventory level at time t.
TC_B	Retailer total cost.
TC_P	Producer's total cost.
TC_{PW}	Producer's warehouse total cost.
TC_S	Supplier's Total cost.
TC	Global total cost(TCS + TCPW + TCP + TCB)
D	Retailer's demand rate for finished goods.
A	Finished goods' ordering cost for retailer per order.

F_B	Finished goods' receiving cost for retailer perreception.
H_B	Finished goods' unitary holding cost per unit of time for retailer.
P_B	Deterioration cost per unit of finished goods for retailer.
Q_B	Deterioration rate for retailer's finished goods
P	Producer's production rate for finished goods.
S_P	Producer's setup cost for each setup.
F_P	Finished goods' delivery cost for producer per deliver.
H_P	Finished goods' unitary holding cost per unit of time for producer
P_P	Deterioration cost per unit of finished goods for the producer.
Q_P	Deterioration rateof finished goods for the producer.
F_{PW}	Raw materials' receiving cost per reception for the producer at warehouse.
H_{PW}	Raw materials' unitary holding cost per unit of time for producer's warehouse
P_{pW}	Deterioration cost per unit of finished goods for producer's warehouse.
Q_{PW}	Deterioration rate for producer's raw materials
S	Raw materials' ordering cost per order for the supplier.
F_S	Raw materials ' delivery cost for the supplier per delivery.
H_S	Raw materials' unitary holding cost per unit of time for the supplier.
P_S	Deterioration cost per unit of raw materials for the retailer.
Q_S	Deterioration rate for supplier's raw materials

Note. Source: Adapted from [8].

d. Retailer: Finished product inventory model

According to [19], the inventory level of finished goods at time t' can be expressed as follows:

$$\frac{dI_B(t')}{dt'} = -D - \theta_B I_B(t'), \qquad 0 \le t' \le t \qquad (1)$$

Solving (1) in its extreme points by the integrating factor method:

$$u = e^{\int \theta_B \, dt'}$$

$$u = e^{\theta_B t'}$$

And by multiplying on both sides of the equation (1) by $e^{\theta_B t'}$, then:

$$\frac{dI_B(t')}{dt'} e^{\theta_B t'} + \theta_B e^{\theta_B t'} I_B(t') = -De^{\theta_B t'} \qquad (2)$$

The right part of equation (2) can be expressed as the derivative of a product as follows:

$$\frac{d(e^{\theta_B t'} I_B(t'))}{dt'} = -De^{\theta_B t'}$$

The result obtained by integrating both sides of the equation and solving the respective integrals can be written as:

$$\int d(e^{\theta_B t'} I_B(t')) = \int -De^{\theta_B t'} dt'$$

(3)

$$e^{\theta_B t'} I_B(t') = -\frac{D}{\theta_B} e^{\theta_B t'} + C$$

Multiplying on both sides of (3) by $e^{-\theta_B t'}$ and simplifying:
Applying the boundary condition $I_B(t)$ in (4) to obtain the

$$I_B(t') = -\frac{D}{\theta_B} + Ce^{-\theta_B t'} \qquad (4)$$

integration constant's value, results in:
Using the constant's value in the expression (4) and sim-

$$C = \frac{D}{\theta_B} e^{\theta_B t}$$

plifying:
Therefore, by setting the boundary condition $I_B(0)$ in (5) it

$$I_B(t') = -\frac{D}{\theta_B} + \left[\frac{D}{\theta_B} e^{\theta_B t}\right] e^{-\theta_B t}$$

(5)

$$I_B(t') = -\frac{D}{\theta_B} + \frac{D}{\theta_B} e^{\theta_B (t-t')}$$

is possible to obtain the initial order quantity. In this way, $I_B(0)=q_B$ and the resulting expression is:

To obtain the expression forinventory amount of standby

$$I_B(0) = -\frac{D}{\theta_B} + \frac{D}{\theta_B} e^{\theta_B(t-0)}$$
$$= -\frac{D}{\theta_B} + \frac{D}{\theta_B} e^{\theta_B t}$$
$$= \frac{D}{\theta_B}\left(e^{\theta_B t} - 1\right) = q_B \tag{6}$$
$$q_B = \frac{D}{\theta_B}\left(e^{\theta_B t} - 1\right)$$

finished products, the equation (6) must be integrated between 0 and t, as follows:

The total cost of offered goods can be expressed as the

$$\int_0^t I_B(t')\,dt' = \int_0^t \left(-\frac{D}{\theta_B} + \frac{D}{\theta_B} e^{\theta_B(t-t')}\right) dt'$$
$$= \left[-\frac{D}{\theta_B}t' - \frac{D}{\theta_B{}^2} e^{\theta_B(t-t')}\right]_0^t$$
$$= -\frac{D}{\theta_B}t - \frac{D}{\theta_B{}^2} + \frac{D}{\theta_B{}^2} e^{\theta_B t}$$
$$= \frac{D}{\theta_B{}^2} e^{\theta_B t} - \left(\frac{D}{\theta_B}t + \frac{D}{\theta_B{}^2}\right)$$
$$= \frac{D}{\theta_B{}^2} e^{\theta_B t} - \left(\frac{D\theta_B{}^2 t + D\theta_B}{\theta_B \theta_B{}^2}\right) \tag{7}$$
$$= \frac{D}{\theta_B{}^2} e^{\theta_B t} - \left[\frac{\theta_B(D\theta_B t + D)}{\theta_B \theta_B{}^2}\right]$$
$$= \frac{D}{\theta_B{}^2} e^{\theta_B t} - \left[\frac{(D\theta_B t + D)}{\theta_B{}^2}\right]$$
$$= \frac{D}{\theta_B{}^2} e^{\theta_B t} - \frac{D\theta_B t + D}{\theta_B{}^2}$$

$$\int_0^t I_B(t')\,dt' = \frac{D}{\theta_B{}^2} e^{\theta_B t} - \frac{D\theta_B t + D}{\theta_B{}^2}$$

sum of the cost of the order, the cost of reception, the cost of maintenance and the cost of deterioration. Therefore, the total cost of the goods offered to the retailer during a planning period T, can be expressed as:

Using the following approach:

$$TC_B = \frac{A}{T} + F_B\frac{n}{T} + \left(\frac{D}{\theta_B^2} e^{\theta_B t} - \frac{D + D\theta_B t}{\theta_B^2}\right) H_B \frac{n}{T} + \left[\frac{D}{\theta_B}\left(e^{\theta_B t} - 1\right) - Dt\right] P_B \frac{n}{T} \tag{8}$$

Proposed by [8] and substituting in the retailer total cost

$$e^{\theta t} = \frac{(2+\theta t)}{(2-\theta t)}$$

equation, the following is obtained:

e. Producer's warehouse: Raw material inventory

$$TC_B = \frac{A}{T} + F_B\frac{n}{T} + \frac{D\left(2+\theta_B\frac{T}{n}\right)}{\theta_B^2\left(2-\theta_B\frac{T}{n}\right)} - \left[\frac{D + D\theta_B\frac{T}{n}}{\theta_B^2}\right] H_B\frac{n}{T} + \left[\frac{D}{\theta_B}\left(\frac{2+\theta_B\frac{T}{n}}{2-\theta_B\frac{T}{n}} - 1\right) - Dt\right] P_B\frac{n}{T} \tag{9}$$

level

The raw material inventory level of the producer's warehouse at time t'can be expressed as follows:

At the extreme points of equation (9), the inventory will

$$\frac{dI_{PW}(t')}{dt'} = -P - \theta_{PW} I_{PW}(t'), \quad 0 \le t' \le t \tag{10}$$

be expressed by the following equations:

Integrating the expressions (11) and (12) from 0 to t and

$$q_{PW} = \frac{P}{\theta_{PW}}\left(e^{\theta_{PW} t} - 1\right) \tag{11}$$

$$q_{nPW} = \frac{P}{\theta_{nPW}}\left(e^{\theta_{PW} t_3} - 1\right) \tag{12}$$

from 0 to t_3 respectively, in the same way as shown in the retailer's model, the inventory quantities of standby raw material at time t and t'are obtained as:

$$\int_0^t I_{PW}(t')\,dt' = \frac{P}{\theta_{PW}^2} e^{\theta_{PW} t} - \frac{P + P\theta_{PW} t}{\theta_{PW}^2} \quad (13)$$

$$\int_0^{t_3} I_{nPW}(t')\,dt' = \frac{P}{\theta_{PW}^2} e^{\theta_{PW} t_3} - \frac{P + P\theta_{PW} t_3}{\theta_{PW}^2} \quad (14)$$

Therefore, according to [8], the producer's total cost for raw material warehousing per cycle T could be represented as the sum of the maintenance cost, the receiving cost and deterioration cost, as follows:

$$\begin{aligned} TC_{PW} &= F_{PW}(n_p+1)\frac{1}{T} + \\ &\left[\frac{Pe^{\theta_{PW} t}}{\theta_{PW}^2} - \frac{P + P\theta_{PW} t}{\theta_{PW}^2}\right] H_{PW} n_p \frac{1}{T} + \\ &\left[\frac{Pe^{\theta_{PW} t_3}}{\theta_{PW}^2} - \frac{P + P\theta_{PW} t_3}{\theta_{PW}^2}\right] * H_{PW} * \frac{1}{T} + \\ &\left[\frac{P}{\theta_{PW}}\left(e^{\theta_{PW} t} - 1\right) - P * t\right] * P_{PW} * n_p * \\ &\left[\frac{P}{\theta_{PW}}\left(e^{\theta_{PW} t_3} - 1\right) - P * t_3\right] * P_{PW} * \frac{1}{T} \end{aligned} \quad (15)$$

f. Inventory level of finished products by the producer

When the retailer orders a quantity of finished product from the producer in period T, the producer begins the production and delivery at time t.

In the first period, the producer achieves a production of finished product equal to in period t. The producer's inventory level of finished product in the first period can be represented as follows:

$$\frac{dI_P(t')}{dt'} = -P - \theta_p I_P(t'), \qquad 0 \le t' \le \quad (16)$$

Solving equation (16), analogous to the differential equation that represents retailer's model bearing the integrating factor method, the inventory level for the extreme points will be:

$$q_P = \frac{P}{\theta_p}\left[1 - e^{-\theta_p t}\right] \quad (17)$$

Thus, the inventory level of finished products for the nth delivery after the first one is obtained, according to [8] with the following differential equation:

$$\frac{dI_{P_i}(t')}{dt'} = -P - \theta_p I_p(t'), \quad 0 \le t' \le t, \quad 0 \le i \le n_p + 1 \quad (18)$$

The inventory of finished product before the i-delivery is . Solving the equation (18) by as initial condition,it is possible to determine the inventory level for the i-th delivery, like this:

$$I_{P_i}(t') = \frac{P}{\theta_p}\left[1 - e^{-\theta_p t'}\right] + Q_{i-1} e^{-\theta_p t'}, 0 \le t' \le t, 0 \le i \le n_p + 1 \quad (19)$$

According to [8], from the previous expression (19) the lot size from the non-production period can be determined as:

$$Q_{non-prod(1)} = \frac{P}{\theta_p} + \frac{q_B e^{3\theta_P t}}{e^{\theta_P (t' + tnp + 2t)(e^{\theta_P t} - 1)}} - \frac{q_B e^{3\theta_P t}}{e^{\theta_P (t' + 2t)(e^{\theta_P t} - 1)}} - \frac{P}{\theta_p e^{\theta_P (t n_p + t')}} \quad (20)$$

In accordance with the model of [8], as soon as the producer reaches the amount of finished product that the retailer needs per order cycle time T, production is stopped. The production time is defined in ($n_p t + t_3$). However, the producer continues to deliver a constant quantity of merchandise, until the entire amount of production of finished products has been delivered to the retailer. This occurs at time T; when the level the producer'sinventory of finished product is equal to zero.

In [19] argue that the final inventory after time t considering a constant rate of deterioration, can be expressed as:
At time ($n_p t + t_3$), producer stops production. The inventory

$$\text{Ending Inventory} = \text{Opening Inventory}(1 - \theta)^t \quad (21)$$

amount of finished goods is $Q_{non/product}$;after time ($t - t_3$) , the inventory becomes Q_{np1} and in compliance with the expression of[19], the outcome will be as follows:
The final quantity of inventory of finished products for

$$Q_{nP+1} = Q_{non-prod(1)}(1 - \theta_p)^{t - t_3} \quad (22)$$

time (n_p+1) can be derived as:
The inventory amount of finished product from the pro-

$$Q_{nP+i} = (Q_{nP+i-1} - q_B)(1-\theta_p)^t, \quad n_p + 1 \le i \le n$$

ducer for the nth time is equal to the lot size per delivery. From (23), the lot size of finished products can be obtained during the non-production period at t=t_3 as:
With $Q_{non/product(1)}$ and $Q_{non/product(2)}$, the values of n_p y t_3

$$P(\mathrm{tn}_p + t_3) - nq_B = (A_1 + A_2 \ldots + A_n)\theta_p = A_p\theta_p$$

can be determined. To find the corresponding values for n_p, the algorithm proposed by[8] needs be followed, which consists on assuming $Q_{non/product(1)}$, $Q_{non/product(2)}$. Thus, the equation is equal to zero and t' is replaced by t. Subsequently, for each value of n, every np value is obtainedalong with the parameters needed for the equation's solution such as the production rate of the producer, the rate of deterioration and the lot size of finished products per delivery from the producer to the retailer.

To estimate t_3, a similar procedure is performed, where t' is replaced by t'. Then, $Q_{non/product(1)}$ and $Q_{non/product(2}$ are equated. In this way, it is possible to find every for its corresponding value.In [8] an algorithm it is presentedto find the value of time and , however, in this document we propose an alternative procedure to determine the value of by matching the expressions and which correspond to the quantity of inventory at the end of the production period and the quantity of inventory at beginning the period of depletion once production has stopped, respectively. The resulting equation is expressed as a function F [t_3] throughwhich we obtain the value of that makes the function equal to zero, this point is defined as the point of intersection with the X axis, which corresponds to value for a number of n defined deliveries.

$$f[t_{3}\_]:=\frac{P}{\theta_p}+\frac{q_B e^{3\theta_p t}}{e^{\theta_p(t_3+t\mathrm{n}_p+2t)}(e^{\theta_p t}-1)}-\frac{q_B e^{3\theta_p t}}{e^{\theta_p(t_3+2t)}(e^{\theta_p t}-1)}-\frac{P}{\theta_p e^{\theta_p(t\mathrm{n}_p+t_3)}}-\left(\frac{q_B((1-\theta_p)^{t_3-nt+n_pt-t}-(1-\theta_p)^{t_3-t})}{(1-\theta_p)^{-t}-1}\right)$$

ThroughWolfram Mathematica, this analysis is validated by making the graph of the mathematical expression, the value obtained with this method is observed to correspond to the value obtained algebraically. In figure 2an arbitrary interval of (-0.003; 0.003) is obtained for the parameters associated with a number of deliveries n = 100, a value of t_3 = 0.0145134 corresponding to the point of intersection with the X axis.

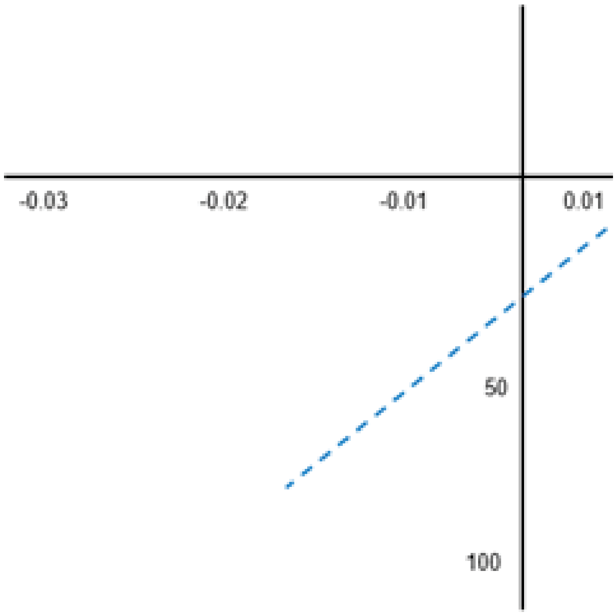

Figure 2: Graphic method for t_3 calculation

Note. Source: Author' own elaboration

The deterioration of the finished products' quality during cycle T is the sum of deteriorated finished products quantity from period 1 to n and is written as follows:

$$P(\mathrm{tn}_p + t_3) - nq_B = (A_1 + A_2 \ldots + A_n)\theta_p = A_p\theta_p \tag{25}$$

The deterioration cost and the maintenance cost of the finished products per order cycle time T can be obtained in the following way:

$$A_pH_p = \left[\frac{(P(\mathrm{tn}_p + t_3) - nq_B)}{\theta_p}\right]H_p \tag{26}$$

Producer's total finished goods cost for planning period T could be represented as the sum of the setup cost, the delivering cost, the cost of maintenance and the deterioration cost, as follows:

$$C_p = \frac{S_p}{T} + \frac{F_p}{T}n \cdot \left[\frac{(P(\mathrm{tn}_p + t_3) - nq_B)}{\theta_p}\right]H_p \cdot [P(\mathrm{tn}_p + t_3) - nq_B]\frac{P_f}{T} \tag{27}$$

g. Supplier Inventory Model

Considering that the supplier's opening inventory is designated as, [19] denote the amount of raw materials per delivery from the supplier to the producers' warehouse, as well as the last quantity provided by the supplier, as follows:

$$q_{PW} = Q_{PW}(1-\theta_S)^t \quad (28)$$

$$q_{nPW} = Q_{nPW}(1-\theta_S)^t \quad (29)$$

Should (28) y (29)de integrated from 0 tot, the final inventory of raw materials can be obtained, as:

$$\int_0^t q_{PW}(t')\,dt' = \int_0^t Q_{PW}(1-\theta_S)^t\,dt'$$
$$= \left[\frac{Q_{PW}(1-\theta_S)^{t'}}{\mathrm{Ln}(1-\theta_S)}\right]_0^t$$
$$= \frac{Q_{PW}(1-\theta_S)^t}{\mathrm{Ln}(1-\theta_S)} - \frac{Q_{PW}(1-\theta_S)^0}{\mathrm{Ln}(1-\theta_S)} \quad (30)$$
$$= \frac{Q_{PW}(1-\theta_S)^t}{\mathrm{Ln}(1-\theta_S)} - \frac{Q_{PW}}{\mathrm{Ln}(1-\theta_S)}$$
$$= \frac{Q_{PW}(1-\theta_S)^t - Q_{PW}}{\mathrm{Ln}(1-\theta_S)}$$

The same applies for:

$$\int_0^t q_{PW}(t')\,dt' = \frac{Q_{PW}(1-\theta_S)^t - Q_1)}{\mathrm{Ln}(1-\theta_S)}$$

In this manner, the quantity of the supplier's order for raw material thatsatisfies the demand of the producers' warehouse from time 0 to t is also defined as:

$$\int_0^t q_{nPW}(t')dt' = \int_0^t Q_{nPW}(1-\theta_S)^t\,dt$$
$$= \left[\frac{Q_{nPW}(1-\theta_S)^{t'}}{\mathrm{Ln}(1-\theta_S)}\right]_c^t$$
$$= \frac{Q_{nPW}(1-\theta_S)^t}{\mathrm{Ln}(1-\theta_S)} - \frac{Q_{nPW}(1-\theta_S)^{(}}{\mathrm{Ln}(1-\theta_S)}$$
$$= \frac{Q_{nPW}(1-\theta_S)^t}{\mathrm{Ln}(1-\theta_S)} - \frac{Q_{nPW}}{\mathrm{Ln}(1-\theta_S)}$$
$$= \frac{Q_{nPW}(1-\theta_S)^t - Q_{nPW}}{\mathrm{Ln}(1-\theta_S)} \quad (31)$$

$$\int_0^t q_{nPW}(t')\,dt' = \frac{Q_{nPW}(1-\theta_S)^t - Q_{n}}{\mathrm{Ln}[1-\theta_S]}$$

$$Q_S = n_p Q_{PW} + Q_{nPW} \quad (32)$$

Eventually, supplier's total cost according to [19], could be represented as the sum of the maintenance cost, set-up cost, delivery cost and deterioration cost:

$$T = \frac{S}{T} + F_S(n_p+1)\frac{1}{T}$$
$$+H_S\left[\frac{n_p(q_{PW}-Q_{PW}) + (q_{nPW}-Q_{nPW})}{Log[1-\theta_S]}\right]\frac{1}{T} \quad (33)$$
$$+P_S[n_p(Q_{PW}-q_{PW}) + (Q_{nPW}-q_{nPW})]\frac{1}{T}$$

$$T = \frac{S}{T} + F(n+1)\frac{1}{T} + H$$

Finally, the global cost of the integrated inventory model could be represented as the sum of the supplier, producer and retailer's individual costs, as follows:

$$TC = \mathrm{TC}_B + \mathrm{TC}_{PW} + \mathrm{TC}_p + \mathrm{TC}_S \quad (34)$$

As presented in equation (34), the Total Cost is the objective function that must be minimized and it is obtained through the sum of costs assumed per each echelon in the supply chain. In order to find the minimum Total Cost, a number of iterations must be executed, varying the number of deliveries n. In each iteration the order quantity and total quantities between echelons are derived. Then, the values of the Total Cost from the different iterations are analyzed and the number of deliveries n that minimizes the objective function TC is defined.

Table 2: Parameters used in the execution of the model

TABLE OF PARAMETERS USED IN THE EXECUTION OF THE MODEL			
BUYER - RETAILER			
Parameter	Computing Method	Value	Units
D	Time forecast series for constant demand	3.718	[Unit/month]
A	Cellphone plan, paperwork order	0,4	[US$/Order]
FB	Cost of loading and unloading per worker per truck	10,8	[US$/Reception]
HB	Warehouse leasing cost, area occupied by citrus fruits, inventory turnover	0,4	[US$/Unit-Month]
PB	It is calculated as a 35% from original sales price.	0,7	[US$/Unit-Month]
THB	Percentage of lemons damaged by deterioration	0,08	
PRODUCER – INTERMEDIARY			
P	Ability to select good quality lemons and pack them in 1kg nets, with an available time of 480 minutes per working day, during 28 days a month	6.240	[Nets of 1kg/ month]
SP	Using production capacity, the number of wages required to satisfy the demand during the planning horizon (1 month) is reckoned and then multiplied by the value of each one(US$ 9,03/day)	167,7	[US$/order preparation]
FP	Value of retailer transportation cost plus the cost of loading	61,4	[US$/delivery]
HP	The leasing cost between the area of finished goods and raw material warehouse is prorated. In each part of the warehouse, 1/10 of production capacity can be stored.	0,1	[US$/Kg*month]
Pp	In this case, up to 70% of the original price can be sold. It means that 30% of the original price fails to be received.	0,3	[US$/Kg]
ThP	Percentage of lemons damaged by deterioration	0,01	-
Fpw	Cost of loading and unloading a truck per worker	10,9	[US$/reception]
Hpw	The leasing cost between the area of finished goods and raw material warehouse is prorated. In each part of the warehouse, 1/10 of production capacity can be stored.	0,1	[US$/Kg* month]
Ppw	What it is not being perceived if it is sold without packing but considering CABAZA price market. Bulk sale price: US$54,2; Cost: US$43,4; Bulk profit: US$10,8; Deteriorating cost / kg: US$10,8 / 60Kg	0,2	[US$/kg]
Thpw	Percentage of lemons damaged by deterioration	0,10	-
SUPPLIER – FARMER			
Hs	Calculation of monthly maintenance costs of one hectare; estimated production per tree a month	0,2	[US$/Kg*month]
Ps	Probability that a tree does not develop correctly multiplied by the cost of the tree	0,05	[US$/Unit]
S	The survey provides the estimated annual cost of reception, given that S is for the planning horizon, it is divided into 12	90,3	[US$/order]
Fs	Cost of pickup and freight is US$ 72,23 for transportation from the supplier to the producer or broker's warehouse	14,8	[US$/delivery (harvest)]
ThS	Percentage of lemons damaged by deterioration	0,15	-

Note.Source: Author' own elaboration.

Table 3: Quantities delivered by the echelons and percentage of deteriorated product along the supply chain for different delivery frequencies

n	n_p	q_B	Q_B	q_P	q_{PW}	Q_{PW}	q_{nPW}	Q_{nPW}	Q_S	Percentage of Deterioration
1	-	3.871	3.871	5.938	6.563	7.721	4.286	5.042	5.042	36%
2	1	1.897	3.793	3.043	3.199	3.470	851	923	4.393	18%
3	1	1.256	3.768	2.046	2.115	2.233	1.854	1.958	4.190	13%
4	2	939	3.755	1.541	1.580	1.645	764	795	4.086	10%
5	3	750	3.748	1.236	1.261	1.302	118	122	4.028	8%
6	3	624	3.743	1.031	1.049	1.078	735	755	3.987	7%
7	4	534	3.739	885	898	919	277	284	3.959	6%
8	4	467	3.737	775	785	801	720	735	3.939	6%
9	5	415	3.735	690	697	710	366	373	3.922	5%
10	6	373	3.733	621	627	637	84	85	3.910	5%
15	9	249	3.728	415	417	422	73	73	3.871	4%
20	12	186	3.725	311	313	315	67	68	3.852	4%
25	15	149	3.724	249	250	252	64	64	3.840	3%
30	18	124	3.723	208	208	209	61	62	3.832	3%
35	21	106	3.722	178	179	179	60	60	3.827	3%
40	24	93	3.722	156	156	157	59	59	3.823	3%
45	27	83	3.721	139	139	139	58	58	3.820	3%
50	30	74	3.721	125	125	125	57	57	3.817	3%
55	33	68	3.721	113	114	114	56	56	3.815	3%
60	36	62	3.720	104	104	104	56	56	3.813	3%
65	39	57	3.720	96	96	96	55	56	3.812	3%
70	42	53	3.720	89	89	89	55	55	3.811	2%
75	45	50	3.720	83	83	83	55	55	3.809	2%
80	48	47	3.720	78	78	78	54	55	3.808	2%
85	51	44	3.720	73	73	74	54	54	3.808	2%
90	54	41	3.720	69	69	70	54	54	3.807	2%
100	60	37	3.719	62	62	63	54	54	3.806	2%

Note.Source: Author' own elaboration.

RESULTS AND DISCUSSION

a) Delivery amounts among echelons

The mathematical model proposed in this work was solved through Matlab using the parameters defined in table 2**.** The results obtained in Matlab were exported to Microsoft Excel in order to display them in a clearer and more practical way.

As a summary, table 3 shows the delivery quantities that each echelon is supposed to

carry along the chain. It can be clearly seen that increasing delivery quantities, lowers the amount of product that deteriorates along the chain.

By increasing the frequency of delivery in the planning time T, there will be a smaller time interval between deliveries. Therefore, the deterioration rate has low consequences for the short time that the product lingers before reaching the consumer.

b) Optimal independent costs and integrated supply chain optimal cost

In Table 4 it is possible to determine the lowest overall cost or optimum total cost of the citrus supply chain under study.It is also possible to establish what the optimal cost for each independent echelon is and the delivery conditions for each specific situation. The lowest total cost for the chain is US$ 1.210 a month. This is achieved when the number of deliveries in the planning period (one month) is equal to 5.

Analyzing the optimal independent costs, the supplier must make 8 deliveries during time T, in this case the total cost of the chain becomes 8% more expensive than

Table 4: Local and global costs for several delivery frequencies

n	n_p	TC_B	TC_PT	TC_S	TC	OptimalEchelon
1	-	833	709	1007	2549	
2	1	428	603	529	1560	
3	1	302	602	383	1288	Producer
4	2	245	637	329	1211	
5	3	215	691	303	1210	Integrated SC
6	3	199	738	276	1213	
7	4	191	800	272	1264	
8	4	187	855	258	1301	Supplier
9	5	187	921	262	1370	Retailer
10	6	189	989	269	1447	
15	9	216	1315	288	1819	
25	15	303	1983	356	2642	
30	18	352	2319	395	3067	
35	21	403	2657	436	3496	
40	24	454	2995	477	3927	
45	27	506	3333	520	4359	
50	30	558	3672	563	4793	
55	33	611	4011	605	5227	
60	36	664	4350	648	5662	
65	39	717	4689	692	6098	
70	42	770	5029	735	6534	
75	45	824	5367	779	6970	
80	48	877	5707	822	7406	
85	51	931	6046	867	7844	
90	54	985	6385	910	8280	
100	60	1092	7065	997	9154	

Note. Source: Author's own elaboration

the lowest total cost for the global solution in the supply chain.

From the producer's perspective, only three deliveries should be made, generating a greater total cost along the chain compared with the global optimum. In this scenario the total cost of the chain is 6% more expensive than the integrated supply chain. The reason why the number of optimal deliveries for the producer is so low is due to cost of delivering, since the product must be transported to the customer's warehouse (retailer), located in a city 90 km away. The cost of making each delivery is US$ 61.4. That is why it is more beneficial for the producer to store raw materials and finished products and assume maintenance and deterioration costs. The aforementioned impacts on the increase of the other echelons' costs. Finally, from the retailer's approach, deliveries must be made every 3 days.In other words, to achieve the optimum cost of the retail echelon, 9 deliveries must be made in the planning period of one month; in this case, the total cost of the chain would be 13% greater than the solution obtained through the mathematical model.

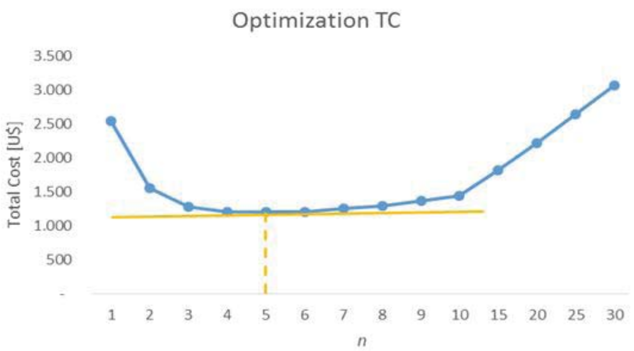

Figure 3: Graphical representation TC function and the optimal value obtained.

According with results shown in table 4 it is possible obtain the value for n that minimize the total cost on the studied supply chain. Results are presented in Figure 3 as a graphic that shows different values for n, as well as the n where the minimum TC is obtained.

c) Inventory control policy for echelons in the lemon supply chain

Taking into account the results presented above and considering the defined planning horizon (one month), it is possible to formulate the inventory control policy for each echelon belonging to the supply chain, thus responding to the three fundamental questions: Frequency of revision, moment of ordering and quantity to order. According to [20]in the case of perishable goods, since they have a limited lifetime, in order to be able to complying with the shelf life time, the length time in the supply chain should not exceed the lifetime value, as each unit of time that is exceeded in the supply chain represent deterioration in the products condition. In this sense the inventory level revisionshould be defined as continuous in each echelon.

Retailer Inventory Management Policy: Review the inventory level continuously; order an amount equal to 750 units of 1 kg of selected lemon when the inventory level in the warehouse reaches zero.

Producer Inventory Management Policy: Check the inventory level continuously; order an amount equal to 1261 kilograms of virgin lemon, when the inventory of raw material in the warehouse reaches zero.

Supplier inventory management policy:Review the inventory level continuously; when the level of inventory of virgin lemon in the warehouse reaches zero, the supplier must harvest an amount equal to 1302 kilograms of virgin lemon during the first 3 deliveries. Nonetheless, in the last delivery only 122 kilograms of virgin lemon need be sent to the producer.

Costing of the current supply chain

In order to determine the costs of the current citrus supply chain, the deliveries made in a planning period are defined with the information provided by the echelons through the surveys carried out. Delivery schedule can be seen in table 5excluding Sundays; 14 deliveries are made per month. This will be the input used to determine the cost of the current chain.

When the current number of deliveries is reckoned, the cost per each component of the relevant total cost can be computed with the purpose of costing the supply chain in its current conditions, as presented in table 6. Subsequently, the comparison with the results of the costs obtained through the proposed model is shown.

Table 5: Current Delivery Schedule: One-month planning period

CURRENT DELIVERY SCHEDULE						
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Monday	Tuesday	Wednesday				

Note. Source: Author's own elaboration

Once the optimal cost of the inventory control system has been attained through the model formulated, and after defining each of the operational costs related to the management of inventory in the supply chain in its current conditions. It is possible to make a comparison between both scenarios; in the first scenario (model implemented) total cost is the objective function minimizedand it is the sum of costs assumed per each echelon in the supply chain. Take in account that to find the minimum Total Cost, a number of iterations must be executed, varying the number of deliveries n. Then, the values of the Total Cost from the different iterations are analyzed and the number of deliveries n that minimizes the objective function TC is defined. A summary for the current situation and the proposed situation results are presented in table 7. The total monthly cost related to inventory management in the current supply chain is US$1.862, while in the proposed model the optimal cost is US$1.210 a month. A 35% reduction is achieved with the specifications of policies, asproposed by the mathematical model developed herein.

It is important to highlight the realization that comes to light with this model regarding the dominance held by the retailer over the other actors. Currently, the frequency of deliveries is defined by him and the other echelons must adapt to his orders without issuing any judgment. From the retailer's point of view, the model suggests to increase the frequency of receptions up to reaching nine deliveries a month, the highest frequency suggested in the optimal local analysis. The high frequency suggested for the retailer by the model, validates the chain's current operation, where a large number of deliveries is required by the retailer.

Effect of variations in deteriorating rate on optimal result

In order to understand deterioration rate impact in the Supply chain, a sensitivity analysis is shown in Table 8. Just one of the rates is modified at the same time remain the rest constant. Original rate value for each MAX scenario is increased arbitrarily by 75% and each rate for each MIN scenario is reduced by the same percentage.

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Table 6: Costs of the current agricultural supply chain

RETAILER		
Cost of Reception	152	US$/month
Ordering cost	0,4	US $/month
Maintenance cost	34	US $/month
Buyer Monthly Cost	186,4	
PRODUCER		
Deliveries	860	US$/month
Preparation	168	US$/preparation of order per month
Maintenance Cost	36	US$/month
Producer Monthly Cost	1064	
PRODUCER WAREHOUSE		
Reception of Raw Material	152	US$/month
Raw Material Maintenance Cost	36	US$/month
Product Warehousing Monthly Cost	188	
SUPPLIER		
Delivery	15	US$/month
Maintenance	319	US$/month
Reception of Supplies	90	US$/month
Supplier Monthly Cost	424	

Note.Source: Author's own elaboration

Table 7: Comparison of the current cost and the optimal cost obtained through the model

Total monthly cost of the current chain	US$ 1862
Total monthly cost of the proposed chain	US$ 1210
Improvement	35%

Note.Source: Author's own elaboration

In general, despite huge deterioration rate variation, the total cost and local costs of each echelon do not vary more than 3%. In addition,deterioration rate has a greater impact on the producer echelon, while in the opposite extreme, the less impact is in the supplier, reaching around 0.5% of variation in the total cost.

Table 8: Comparison of the current cost and the optimal cost obtained through the model

COST	ThS=0,15		ThPW=0,1		ThP=0,1		ThB=0,08		ORIGINAL SCENARIO
	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	
	0,2625	0,0375							
TC_S	187	187	187	187	187	187	196	178	187
TC_p	602	602	611	591	640	560	604	601	602
TC_b	262	255	259	258	263	257	259	258	258
TC	1216	1203	1216	1203	1241	1175	1226	1189	1210

Note.Source: Author's own elaboration

In general, despite huge deterioration rate variation, the total cost and local costs of each echelon do not vary more than 3%. In addition,deterioration rate has a greater impact on the producer echelon, while in the opposite extreme, the less impact is in the supplier, reaching around 0.5% of variation in the total cost.

Model limitations

In order to adjust the proposed model to the more real situation it would be interested to consider agricultural producer cultivate different product. In that sense this model has some limitations because does not consider several fruits but just lemon as a single product in supply chain. In addition, the capacity of the lemon truck transporting is not included in the analysis. Finally model only takes in account one single member per echelon when in this kind of supply chain frequently has a several players in each of them.

CONCLUSIONS AND OPPORTUNITIES FOR FUTURE RESEARCH

Efficiently managing a supply chain involves its overall optimization. Since supply chains operate under different conditions due to their nature, it is necessary to implement an adequate inventory control system bearingthe integration of each of its echelons as its fundamental principle in order to maximize the total value generated by it. An integrated supply chain should seek real-time information sharing by its members with the aim of generating such synergy, so that the highest possible performance is achieved.

The pertinence of the three-level supply chain proposed in this work, namely stated as supplier, producer and retailer, was validated. Data on the costs related to the management of inventories in each echelon were obtained, which became an important input for the proposed study.

Finally, it is evident that there are large price fluctuations of citrus and high-rising supply costs in the chain under study. In times of oversupply, when the prices fall significantly, the need to minimize logistics costs along the chain is met through an integrating model approach.

This research has shown that an optimal supply chain works perfectly from an integration approach and not from a particular point of view. The mathematical model used allowed to define the optimal quantity for orders, the moment of ordering and the frequency with which the inventory of the citrus chain under study in the rural area of Tulua- Andalucia, Valle del Cauca, Colombia, must be revised.

The integration of the supply chain through the exchange of information, as posed by the synchronized supply chain archetype where information on demand and the inventory level is shared, enables the adequate functioning of the chain's overall performance, allowing the producer to fithisyield to the information provided by the next echelon in the supply chain, thus reducing logistics costs.

With the goal of validating and proving the mathematical model with the data collected from the supply chain under study, and determining ordering optimal quantity and time, and inventory review frequency, the total current chain cost per month was determined (taking into account that one hectare is sufficient to satisfy the demand along the supply chain under study), as the sum of the cost incurred by each echelon from an individualistic approach. To that end, the current delivery schedule, the reception, delivery, maintenance, loading, unloading and the ordering cost were taken into consideration. The current total cost was compared with the optimal cost obtained through the mathematical model and under an integration approach, wherein the total cost of inventory management in the citrus chain under study was found to have reduced around 35%.

This paper can be the basis for future research considering some additional conditions in which the citrus supply chain currently operates. It is relevant to study this model bearing in mind a bigger supplier basis and bigger number of retailers. Furthermore, this model does not consider the transport lemon truck capacity and therefore it is highly recommended to raise this restriction for the model to resemble reality even more. It is also proposed to study the rate of deterioration by analyzing the problem from the chemical and biological standpoints of the product in different scenarios in order to determine this percentage more accurately and obtain more reliable results through this mathematical model.

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