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A shelf-life model considering mechanical injury and natural decay to optimize fresh fruit distribution

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Abstract

This paper develops a specific quality attribute model considering mechanical injury (MI) and natural decay (ND) in fresh fruit, for problem solving in operations research. The model resolves shortcomings found in the widely adopted models mainly focused on a set or an undetermined shelf life, through a multi-objective framework designed to study the economic benefits of fresh fruit distribution. The multi-objective optimization model integrates the transportation and inventory planning of fresh fruit (MOTIP). It is based on a bi-objective function maximizing the total net profit (NP) and the percentage of the remaining fruit quality (%RQ), using a Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to solve the problem. The results indicate the accuracy of NSGA-II algorithm to solve the problem of fresh fruit distribution. The optimal Pareto front curves of the TIP model show a strong positive correlation between the %RQ and the NP. While the specific kinetic shelf-life model can be used to decide on the best schedule for transporting and storing fruit in order to optimize the net profit and remaining quality, the MOTIP-model allows a significant improvement in the benefits related to the export of fresh fruit while minimizing the loss of quality. The developed model is a decision support tool that allows exporters to better plan the transport and storage of exported fresh fruits.

Keywords: *fresh fruit quality; fresh fruit distribution; shelf-life model; quality loss; multi-objective decision-making*

1. Introduction

Over the past five years, international trade in fresh fruit and vegetables increased constantly to meet consumer demand for the regular supply of good quality, safe, and nutritious fresh food products [1]. As Segovia et al. [2] have shown, the total global import value of fruit and vegetables increased by 23% from 2014 to 2018. Quality loss is an important issue in fruit distribution management (FDM). An estimated 30% of the fruit produced for human consumption is lost or wasted somewhere along the fruit supply chain [3]. Fresh fruit distribution under quality control has to integrate many parameters. It is characterized by long supply lead times combined with significant supply and demand uncertainties, and relatively thin margins. With regard to temperature and humidity, the limited shelf life of fresh fruits is impacted by conceivable interaction effects between fruits, time windows for transportation and high customer expectations [4]. This complexity generates a huge need for decision-making approaches that can balance and optimize fresh fruit distribution.

Maintaining fruit quality is critical to the efficiency of the fruit logistics network. The complexity and particularities of the mechanisms of quality loss differ for each fruit type, and thus require a specific distribution system to maintain fruit quality throughout the fruit supply chain. The quality loss in fruit generally stems from the combined action of two leading causes: mechanical injury (MI) and natural decay (ND) [5]. Mechanical injury (MI) concerns the damage during fruit distribution [6] and is the main cause of downgrading and wastage of fresh fruit. It represents a high cost for companies [7]. Natural decay (ND) is the process of physiological change in fresh produce due to the loss of freshness, the natural ripening of fruit, and micro-organism contamination. The rate of quality loss depends on the type of fruit and is closely related to the physiological and morphological characteristics of each individual fruit.

Many shelf life models are applied in the operations research model (ORM) to assess the degree of quality loss, based on available fresh fruit data and knowledge [8]. Most operations research models (ORM) use freshness cues, that is, the shelf life remaining after the expiration date stated on the label. However, the application of the shelf life model in ORM for quality loss assessment does not consider the characteristics of quality loss of each individual fruit. This may result in an assessment of quality loss and its cost that is inconsistent with reality in fresh fruit distribution management.

This research paper develops a specific quality attribute model to assess the cost of fresh fruit degradation that takes into consideration the loss of quality due to MI and ND through a multi-objective optimization framework. On this basis, a multi-objective optimization model that integrates the transportation and inventory planning of fresh fruit (MOTIP) to schedule its export is developed. This multi-objective optimization model relies on a multi-criteria optimization approach that maximizes the exporter's total net profit (NP) and the remaining quality (% RQ) of fruit on the market. We apply NSGA-II algorithm to solve the multi-objective problem. Solution spaces are analyzed through numerical study with restrictions in terms of variability of raw material prices, selling prices, supply and demand.

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To evaluate the accuracy of the algorithm, we compare the NSGA-II results with those obtained from an adjusted weight-sum approach based on a genetic algorithm. Finally, based on the relationship between %RQ, NP, and decision variables, the model can be used as a decision support tool for scheduling the transport and storage of fresh fruit to optimize net profit and remaining quality.

The paper provides an extensive review of the shelf life model, and thus a relevant contribution to the development of a quality degradation model, presented in Section 2. In Section 3, we propose a new framework for modelling quality loss in mangosteen distribution planning. In Section 4, we implement the new framework modelling quality in fresh fruit distribution. We discuss the numerical results regarding fresh fruit distribution and show how our modelling approach can be applied. Finally, Section 5 sets out the conclusions.

2. Related work

2.1. Shelf Life model

A wide diversity of shelf-life mathematical models has been applied in the operations research model for dealing with perishable food, especially in the inventory literature, because of the prevalence of the OR model in the food industry. The majority of the shelf-life model applications focus on measuring the quality level, based on the monitored supply chain conditions across time. They are designed to be utilized for first-, second- and third-order supply chain logistics, as shown in Figure 1. First-order logistics utilize the raw data for consistency issues, to establish whether the conditions remained within their endorsed ranges throughout the supply chain. Second-order logistics include processing the observed data into more valuable data, for example remaining shelf life and product quality. Finally, third-order logistics use data derived from second-order logistics for smart supply chain decisions [9].

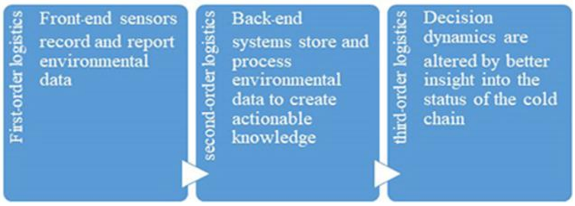


Fig.1. First-, second- and third-order logistics in a monitored cold chain.

In the creation of shelf-life models in ORM, three approaches of increasing complexity are considered: Statistical Process Control (SPC), Generic Shelf-life Models and Specific Quality Attribute model.

The SPC lays the foundations of first-order logistics. The application of SPC in ORM is about monitoring process variables to make sure that the weather conditions remain within their prescribed ranges throughout the supply chain [10]. Most ORM use SPC as a basis for controlling the time of transportation and storage, warehouse location selection, and allocated inventory. For instance, Govindan et al. [11] developed a multi-objective function of a sustainable perishable food supply chain network which considers the time window violation penalty of food transportation as the SPC to minimize the logistic costs and environmental impacts of CO2 emissions. The study applied three cost/time unit penalties for food distribution: waiting penalty, lateness penalty, and violation penalty to control the quality of perishable food throughout the supply chain. Sahraeian and Esmaeili [12] proposed a mixed-integer non-linear approach to address the tri-objective function of a two-echelon capacitated vehicle routing problem to minimize the total travel cost, customer waiting times, and carbon dioxide emissions in perishable product distribution. A maximum allowable delivery time is taken into account as the SPC for the optimization of the supply chain network. They reported that decreasing customer waiting times leads to increases in customer satisfaction since the products are perishable and shorter delivery times cause more freshness and so more satisfaction.

The Generic Shelf Life Models focus on second-order logistics, which include processing the observed data into more valuable information such as product quality and remaining shelf life. In the logistic chain, the shelf life of a product is demonstrated as a function of the environmental conditions, considering the overall acceptance by consumers and focusing on the product's appropriateness for marketing [9]. The model predicts the quality of the logistic handling chain by evaluating the effect of the logistic conditions on product quality in terms of the days of remaining shelf life. The shelf-life or freshness cues based on the period remaining before printed expiry dates are often used to estimate the remaining quality of fruit after the production date for the generic shelf life models, as shown in Figure 2 [13]. The freshness cues generally refer to the remaining marketable period of a product from any due date (d), which may be the day the fruit is sold to the consumer after production date, to the expiry dates. The expiry dates are otherwise called Best Before Dates (BBD), which are characterized as the shelf life (sl) or the end of the period in which fresh fruit is still of overall acceptable quality to consumers (e.g., color, texture, and taste), under any stated storage conditions [14].

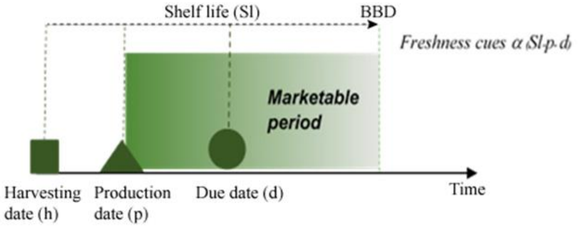


Fig.2. Diagram of the freshness cues related to production date, due date, and BBD [14].

Most research papers use the freshness cue base to decide on the remaining shelf life or marketable period. Rabbani et al. [15] proposed the perishability level as a freshness cue to obtain optimal delivery routes for vehicle routing problems (VRP), considering multi-middle depots for perishable food delivery. The proportion of remaining shelf life estimates the perishability level after the product had been transported. Wang and Li [16] proposed the freshness of perishable product quality based on the exponential function of remaining shelf-life as the cues to estimate the quality level of a perishable product. These cues are incorporated into a multi-objective VRP optimization model to minimize the distribution costs and maximize the freshness of perishable products. Some research papers incorporate a customer satisfaction function into freshness cues. An example of research is given by the work of Song and Ko [17]. The function represents the decreasing customer satisfaction according to the elapsed time from a depot to certain customer nodes when that customer orders food.

The specific quality attribute model concerns the third-order logistics, which utilize this derived quality of product and remaining shelf-life information for smart supply chain decisions. The model describes the advancement of a particular quality attribute for a particular product as a function of the supply chain handling conditions. It provides enough information, which can be implemented into smart supply chain and logistics management systems or a model-based approach to improve logistics efficiency. For example, Aiello et al. [18] presented specific quality attribute models to be applied to production and distribution planning. Their model can be used to plan and operate food distribution systems, utilizing both food quality and cost rules.

The generic shelf-life models are not expected to show the product's physiology, only the ideal opportunity for which a perishable product will remain quality adequate to a shopper. The specific quality attribute models do however claim to describe the processes going on inside the perishable product, that lead to the noticed change in quality.

2.2. Discussion and statement

Specific quality attribute models can give more detail to evaluate the cost of quality loss corresponding to the form of fruit quality deterioration and consumer behavior than SPC and generic shelf-life models. However, the application of specific quality attribute models to the operation planning of the FDM is still quite limited because it lacks enough information in quality loss assessment. As noted above, the operation planning models dealing with perishable products very often fail to incorporate shelf life and stochastic highlights in the various functional areas of the food distribution network [19].

First, most ORMs focus on developing the operating model for short-distance transportation, where mechanical injury (MI) can be neglected. In case of long-distance transport such as for fruit exportation, MI evaluation can help exporters to better analyze logistics costs and to choose the optimal transportation route.

Second, most operation research models use SPC and generic shelf-life models based on data history and freshness cues to estimate the quality loss in fruit. These approaches are indirect methods to assess fruit quality loss and cannot be used to evaluate properly the real quantity of fruit that is lost during distribution. They fail to calculate the cost of quality loss, especially for fruits that have an exponential decay type of quality loss. Utilizing a specific quality attribute model can provide more detail on the quantity of fruit loss and its cost. It can also be applied to set the markdown price to stimulate consumer demand.

Finally, customers give the fruit a lower valuation when fruit starts to decay. All major retailers and wholesalers normally employ single-price markdown policies to attract customers to buy products moving toward their expiration date [16]. As a result, two different selling prices are set in the selling period, as described in equation 1. Tm is the price markdown time after which a price discount θ (0<θ<1) is set for a given product. As a price markdown is constantly applied before a product arrives at its expiration date, the selling timeframe can be isolated into two intervals: (0, Tm) and (Tm, Sl).

$$p(t) = \begin{cases} p & 0 \le t \le T_m; \\ p*(1-\theta) & Tm \le t \le Sl; \end{cases} \tag{1}$$

Regarding the application of the shelf-life model, Tm associated with a kinetics parameter of product stability or lag time before the date of fruit quality deterioration (DFD), as shown in Figure 3. After a lag time, ageing fresh fruit may require price markdowns or removal of the spoiled products until the end of the shelf life (Sl) or marketable period. Most operation research is applied to the shelf-life model without considering product stability. Overlooking the time lag may lead to an underestimation of shelf life, with significant economic losses for fruit exportation, as well as a lack of sufficient information for reducing fruit prices, which is necessary to stimulate consumer demand.

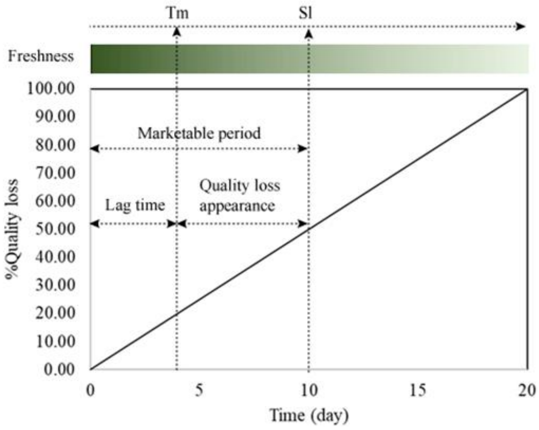


Fig.3. The marketable period, lag time, and quality loss appearance in fresh fruit caused by ND with zero-order kinetics

As mentioned above, using specific quality attribute models can provide more details for evaluating the cost of quality loss corresponding to the form of fruit quality deterioration and consumer behavior than generic shelf-life models.

2.3. Specific quality attribute modelling

Quality assessment in fresh fruit distribution is a complex task because of the range and dynamics of fresh fruit characteristics, as well as environmental conditions. Some models have been developed for quality loss assessment in fruit, which are specific to each fruit. In the following, we briefly review the specific quality attribute model of two main quality loss assessments in fresh fruit: MI and ND, as this plays an important role in quality loss assessment in fruit distribution.

2.3.1. Modelling MI

MI induced by vibration is a known cause of quality deterioration and wastage of fresh fruit in fruit distribution. It occurs due to the energy transferred and absorbed by fresh fruit. The energy is produced by the input vibration excitation of the truck floor as a result of the Road-Vehicle-Load (RVL) interaction during road transportation [20]. It can be determined from the root mean square acceleration (RMS G2) measured in specific gravity units (g) in any instance within a given bandwidth (BW) of frequencies 0.1-100 Hz, as this frequency band represents the most damage-causing component for packaged fruit [21]. This is shown in equation 2. PD is a power density of a given vibration signal within a band wide of frequencies (BW), and N is the number of samples in a given vibration signal.

$$PD = \frac{1}{BW} \sum \frac{RMS\ G^2}{N} \tag{1}$$

The relationship between the vibration level encountered at RMS G^2> the least levels of vibration intensities causing mechanical damage to produce (LRMS), and the percentage of mechanical injury (%MI), is a linear function (Figure 4). Therefore, we can estimate the MI function with the vibration level in a given transit route (RMSG^2j: j= 1,..m.), according to equation 3, where β is the relative change of MI, and ϕ is the intercept value of the %MI axis. Using these equations, we can calculate the expected quality loss of fresh produce due to transport in each transportation route.

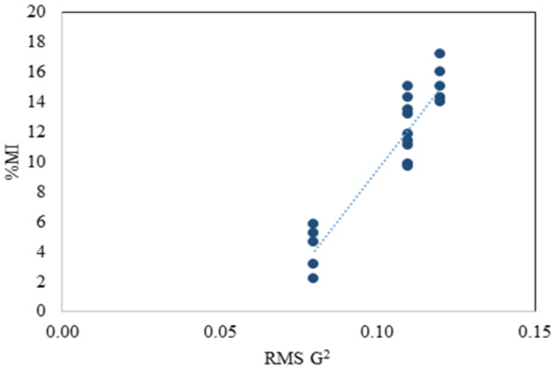


Fig.4. The quality loss level of products due to MI for the top tier cartons in the trailer positions with different RMS vibration. (Fernando, Fei, and Stanley 2019).

$$\%MI = \begin{cases} 0 \ : RMS\ G_j^{\,2} < LRMS \\ \sum_{i=1}^{m} \beta * RMS\ G_j^{\,2} - \phi : RMS\ G^2 \geq LRMS \end{cases} \tag{2}$$

2.3.2 Modelling ND

Kinetic shelf-life models have been widely used to generically describe sophisticated quality attributes in perishable food, and play an important role in ND assessment for fresh fruit distribution. The kinetic of quality loss can be described by equation 4, where q is the quality of a product, k is the rate of quality loss due to ND, depending on environmental conditions like temperature, and n is a power factor called the order of the reaction, determining whether the reaction rate is dependent on the amount of quality q left [7].

$$\frac{dq}{dt} = kq^n \tag{3}$$

Concerning the power factor n, we can identify two types of ND related to different physiological change characteristics in each fruit: zero-order kinetics (n = 0) and exponential decay (n = 1), as shown in Figure 5. The ND with zero-order kinetics is mostly associated with freshness loss (weight loss) and enzymatic degradation, while the ND with exponential decay (n = 1) generally concerns microbial growth and vitamin losses [22].

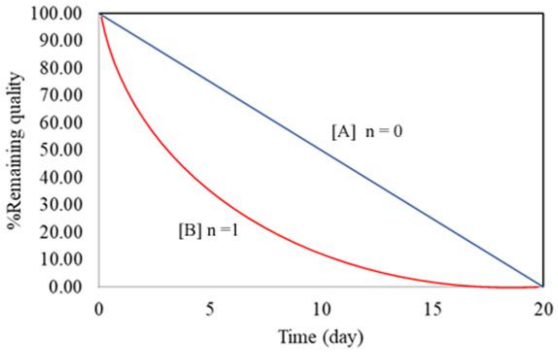


Fig.5. The percentage of remaining quality of food products caused by ND at various times: linear function [A] and non- linear function [B].

The degree of ND is a function of the holding period in each activity in the fresh fruit supply chain. So, we can estimate the quality of fresh fruit at a certain location in the production and distribution network, based on initial quality (q0), subsequent total holding period (t_i) i = 1,., m, and degradation rate (ki) (depending on the temperature Ti), according to equation 5 for zero-order kinetic and equation 6 for exponential decay, respectively.

$$q = q_0 - \sum_{i=1}^{m} k_i t_i \tag{4}$$

$$q = q_0 * \exp\left[-\sum_{i=1}^{m} k_i t_i \right] \tag{5}$$

To conclude, considering the application of the shelf-life model in ORM for fresh fruit exportation, three issues regarding quality loss assessment are involved, which have not received much attention in the existing literature: (1) MI due to long-distance transportation of fruit exportation should be considered; (2) the ability of the shelf-life model to evaluate quality loss covering all types of Natural Decay needs to be examined; and (3) the relation between the quality level and consumer acceptance level should be identified.

To fill the gap in the literature, we have proposed a new framework for modelling fresh fruit shelf life, which integrates the specific quality attribute model of MI and ND with zero-order kinetics assessment in MOTIP. An assessment of MI helps to reflect the estimated MI level and its cost from long-distance transportation in fruit exports, as indicated by the dot (-•-) in Figure 6.

It is also helpful in choosing the optimal transportation route, including the development of a packaging system for transportation to reduce quality losses. At the same time, the assessment of ND related to lag time for the DFD and kinetics of quality loss can help fruit exporters to estimate the actual cost, which is consistent with the ND mechanism of fruit and the buying behavior of fruit consumers with significant economic losses through fruit exportation, as indicated by the dashes (-.-) in Figure 6. It also provides more information to set the price markdown time, and improve logistics efficiency by comparison with the generic shelf life based on the freshness cues.

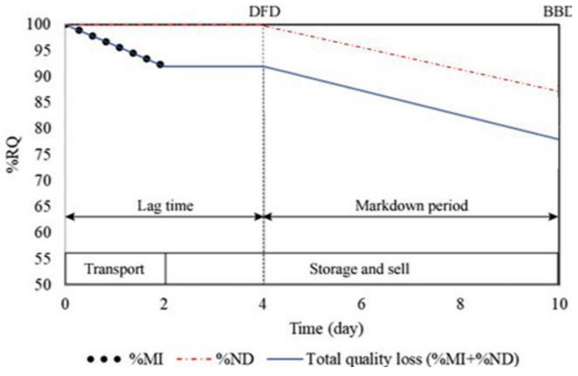


Fig.6. Behavior of quality loss in fresh fruit distribution based on MI and ND in the form of zero-order kinetics

3. Modelling quality loss and fruit distribution planning

Our modelling approach is based on real case study of mangosteen exportation, as shown in Figure 7. This case is used as it includes all the main element of production, transportation and storage. Exporters collect fresh fruit from one or more farmers and distribute it to their packinghouse where the fruit is graded, cleaned, packed and loaded into containers. It is then immediately transported from the packinghouse to distribution centers with a cold-chain system, either by truck (short route) or by cargo ship (long route).

The exporter needs to determine the optimal volume of fruit exported daily (i), and to choose the appropriate transit route and storage plan to maximize total profits from the sale to retailers at distribution centers every day. The process of exporting fruit must be done within the constraints of various factors, including quality loss during transportation and storage, and variability in raw material prices, selling prices, total fruit supply and consumer demand each day.

To facilitate this narrative, we adopt assumptions, indices, parameters and decision variables that are applicable to the multi-objective model, as shown in the following:

Assumptions

(1) The exporter has a policy for the maximum holding time (transit time and storing time) based on the shelf life of the mangosteen fruit (10 days) to guarantee a final product with sufficient residual life.

(2) Shortage or back ordering is allowed.

(3) A first-in-first-out (FIFO) issuing policy is used

Indices

i	any day on a horizontal time line
j	route number of transportation
k	number of days of fruit storage

Parameters

CO	communications and other costs of fruit exportation per unit
DM_i	total consumer demand on day i
L_j	lead time for each route j
MH	cost of material handling per unit
ms_j	maximum number of storage days of fruit for route j
PM_i	price of fruit material per unit on day i
SC_k	storage cost of a reefer container per unit per day at the optimal temperature
SP_i	selling price of fruit per unit on day i
TC_j	transportation cost per unit for route j
TS_i	total fruit supply on day i
ctn	container (40-foot Container, Full truck load 40 Tons)
DFD	date of fruit quality deterioration
Sl	shelf life of fruit
ms_j	maximum number of days the fruit can be stored for each route j (ms_j=Sl-L_j)

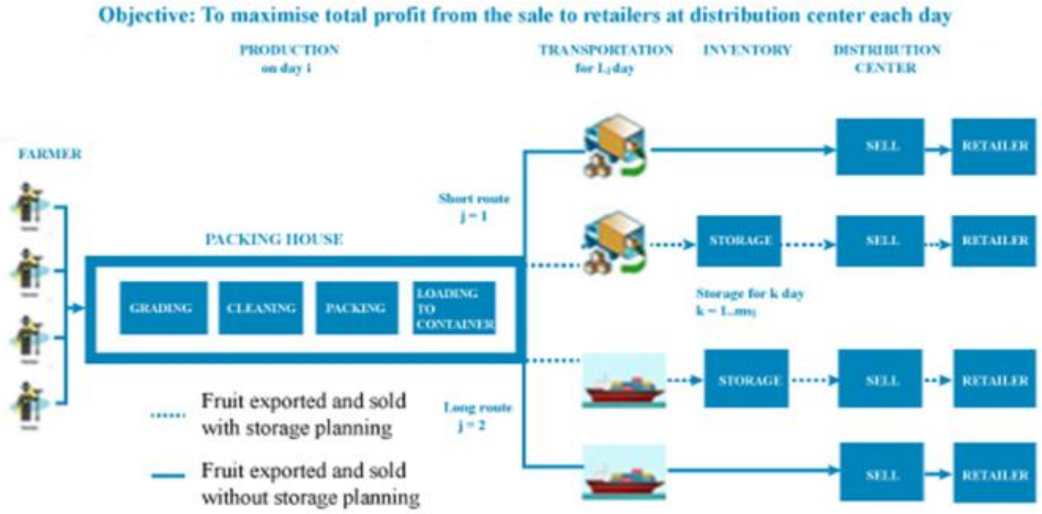


Fig.7. Behavior of the fruit exportation model in a seasonal fruit

Decision variables

bi	total communication and other costs of fruit on day i
ci	total material cost of exported fruit on day i
di	total transportation cost of exported fruit on day i
gi	total cost of MI due to handling and transportation

hi	total storage cost of fruit on day i
mi	total material handling cost of exported fruit on day i
$q0_i$	cost of ND with zero-order kinetics
r_i	revenue derived from the sale of exported fruit on day i
s_{ij}	quantity of fruit sold immediately from route j at the arrival time on day i
%RQ	percentage of remaining quality for exported fruit at the distribution center
w_{ij}	quantity of fruit in inventory transported from route j and sold on day i at the distribution center
x_{ij}	quantity of fruit exported without storage planning from route j on day i
y_{ij}^{k}	quantity of fruit exported from route j on day i, with storage planning for k day

3.1 Planning horizon time

We consider two sets of decision variables to determine the amount of fruit exported and sold each day: without storage planning (x_{ij} and s_{ij}) and with storage planning (y_{ij}^{k}, and w_{ij}), as shown in Figure 7.

For the first set, we set x_{ij}, the quantity of fruit exported from the packaging house on day i, transported by route j without a storage plan; and s_{ij}, the quantity of fruit transported by route j and sold immediately at the DC on day i. We consider that x_{ij} is an integer with $x_{ij} >= 0$ except in the last period before the end of the season for fruit exports (EOS), due to an inability to deliver fruit for EOS-Lj day.

In case of s_{ij}, all fruit with xij transported on day i will arrive in DC on day i+Lj and be sold immediately at DC in an amount of s_{ij}. However, fruit cannot be sold if i < Lj because the fruit is being transported. So, we can formulate s_{ij}, according to

$$s_{ij} = \begin{cases} 0 & : i \le L_j \\ x_{(i-L_j),j} & : i > L_j \end{cases} \tag{6}$$

For the second set, we consider y_{ij}^{k}, the quantity of fruit exported from the packaging house each day, with route j, with a storage planning for k days; and wij is the quantity of fruit in inventory that was transported by route j and sold on day i.

In the case of y_{ij}^{k}, all fruit transported on day i, which arrives in inventory on day i+ Lj, is stored in the cooling room for k days and sold on day i+ Lj +k. We consider that y_{ij}^{k} is an integer with $y_{ij}^{k} >= 0$ except on the last period before the end of the season for fruit exports (EOS) due to an inability to deliver fruit in advance for Lj day of the end of EOS.

In the case of w_{ij}, the total fruit from yijk in inventory is sold every day. If i =< Lj +1, no fruit can be sold because there is no fruit in inventory due to it being in transport, so $w_{ij} = 0$. If Lj +1< i =< Sl, (Sl= Lj +msj), some fruit exported with a storage plan from k=1 day to k = ms_j -1 day arrived in inventory, and the total fruit in the inventory sold each day (w_{ij}) can be estimated, according to

$$w_{ij} = \sum_{k=1}^{i-(L_j+1)} y_{i-(L_j+k),j}^{k} \tag{7}$$

.

Finally, if i > Sl, all fruit with a storage plan from k=1 to k=msj is sold. So w_{ij} can be estimated according to:

$$w_{ij} = \begin{cases} 0 & : i \le L_j + 1 \\ \sum_{k=1}^{i-(L_j+1)} y_{i-(L_j+k),j}^{k} & : L_j + 1 < i \le Sl \\ \sum_{k=1}^{ms_j} y_{(i-L_j-k),j}^{k} & : i > Sl \end{cases} \tag{8}$$

3.2 Estimation of MI parameter

We use the relation of vibration level and the %MI of mangosteen exportation, which are obtained from the simulation results of vibration testing with various average vibration levels (RMS G_i), by the vibrator in the laboratory as shown in Figure 8 [23]. The %MI of mangosteen expresses a linear relationship with the RMS (Gj>0.94 (A-B)). Using simple linear regression, we obtain MI% function according to (R-squared value (R^2) =.0.9755)

$$\%MI_j = 13.698 RMS\ G_j - 12.82 \tag{9}$$

To estimate the %MI of mangosteen per unit for each route of transportation (%MI_j) from equation 9, we use the vibration data for each transportation route (Gj) obtained from three piezoelectric triaxial accelerometers installed on the refrigerator container of truck (j=1) and cargo ship (j=2). The vibration level and %MI in each route of transportation is shown in detail in Figure 8

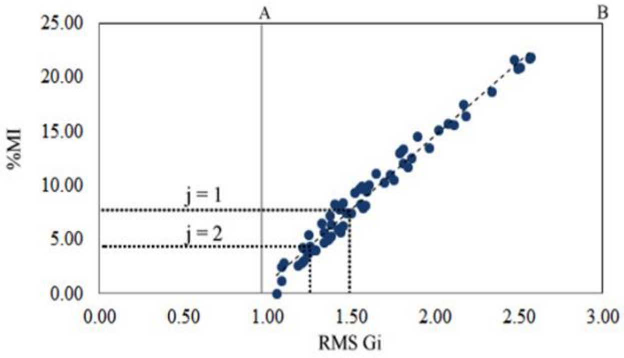


Fig.8. The relation of the average RMS Gi and %MI of mangosteen

We estimate the cost of MI per container (ctn) (δ_j) in each transportation route, according to δ_{ij} = (PM_i*%MI_j)/100, where PMi is the price of material each day. Lastly, we can determine the total cost of MI in fruits exported without storage and with storage planning each day:

$$g_i = \left(\sum_{j=1}^{m} x_{ij} + \sum_{j=1}^{m} \sum_{k=1}^{ms_j} y_{ij}^{k} \right) * \delta_{ij} \tag{10}$$

3.3 Estimation of ND parameter

We consider the characteristics of ND of mangosteens in terms of freshness loss measured in a ctn of % weight loss (%WL_{jk}) at various holding times, with the linear function of time as shown in Figure 9 [23] . Using the simple linear regression, we formulate the accumulative %WL_{jk} with holding time (R^2=0.9898), according to :

$$\%WL_{jk} = 3.2542(L_j + k) + 2.2571 \tag{11}$$

Where (Lj+k) is a total holding time calculated from the sum of transit time and storage time (t= Lj+k). The cumulative cost per ctn of $\%WL_{jk}$ for zero-order ($Ho_{ij}^{k}(Lj+k)$) can be estimated according to:

$$Ho_{ij}^{k}(L_j+k)=\frac{PM_i*\%WL_{jk}}{100} \tag{12}$$

Figure 10 plots the $Ho_{ij}^{k}(Lj+k)$ at various prices of material (PMi). The graphs are a straight line with the difference of slope ($\tilde{h}$) and the intercept (ϖ_i) depending on PMi each day. So, we estimate the $Ho_{ij}^{k}(Lj+k)$ function with holding time [24] according to:

$$Ho_{ij}^{k}(L_j+k)=\tilde{h}(L_j+k)+\varpi_i \tag{13}$$

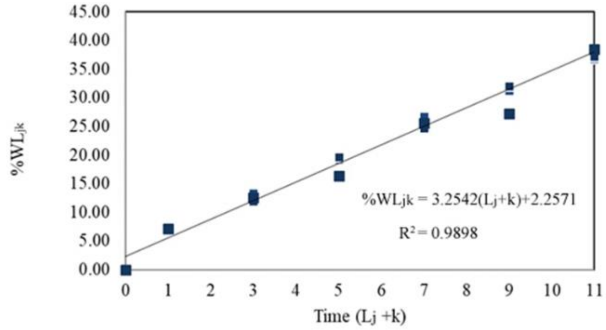


Fig.1.The cumulative $\%WL_{jk}$ of mangosteen stored at 13°C/75%RH at various holding times (day)

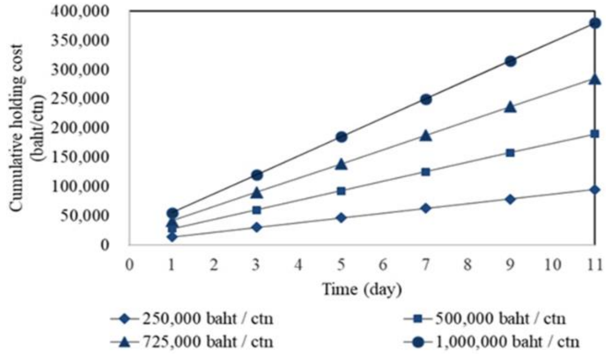


Fig.2.The convex approximation for cumulative holding cost of mangosteen stored at 13°C/75%RH at various storage times and different PMi.

We note that the customer begins to be sensitive to quality changes of fruit on DFD, while the accumulated cost of losing the quality of fruit that is consistent with price markdown policies to attract customers to purchase products approaching their expiration date will begin to be considered [16]. So, total cumulative cost of zero-order kinetics for fruit exported without storage planning and with storage planning can be estimated, according to equation 14 and equation 15 The total cumulative cost of zero-order kinetics (qo_i) can be estimated by $qo_i = qox_i + qoy_i$

$$qox_{i,}=\begin{cases}0 & : L_j \le DFD\\ \sum_{j=1}^{m} x_{ij}*\left(\eta_i*\mathrm{L}_{\mathrm{j}}+\gamma_{\mathrm{i}}\right): L_j > DFD\end{cases} \tag{14}$$

$$qoy_{i,}=\begin{cases}0 & : L_j+k \le DFD\\ \sum_{j=1}^{m}\sum_{k=1}^{ms_j} y_{ij}^{k}*\left(\eta_i*(\mathrm{L}_{\mathrm{j}}+\mathrm{k})+\gamma_{\mathrm{i}},\right): L_j+k > DFD\end{cases} \tag{15}$$

3.4 Model formulation

The integrated transportation and inventory planning of perishable goods with quality loss assessment based on zero-order kinetics may be formulated as a multi-objective mixed-integer model, as in equation 16 and equation 17. These objective functions aggregate the measurable economic importance throughout the considered fruit distribution. In the first objective, the net profit (NP) is maximized:

$$\max NP=\sum_{i=1}^{n=1} r_i - TC \tag{16}$$

It is composed of total revenue (ri), and total cost (TC), each expressed in equation 18 and equation 19. In the second objective, the percentage of mean remaining quality of fruit exportation (%RQ) considering the average percentage of MI each route and %WL throughout the fruit supply chain is maximized, according to:

$$\max \%RQ=100-\left[\sum_{j=1}^{m}\%MI_j+\sum_{j=1}^{m_i}\sum_{k=1}^{ms_j}\%WL_{jk}\right] \tag{17}$$

The ri generated from the sale of fruit exported without storage (s_{ij}) and with storage (w_{ij}) at DC. It depends on the sale price of fruit each day (SPi), according to:

$$r_i=\left[\sum_{j=1}^{m}s_{ij}+\sum_{j=1}^{m}wij\right]*SP_i \tag{18}$$

The TC consists of material cost (ci), common logistics cost (CLC) and the total cost of quality loss (TQL), according to:

$$TC=\sum_{i=1}^{n}c_i+CLC+TQL \tag{19}$$

The c_i is expenses incurred from purchasing fruit materials estimated by the sum of all the fruit exported from the packaging house, multiplied by the price of fruit material (PMi), according to:

$$c_i=\left[\sum_{j=1}^{m}x_{ij}+\sum_{j=1}^{m}y_{ij}^{k}\right]*PM_i \tag{20}$$

We estimate the CLC based on activity-based costing (ABC) systems [25], according to:

$$CLC=\sum_{i=1}^{n}\left(m_i+d_i+h_i+b_i\right) \tag{21}$$

The costs cover expenses incurred from material handling, transportation, storage, and logistics communication, respectively, according to equation 22 to 25

$$m_i = \left[\sum_{j=1}^{m} x_{ij} + \sum_{j=1}^{m} y_{ij}^{k}\right] * MH \tag{22}$$

$$d_i = \left[\sum_{j=1}^{m} s_{ij} * \sum_{j=1}^{m} w_{ij}\right] * TC_j \tag{23}$$

$$h_i = \sum_{j=1}^{m}\sum_{k=1}^{o} y_{ij}^{k} * SC_k \tag{24}$$

$$b_i = \left[\sum_{i=1}^{n} x_{ij} + \sum_{i=1}^{n} y_{ij}^{k}\right] * CO \tag{25}$$

The total cost of quality loss based on MI (gi) and ND in the form of zero-order (qoi) is estimated, according to:

$$TQL = \sum_{i=1}^{n} g_i + \sum_{i=1}^{n} q_{oi} \tag{26}$$

Regarding the constraints that bound this model, the total quantity of export fruit each day cannot be greater than the fruit supply each day in equation 27, while total quantity of export fruit that was sold each day cannot be greater than consumer demands each day in equation 28:

$$TS_i \geq \sum_{j=1}^{m} x_{ij} + \sum_{j=1}^{m}\sum_{k=1}^{o} y_{ij}^{k} \tag{27}$$

$$DM_i = \sum_{j=1}^{m} s_{ij} + \sum_{j=1}^{m} w_{ij} \tag{28}$$

4. Case study of mangosteen distribution Conclusion

We apply the MOTIP models in an illustrative case study. We consider historical data patterns of the quantity of fruit supply and demand, material price, and selling price of fruit exportation from Thailand to Chinese fruit markets, as a case study, according to Figure 11 (ITCC, 2019). Based on historical data, we set the total quantity of fruit supply at 800 ctn and total fruit demand at 200 ctn. We choose the normal pattern of supply rate and demand rate. The demand rate consists of the high demand rate at two periods of seasonal time (A and B). During the first period, the demand rate is high because the total quantity of fruit and the other seasonal fruits of China released on the market at that time is low, which causes the price of raw materials and the market price to be high as well. During the second period, fruit consumption increases again due to the effect of a Chinese festival, which stimulates higher PMi.

The model was implemented in Matlab R2017a. We applied a fast and elitist multi-objective genetic algorithm (NSGA-II) to solve multi-objective problems, based on the research of Deb et al. (2002), and an adjusted weight-sum approach with a genetics algorithm (AWS-GA), based on the research of Liu and Reynolds (2014) for optimizing multi-objective problems. In our experiment, we evaluate the performance of the algorithm by comparing the NSGA-II results and ASW-GA results. We illustrate the effect of application of the specific shelf-life model on overall fruit exportation planning, as shown in detail in the following.

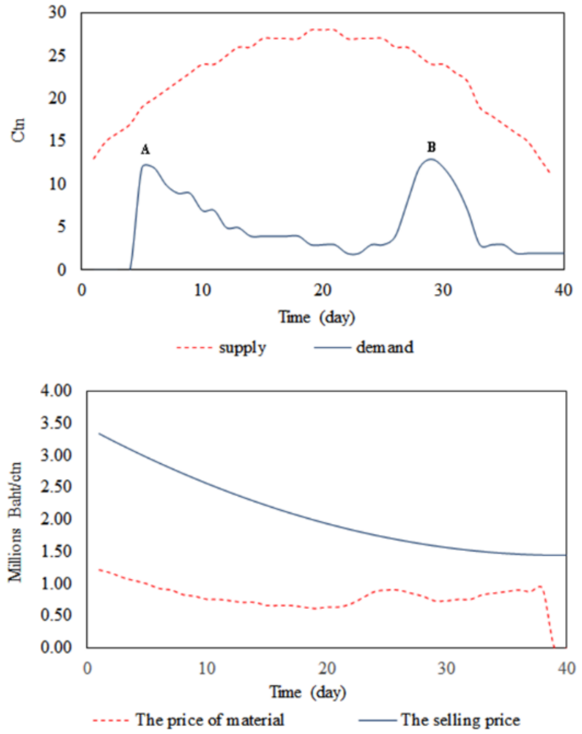
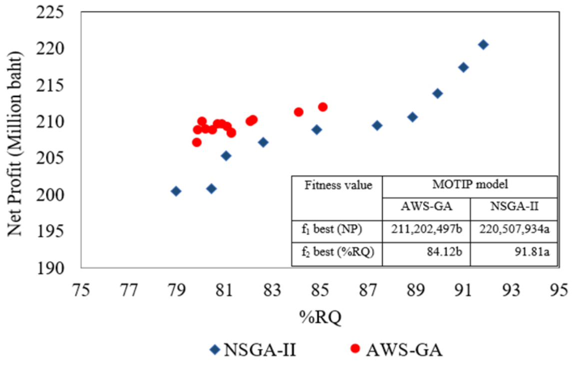


Fig.11. Fruit supply, demand, PMi and Spi

4.1 Evaluating the performance of the algorithm

We considered the Pareto front of the MOTIP model solved by the multi-objective problem using AWS-GA and NSGA-II to evaluate the performance of the algorithm, as represented in Figure 12.



Fitness value	MOTIP model	
	AWS-GA	NSGA-II
f_1 best (NP)	211,202,497b	220,507,934a
f_2 best (%RQ)	84.12b	91.81a

Fig.12. The Pareto front of the MOTIP model solving the multi-objective problem by using AWS-GA and NSGA-II. *All fitness values are compared by the paired sample t-test, and a, b different letters within a row indicate significantly different (P < 0.05)

We found that both the optimal front curves of AWS-GA and NSGA-II tend to have similar behaviors, in that they have more NP and more %RQ. However, it is rather clear from the comparison of the Pareto fronts that NSGA-II is much more dominant than AWS-GA. NSGA-II is significantly more capable to find a better fitness value and can capture the non-convexities better than AWS-GA (P<0.05).

4.2 The effect of quality loss on overall fruit exportation planning

We consider the relative importance between the holding time, natural profit (NP) and %RQ, as shown in Figure 13. It is interesting to note that the quality loss of fruit is a function of total holding time. We discern that there is the same solution space on the appropriate transit time (TT) and storage time (ST). The decrease in transportation and storage time markedly affects the increase of %RQ and NP in FDM. To gain maximization of NP and %RQ, the average transportation time (Lj) should be 2 days, while the average storage time of fruit (k) should be 1.60 days.

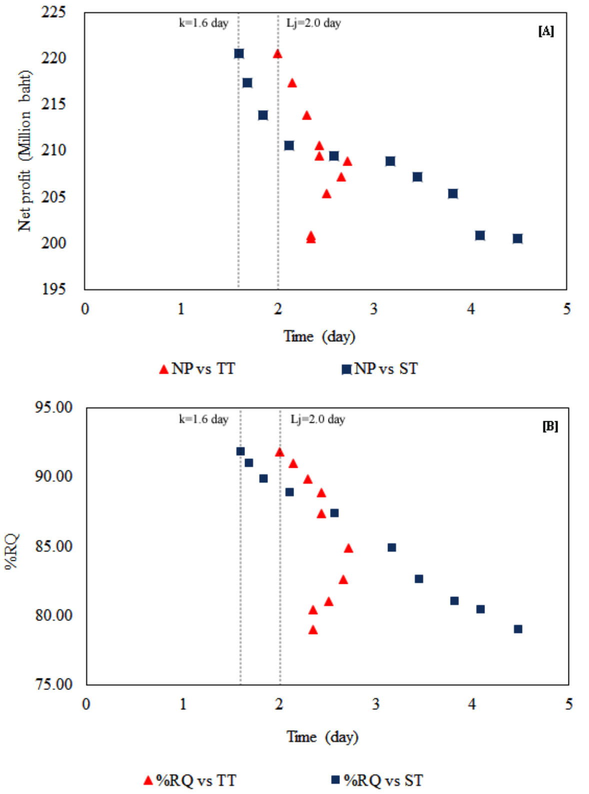


Fig.13 Relative importance regarding net profit, transportation time and storage time [A]; and Relative importance regarding %RQ, transportation time and storage time [B]

The result supports the fact that the decreased ST corresponds to the increased NP and %RQ with r(NP-ST) = -0.9502 and r(%RQ-ST) = -0.9965, while, the decreased TT has less correspondence to the increased NP and %RQ which can be confirmed by r(NP-TT) = -0.5543 and r(%RQ-TT) = -0.5377. All results indicate that reducing fruit holding time by choosing the short route and taking the least time to storage fruits are the best way to maximize NP and %RQ in FDM

Figure 14 presents the effects of the four fruit distribution schemes: fruit exported without a storage plan via the short route (x1), and long route (x2), and fruit exported with a storage plan via the short route (y1), and long route (y2), on NP and %RQ. We found that choosing x1 together with y1 has the most influence on changing both NP and %RQ on FDM, while the effects of choosing x2 and y2 are not as apparent on NP and %RQ maximization. The scatterplots represent a spectrum of different correlation coefficient values for the relationship between two continuous variables. There is a fairly strong positive relationship between x1 and the strong negative relationship of y1 with NP and %RQ. They present the correlation values at r(NP-x1) = 0.9905, and r(NP-y1) = -0.9713. At the same time, we cannot find a relationship between x2 and y2 with NP and %RQ.

We consider the appropriate distribution scheme at maximum NP and %RQ. The distribution scheme requires the maximum x1 at 180 ctn and 173 ctn, and y1 at 20 ctn and 27 ctn. No selection was found for the use of the long route without storage (x2) and with storage planning (y2) for exportation. This finding demonstrates how choosing a short route to transport fruit can help to increase the NP and %RQ in FDM.).

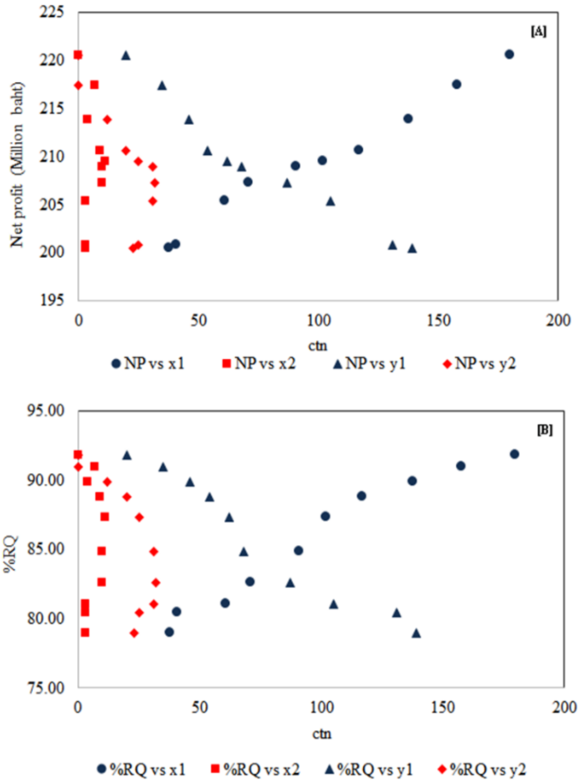


Fig.14. Relative importance regarding net profit and the average distribution scheme [A]; and Relative importance regarding %RQ and the average distribution scheme[B].

Finally, we found that the algorithm tries to control the total holding time of fruits(THT) not to exceed the lag time for date of fruit quality deterioration (DFD) by using the short route (Lj =2 days) and a short time to storage fruit (k<2 days), to avoid the cost of ND from holding the fruit for a long time and the markdown policy to stimulate consumer purchases, as shown in Figure 15.

Understanding the relationship between the characteristics of the continued decline in fruit quality and consumer evaluation of fruit quality can be applied to set up the inventory management policy in terms of just in time (JIT) and first-in, first-out (FIFO) policy.

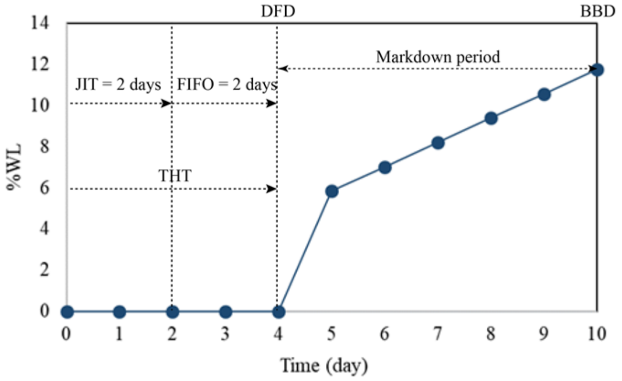


Fig.15. The amount of cumulative quality loss in fruit with zero-order kinetics.

5. Conclusion

In this paper, we have discussed the importance of the shelf-life model for application in operations research models dealing with fresh fruit products. We have developed the specific quality attribute model considering MI and ND to assess a loss of quality contributing to the cumulative holding costs of each fruit distribution period. The cost from MI is estimated by the relationship between the level of vibration and the degree of MI from the fruit transport, while the cost of ND is estimated by the kinetic shelf life model – with zero-order reaction – considering the lag time for the apparent quality loss.

We explored a MOTIP model developed to optimize fresh fruit distribution. The main objective was to maximize the NP and %RQ of the fresh fruit distribution. The NSGA-II was applied for these cases to solve the problem. Solution spaces of MOTIP models were analyzed through numerical study with restrictions in terms of variability of raw material prices, selling prices, and supply and demand in the fruit distribution.

The results indicate the usability of the MOTIP model and the efficiency of the NSGA-II algorithm in solving the problem for FDM. The optimal Pareto front curves of the MOTIP model show a strong relationship between %RQ and NP, which can be applied to decide on the optimal schedule for transporting and storing exported fruit, and to consider the cost-effectiveness of the new packaging system design to reduce quality loss in the fresh produce supply chain. The results confirm the value of using a specific shelf-life model based on consumer behavior and markdown policy. The MOTIP model can give a particular solution which is related to the attribute of natural quality loss of fruit and its actual cost in each type of fruit. The developed multi-objective model allows for a comprehensive and realistic understanding of these intertwined planning problems. It also provides an important improvement in the profit and cost of fruit exportation concerning fruit quality. This improvement is more significant for logistics exporters who make decisions concerning export planning and choosing the appropriate distribution scheme and inventory policy under uncertainty of the demand and supply rate. In this paper, we considered a quality loss in the form of zero-order kinetics in a single fruit distribution network. Further research could therefore also include the consideration of quality loss of fruit in the form of exponential decay in fruit distribution planning. Multiple types of products and interactions between the different products might then also have to be taken into account

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