Nonlinear quality decay functions in optimization problems in the food industry

Master Thesis

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Abstract

The quality of food is constantly changing along the supply chain, and quality decay is inevitable. The dynamics of quality decay play a crucial role in optimization problems of food supply chains. In this thesis, the decay of fruit quality is investigated using navel oranges as an example. This study aims to formulate a quality decay function for navel oranges through the regression method using the solver of Microsoft Excel, then apply the function to an optimization problem and finally analyze the sensitivity of the optimization model regarding different decay rates. The literature review demonstrates that the exponential quality decay function is suitable for describing the deterioration of navel oranges. The exponential decay function formulated by the exponential regression method using Excel Solver can be applied to the optimization model. This study also includes a sensitivity analysis of the optimization model concerning the decay rates obtained from different quality decay functions. The exponential quality decay function formulated in this study can be widely applied in the citrus supply chain.

Keywords: Fruit supply chain, quality decay function, exponential regression, optimization model

Chapter 1

Introduction

Food companies are experiencing rapidly changing markets, advancements in new technologies and fast-growing global competition nowadays (Luning and Marcelis, 2009). In the meantime, as consumer awareness of food safety, quality and freshness continues to increase, the food supply chain is under pressure to meet these demands (Zhong et al., 2017). Thus, the food industry needs integrated management of the supply chain to tackle these challenges. One of the most fundamental food attributes to be considered throughout the supply chain is food quality (Rong et al., 2011). The quality of food is constantly changing along the supply chain, and quality decay is inevitable (He et al., 2018). Just as fruits deteriorate rapidly after harvest, which results in poor food quality and ultimately to food waste. In 2012, the World Food and Agriculture Organization estimated that around 45% of total fruit and vegetable production is wasted, which could result in serious social and economic consequences (Ciccullo et al., 2021). The social consequences can involve food shortages, mass migration, and even political instability (Stancu et al., 2016). The limited shelf life of fruit places high demands on the management of time and temperature during the storage phase of the food supply chain. Compared with storage temperature and other factors, storage time is the most significant characteristic affecting fruit quality (Owoyemi et al., 2022). It is therefore of interest to understand and explore the relationship between food deterioration and storage time.

Due to the perishable nature of the fruit, fruit quality can be seen as a dynamic state of constant decline until it is unfit for sale or consumption (Wang and Li, 2012). The dynamics of quality decay play an important role in optimization problems in the food supply chain (Rong et al., 2011). These optimization problems require the data of quality decay as input parameters. Unfortunately, these data are uncertain. In this study, navel oranges are used as an example to investigate the deterioration of fruit quality. The navel orange is a kind of citrus fruit, which is loved by consumers worldwide for its sweet, juicy taste and rich nutrition. However, navel oranges are susceptible to pathogens during post-harvest storage, which can lead to quality decay (Tang et al., 2018). It is therefore important to figure out how fruit deterioration varies with storage time, which has significant implications for the food supply and our health, as well as providing insight into effective fruit quality control strategies.

Gao et al. (2019) assessed the quality of navel oranges under three different storage methods. Specifically, the researchers presented the data on the decay rate of navel oranges at different storage time. Studies by Wu et al. (2018) and Shrivastava et al. (2022) on how to slow down fruit deterioration refer to quality decay functions, which can characterize the change in decay rate with time. This study uses the data set from Gao et al. (2019) to formulate the quality decay function of navel oranges, as the function and the appropriate parameter of it remain unknown. Regression method is a desirable way to estimate the parameter of the quality decay function (Van Boekel, 2008). The parameter can be employed to have a concrete function to fit the observed data of navel oranges. In order to take advantages within optimization problems, it is worth exploring what does the decay function of navel oranges look like and how it can be applied in the food supply chain.

Consequently, the aim of this study is to formulate the quality decay function of navel oranges by means of regression method in Microsoft Excel, then apply the function into an optimization problem in the food industry and finally investigate the sensitivity of the optimization model regarding different decay rates. Based on the research aim, three research questions are formulated:

1. What kind of quality decay functions are described in the literature and which one is suitable to describe the deterioration of navel oranges?

2. How can optimal parameters for these quality decay functions be computed based on the data from the literature and which regression method is suitable for this study?

3. How can we use the quality decay function in optimization problems that typically arise in practice?

The first research question can be answered by conducting a systematic literature review related to quality decay functions in the food industry and the deterioration of navel oranges. These quality decay functions are summarized and compared to find the suitable functions to describe the quality decay of navel oranges. Afterwards, the quality decay function is formulated using the regression method in Microsoft Excel with data from Gao et al. (2019), to tackle the second research question. This information is then incorporated into an example of optimization problems. For the last research question, the resulting model is solved and the sensitivity of the model to different decay rates is checked using the optimization solver FICO Xpress.

The structure of this thesis is as follow: Chapter 2 presents the systematic literature review on the keywords of this research. Chapter 3 details the methodology of this study, including the formulation of quality decay functions using the regression method, the interpretation of the optimization model and so on. The results of solving the model and sensitivity analysis are provided in Chapter 4. Chapter 5 discusses the outputs of the research question. The conclusions and limitations of this research are summarized in Chapter 6.

Chapter 2

Literature review

The following sections highlight a review of the literature on quality decay, fruit supply chain, quality decay functions and the deterioration of navel oranges, which can be used to address the first research question. This chapter also summarizes some literature related to the application of quality decay functions to optimization problems. Scientific databases such as Google Scholar and Scopus are used to conduct the systematic literature review. The review process follows the study by Abidi et al. (2014), focusing on searching, screening and reporting. The detailed process can be viewed in the Appendix. There are twenty papers used in the literature review.

2.1 Quality decay in the fruit supply chain

Quality decay in the supply chain is a growing concern for the food industry (Wu et al., 2018). Considering the dynamic and complex nature of agricultural production, it is imperative to manage food manufacturing, distribution, and retail at the supply chain level (Luning and Marcelis, 2009). Food supply chain management refers to maintaining food quality and safety effectively during production, transportation, and consumption of various food (Zhong et al., 2017).

Considered one of the most challenging segments of the food supply chain, the fresh fruit industry is proliferating and gaining attention from supply chain managers due to increasing customer demand for healthier eating, food quality requirements and year-round fruit availability (Reynolds et al., 2014, Romsdal et al., 2011). Fruits are perishable after harvest, which requires coordinated action by growers, storage operators and retailers to maintain the quality (Mahajan et al., 2017). Obviously, fruit quality can only be maintained, not improved after harvest (Ertan et al., 2019, Mahajan et al., 2017). The rapid processing and seasonality of fruit are associated with fluctuations in supply and demand, making storage a crucial activity in managing and stabilizing Fruit Supply Chain (FSC) (Soto-Silva et al., 2016). The storability of fruit is usually limited and is determined by the initial quality of the fruit at the time of harvest (Glowacz and Rees, 2016).

Notably, quality loss is a significant problem in the FSC (Ciccullo et al., 2021). According to Gustafsson et al. (2013), post-harvest losses of fruits can be up to 38% from the time of harvest until the fruit reaches the customer. Therefore, optimising the FSC is essential to minimise food losses and ensure the availability of fruit worldwide (Shoji et al., 2022). However, stakeholders have been unable to assess how much of the quality of these fruits has been lost. Agricultural companies need to identify food losses along the FSC and then take preventative measures to reduce these post-harvest losses (Ertan et al., 2019). In order to reduce post-harvest losses and increase the economic efficiency of the orchard, it is essential to be aware of the fruit deterioration process in addition to having the suitable storage conditions (Wu et al., 2018). Thus, the relationship between fruit deterioration and storage time is worth exploring.

2.2 Quality decay functions in food supply chains

It is crucial to recognize that food is very complex and many interactions can occur when developing functions to describe quality changes (Van Boekel, 2008). Generally, the quality decay function of perishable food is mainly linear or exponential, where the exponential quality decay is due to microbial growth (Rong et al., 2011). According to Van Boekel (2008), the model for food decay varies due to different quality-related reactions (chemical reactions, microbial reactions, etc.). For example, in chemical reactions, the linear function is used to form reactions, while the exponential function is involved in heat-induced degradation of pigment compound (Torres-Sánchez et al., 2020, Van Boekel, 2008). Besides, Michaelis-Menten kinetics is applied to model most enzyme reactions, and nonlinear regression method is a preferable approach to estimate the parameters of the quality decay function. In microbial change, a modified Gompertz model is frequently used (Van Boekel, 2008). Gompertz function is an ”S” shaped curve that depicts the slowest growth at the beginning and end of a given period. The following table (Table 2.1) gives an overview of the different quality decay functions and their applications.

Table 2.1: Summary and application of quality decay functions

publication	type of decay function	application
Rong et al. (2011)	linear decay function	fresh vegetables
	exponential decay function	fresh meat and fish
Van Boekel (2008)	linear decay function (zero-order reaction)	chemical reactions: formation or decomposition reactions
	exponential decay function (first-order reaction)	chemical reactions: heat-induced degradation of pigment compound
	second-order reaction	chemical reactions: changes of amino acids involved in the Miillard reaction
	Michaelis-Menten equation	enzyme reactions: enzymes browning of potatoes
	modified Gompertz model	microbiological changes: growth of *Salmonellae* in a medium
Wu et al. (2018)	linear decay function	quality loss of citrus fruit
	exponential decay function	quality loss of citrus fruit
Shrivastava et al. (2022)	exponential decay function	decay of citrus quality

In some experiments related to the cold chain of citrus fruits, researchers tend to use exponential functions to describe the decay process of the fruit (Shrivastava et al., 2022, Wu et al., 2018). The research of Wu et al. (2018) used both linear and exponential quality decay functions to predict the change of quality attributes. Shrivastava et al. (2022) employed only the exponential decay function in their study, because they considered that most food deterioration could be adequately modelled by the exponential function. Based on Van Boekel (2008), a generic exponential quality decay function can be expressed as:

$$y(t) = e^{at} \tag{2.1}$$

in which $y(t)$ represents the decay rate, ranging from 0 to 100%, t is the storage time, and a is a parameter. When $y(t)$ is 0%, it means that no fruits has decayed. Also, when $y(t)$ is 100%, it demonstrates that all the fruit has decayed. Exponential regression is one of the most commonly used methods when the parameter a needs to be determined (Goisser et al., 2020, Petrasch et al., 2022, Van Pham et al., 2007).

Nevertheless, the quality decay function of navel oranges remains unknown, and further research is still expected.

2.3 Decay of navel oranges

Navel oranges are vulnerable to pathogens during post-harvest storage (Tang et al., 2018). Fungal diseases of oranges during storage are mainly caused by latent fungal infections on the surface of the fruit and by tissue wounds in the orchard during harvest (Koyuncu et al., 2023). Navel oranges are susceptible to *Penicillium digitatum* and *Penicillium italicum* during storage, causing metabolic changes that can lead to quality deterioration and significant economic losses (Costa et al., 2019, Du et al., 2021, Koyuncu et al., 2023, Tang et al., 2018). The growth of fungal diseases in oranges after harvest is related to storage conditions and the physiological state of the fruit. Experiments have shown that as the physiological age of fruits increases, they tend to be more susceptible to infection (Buron-Moles et al., 2012, Vilanova et al., 2012). Specifically, the dynamics of decay at 4 °C and 20 °C demonstrated an exponential growth pattern at low concentrations of *P.digitatum* inoculum (Vilanova et al., 2012).

2.4 Application of quality decay functions to optimization problems

Optimization models have been widely used by decision makers in perishable food supply chains, particularly in relation to harvest scheduling (Taşkıner and Bilgen, 2021). For instance, the harvest scheduling model developed by Caixeta-Filho (2006) considered the transport process, the capacity of the orchard and the orange quality. The solution could allow farmers to choose harvest in one go or in batches over a month, when sufficient labour and capital are available. In addition, the quality decay function plays a key role when it comes to the optimization problems of the FSC (Rong et al., 2011). de Keizer et al. (2017) incorporated the quality decay function into a network design model. They proposed a mixed integer linear model in order to maximize profits subject to quality constraints. These studies show that quality decay functions should be taken into account in optimization problems, as quality decay can affect harvest planning, network design and economic efficiency (de Keizer et al., 2017, Taşkıner and Bilgen, 2021).

Combining the results of these studies can provide a theoretical foundation for formulating quality decay functions of navel oranges. *Penicillium* is the main cause of deterioration of navel oranges during storage (Koyuncu et al., 2023), and its growth is exponential (Vilanova et al., 2012). Simultaneously, food quality decay can be expressed as the exponential function (Rong et al., 2011, Van Boekel, 2008). Therefore, the current literature review indicates that the exponential quality decay function is more suitable to describe the deterioration of navel oranges compared to other decay functions.

Chapter 3

Methodology and data description

In accordance with the latter two research questions, the formulation of exponential quality decay functions using the nonlinear regression method and the development of an optimization model are the two main elements of this study, which are described in this chapter. The following sections begin with a detailed description of the data set from Gao et al. (2019), followed by the formulation of exponential quality decay functions, and finally an explanation of a simple optimization model.

3.1 Formulation of exponential quality decay functions

3.1.1 Data set description

The data set obtained from Gao et al. (2019) is used to formulate quality decay functions (Figure 3.1). In Gao et al. (2019), the quality of navel oranges was assessed under three different storage methods, which were ventilated warehouse (VW) storage, mechanical refrigeration warehouse (MRW) storage and mountain evaporative cooling ventilating warehouse (MECW) storage. The VW can only manage the warehouse environment through ventilation and cannot adjust the temperature as required. The MRW has mechanical cooling equipment that allows flexible temperature and humidity control, but it is expensive to run. Moreover, MECW is a naturally ventilated warehouse located at the foot of a mountain, taking advantages of the terrain to channel mountain springs (Yizhong et al., 2014). Water is then sprayed from sprinkles on the roof to effectively reduce storage temperature, while water circulates through the ditch of the warehouse to increase storage humidity. Compared with VW and MRW, MECW provided the preferable storage results, which not only saved energy and money but also extended the shelf life of navel oranges, however, which is only possible in certain areas where there are suitable mountains (Gao et al., 2019). Thus, only the data set of MECW is used to formulate the quality decay function of navel oranges, which refers to the blank pillars in Figure 3.1.

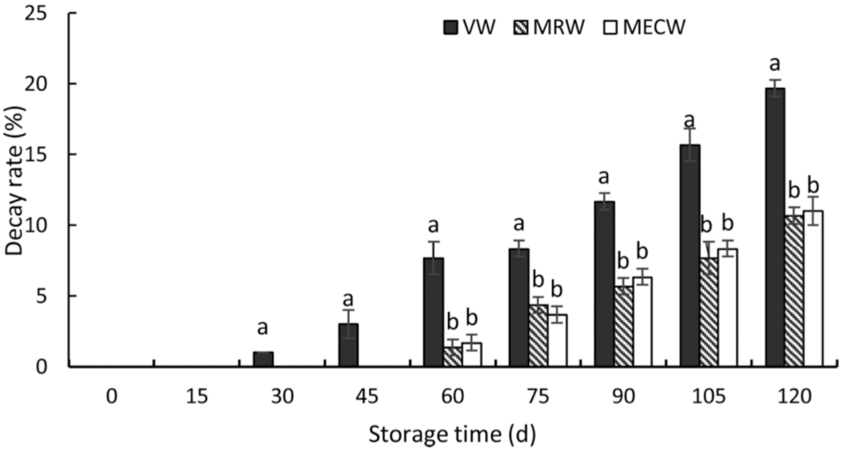

Figure 3.1: Effect of different storage methods on the decay rate of navel oranges (Gao et al., 2019)

In Figure 3.1, the decay rate of navel oranges is on the vertical axis, indicating the number of decayed fruits as a percentage of the total amount of fruits, taking values between 0 and 100%. The number of rotting navel oranges was recorded every 15 days, represented by the storage time on the horizontal axis with an interval 15 days (Gao et al., 2019). The points in the graph are discrete data points as they were unconnected. However, these discrete data points are used to formulate the continuous quality decay functions. As can be seen in Figure 3.1, the first four points all have a vertical coordinate value of zero, which means that there was not a single rotten navel oranges found in MECW until 45 days of storage. The y-axis therefore starts with four points with zero percent decay rate, which is important in the following sections. Data for decay rate in the MECW is extracted from Figure 3.1 via GetData Graph Digitizer (http://getdata-graph-digitizer.com/). The specific data is shown in Table 3.1 below. After 45 days, the decay rate of MECW fruit keeps rising from 1.71% to 11.00%.

Table 3.1: Data set of Gao et al. (2019)

storage time (days)	decay rate (%)
0	0
15	0
30	0
45	0
60	1.71
75	3.68
90	6.35
105	8.32
120	11

In addition, as can be seen from Figure 3.1, the relationship between food deterioration and storage time appears to be nonlinear.

3.1.2 Exponential regression

After obtaining the data, the data set is plotted to examine the trend (Figure 3.2). Taking the four zero-valued points with into account, the trend of the decay rate is nonlinear as the storage time increases. More importantly, based on a review of the literature on quality decay functions and orange deterioration, the exponential function is more suitable for describing the deterioration of navel oranges. For that reason, in the remainder of this thesis, we consider that the quality deterioration of navel oranges follows an exponential curve.

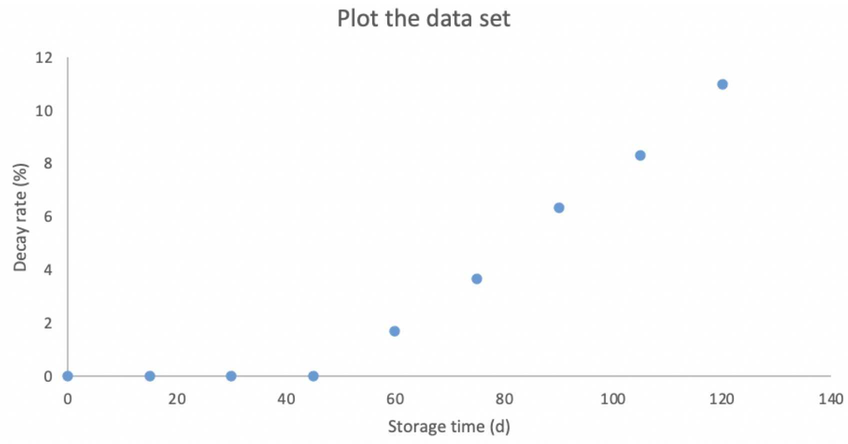

Figure 3.2: The relationship between decay rate and storage time for MECW

Among other alternative methods, exponential regression is considered to be a classic method for determining the parameter a of the exponential quality decay function (Goisser et al., 2020, Petrasch et al., 2022, Van Boekel, 2008). According to Fox (2011), when performing an exponential regression with Excel Solver, the natural logarithm of both sides of the exponential function form is first taken. This means that the previously mentioned exponential function

$$y(t) = e^{at} \tag{3.1}$$

is transformed to:

$$\ln(y(t)) = at \tag{3.2}$$

After that, a linear regression model is obtained to approximate the function. Because the logarithm of zero is not defined, those previously mentioned points with a value of zero present some technical challenges. In fact, these zero values do not mean that navel oranges are not perishable at all within 45 days, as some little deterioration is not visible. Just as in the early stages of infection with *Penicillium*, no deterioration was observed on the surface of the oranges, although *Penicillium* was gradually growing (Vilanova et al., 2012).

3.1.3 Exponential quality decay functions

The parameter of the quality decay function can be determined by using exponential regression (Van Boekel, 2008). Since it is not possible to take the logarithm of zero, we need to rebuild the data set to resolve the problem of having four points with a value of zero. Two possibilities are investigated to formulate the exponential quality decay function using Excel Solver, but both involved difficulties. The first possibility is to exclude the first four points, so the x-axis starts from the visible initial rotting day. The other possibility is to add a certain value to the original decay rate so that the y-axis does not start from zero. After the exponential function has been formulated, this value is then subtracted. The following paragraphs demonstrate the result of using these two methods. The summary output of Excel Solver is demonstrated in the Appendix.

Exclude the zero-valued points

In the summary output of Excel Solver, the R-squared value is used to indicate how well the function fits. R-squared value is a goodness-of-fit measure for regression models. The possibility of removing the first four coordinate points (R^2=0.97) to formulate the exponential function is more accurate than the second possibility (R^2=0.94), as the R-squared value is higher in the first possibility. However, the first possibility does not take into account the R-squared values of the first four points.

The differences between the actual data from Gao et al. (2019) and the computed value of the exponential function for the first possibility are shown in Figure 3.3. In the first possibility, the first four points are ignored, thus the exponential quality decay function starts from the fifth value on the x-axis. In order to show the difference from the initial data set, the first four data points derived from the quality decay functions are included in Figure 3.3.

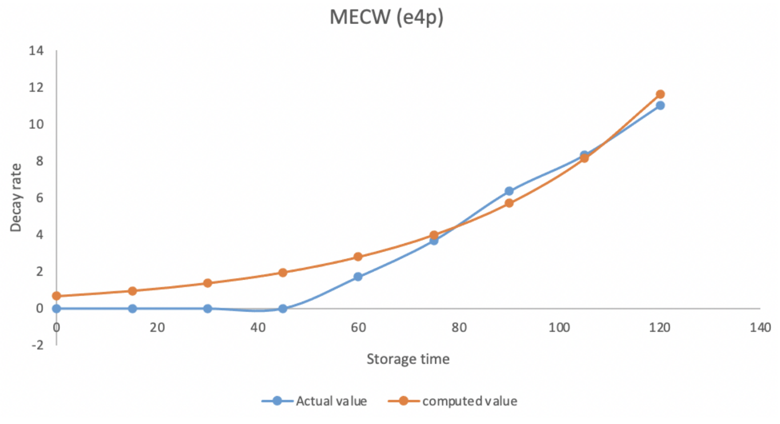

Figure 3.3: The exponential function graph of the first possibility

The exponential function of the first possibility is:

$$y(t) = 0{:}6744e^{0{:}0237t} \tag{3.3}$$

The parameter a of this function is 0.0237. The nine decay rates obtained from this exponential decay function are later applied to an optimization problem.

Add a certain value

In the case of the second possibility, an arbitrary value is added to the original decay rate, also referred to as y-axis. After the exponential function has been formulated based on the output of Excel Solver, the added value is then subtracted. We have experimented with four specific values (0.1, 1, 10, 100) to see how they actually behave. Four exponential function graphs vary from an exponential to an increasingly linear-like pattern from adding 0.1 to adding 100. The exponential function formulated by adding 10 (R^2=0.9397) fits better than adding 0.1 (R^2=0.881), adding 1(R^2=0.938) and adding 100 (R^2=0.9218). The difference between the actual value from the original data and the computed value of the exponential function for the second possibility is shown in Figure 3.4.

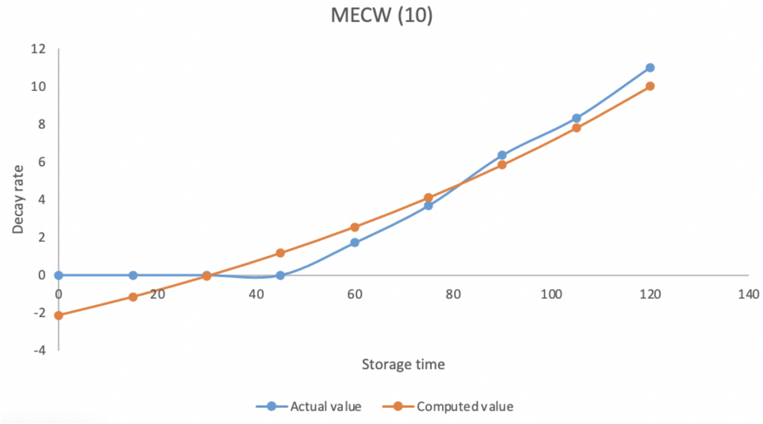

Figure 3.4: The exponential function graph of the second possibility

According to the procedure, the following function of the second possibility is obtained:

$$y(t) = 7{:}8743e^{0{:}0078t} \quad 10 \tag{3.4}$$

Since the value previously added to the vertical coordinate has to be subtracted at the end, the exponential quality decay function formulated on the basis of the second possibility generates negative decay rates for the first three data points. However, this is not possible in practice, as fruit quality can not be improved after harvest (Ertan et al., 2019, Mahajan et al., 2017). Therefore, in order to apply the second possibility in the optimization model, the first three decay rates are assumed to be zero and the remaining six decay rates are obtained from the decay function.

3.2 Using exponential quality decay functions in an optimization problem

This section presents a relatively simple model with a linear objective function and constraints. This model is developed to test whether the results in Section 3.1 actually make sense for the optimization problem. This optimization model may help farmers plan the sales quantity and inventory of their oranges reasonably.

The decision variables and parameters of the model are listed in Table 3.2. For instance, we use x_{qt} to denote the quantity of navel oranges in quality level q sold at time period t in a orchard. In Section 3.1, decay rates for 9 time periods out of 120 storage days are used to formulate the quality decay functions. In order to be consistent with the previous sections, 9 time periods and 9 quality levels are set in the optimization model. There is a 15-day interval between each time period, as before. When q is 1, the navel orange has the highest quality.

Table 3.2: The sets, parameters and variables of the optimization model

sets	definition
$Q=\{1,2,...9\}$	set of quality levels
$T=\{1,2,...9\}$	set of time periods
decision variables	definition
x_{qt}	quantity of navel oranges in quality q sold at time t
I_{qt}	inventory level of navel oranges in quality q at the beginning of time period t
parameters	definition
p_q	selling price for navel oranges of quality q
h_t	maximum number of navel oranges that can be harvested at the highest quality level at time period t

The model is developed to maximize the revenue of the orchard while allowing retailers to purchase better quality navel oranges. The revenue of an orchard is usually associated with the selling price and quantity of navel oranges. According to Timmermans et al. (2014), the economic efficiency of perishable food depends on the quality loss. In other words, as oranges gradually deteriorate with storage time, the selling price of oranges continues to fall until they become unsaleable. Oranges harvested t time periods ago are considered to be of quality q=t. Then, we have

$$p_q = p_1 \quad 1 \quad \frac{y(t)}{100} \tag{3.5}$$

We use p_1 to denote the selling price of navel oranges at the highest quality level, and $y(t)$ is the decay rate of the nonlinear quality decay function. By utilizing the above parameters and decision variables, the following mathematical model maximizes revenue while fulfilling the demand for the quality of navel oranges:

$$\max \sum_{t=1} \sum_{q=1} p_q x_{qt} \tag{3.6}$$

subject to

$$x_{q;t} = 0 \qquad \forall q > t \tag{3.7}$$

Constraints (3.7) mean that when t is equal to 1, the farmer can only sell oranges with a quality level of 1, and oranges with a quality level of 2 to 9 do not exist. Similarly, when t is equal to 2, the oranges with a quality level of 3 to 9 do not exist.

$$I_{1,t} = 0 \qquad \forall t = 1,\ldots,T \tag{3.8}$$

Constraints (3.8) imply that the inventory level of oranges at the highest quality $I_{1,t}$ does not exist and is therefore equal to 0.

$$I_{2,t+1} = h_t - x_{1,t} \qquad \forall t = 1,\ldots,T-1 \tag{3.9}$$

Constraints (3.9) indicate that the inventory level for the next time period in the second quality level $I_{2,t+1}$ is equal to the number of oranges harvested h_t minus the number of oranges sold $x_{1,t}$.

$$I_{q+1,t+1} = I_{qt} - x_{qt} \qquad \forall q = 2,\ldots,Q-1; \forall t = 1,\ldots,T-1 \tag{3.10}$$

Constraints (3.10) mean when the orange quality q is greater than 2, the next time period's inventory level in quality $q+1$ is equal to the previous time period's inventory level of quality q minus the sales quantity of quality q.

$$I_{q,9} = 0 \qquad \forall q = 2,\ldots,Q \tag{3.11}$$

Constraints (3.11) imply that the oranges that is still left in the inventory is sold at the end of the planning horizon.

$$x_{1,t} \leq h_t \qquad \forall t = 1,\ldots,T \tag{3.12}$$

Constraints (3.12) mean that the number of navel oranges sold at the highest quality level should be no more than the quantity harvested in the same time period.

$$h_t + \sum_{q=1}^{Q} x_{qt} \leq 100 \qquad \forall t = 1,\ldots,T \tag{3.13}$$

Constraints (3.13) are labour time constraints. We assume that workers have 100 units of time available. Besides, the worker who harvest the navel oranges can also sell them, but not at the same time. The time required to harvest the oranges is the same as the time required to sell them.

$$I_{qt} \leq 40 \qquad \forall q = 1,\ldots,Q; \forall t = 1,\ldots,T \tag{3.14}$$

Constraints (3.14) relate to the inventory capacity of the orchard. No more than 40 tonnes of navel oranges of any quality level may be in stock at any time period.

$$x_{qt}, I_{qt} \geq 0 \qquad \forall q = 1,\ldots,Q; \forall t = 1,\ldots,T \tag{3.15}$$

Constraints (3.15) are non-negativity constraints.

Chapter 4

Results and research design

This chapter contains a summary of the research design (Section 4.1), optimal solutions of the optimization model (Section 4.2) and a sensitivity analysis of the solution (Section 4.3).

4.1 Research design

After the optimization model has been developed, the optimization solver FICO Xpress Version 8.14 is used to test the feasibility of this model. The model file and the Excel data file are required before running the model to obtain the optimal solution. The model file includes declarations of the sets, parameters and decision variables, as well as the definitions of objective function and constraints. Besides, the data file contains the values of the parameter p_q and h_t. In this case, the selling price of different quality levels of navel oranges p_q is determined based on the decay rate $y(t)$ previously obtained by means of the exponential functions and the selling price of the highest quality level p_1. Since the exponential quality decay functions are formulated in two possible ways, the optimal solution can be found using the values of p_q under each of the two possibilities. Following the average selling price of oranges in the Dutch open markets and supermarkets, we assume p_1 to be 1000 euros per tonne. Whereas, the values for harvest quantity at different time periods h_t are developed by the author (Table 4.1). Table 4.1 also presents the exact data on the sale price of navel oranges based on the first and second possibility of decay rates, where price 1 relates to the first possibility and price 2 relates to the second.

Table 4.1: Data on sales price and harvest quantity

time period t	price 1 p_q (euros)	price 2 p_q (euros)	h_t (tonnes)
1	993.256	1000	60
2	990.375	1000	55
3	986.262	1000	50
4	980.393	988.299	70
5	972.016	974.491	45
6	960.059	958.977	50
7	942.995	941.546	50
8	918.64	921.959	40
9	883.879	899.952	30

4.2 Optimal solution of the model

The optimal solution to the model, obtained according to the decay rate of the first possibility, is given in Table 4.2. The objective function value, i.e. the maximum revenue, is 445788.35 euros. Due to inventory capacity and labour constraints, not all the navel oranges harvested during the time period have to be sold on the same day, except for the ninth period. According to the model in Section 3.2, it is possible to store oranges for more than two time periods, but in view of the computed optimal point, in fact, the harvested navel oranges are never stored for more than two time periods. Of these, part of the navel oranges harvested in time periods three to six can be stored for two time periods and those harvested in time periods one, two, seven and eight can be in storage for one time period.

Table 4.2: Optimal solution of Fico Xpress for the first possibility

sell quantity x_{qt}	inventory level I_{qt}	revenue
$x_{11}=40$ $x_{12}=25$ $x_{13}=20$	$I_{22}=20$ $I_{23}=30$	445788.35 euros
$x_{14}=30$ $x_{15}=5$ $x_{16}=10$	$I_{24}=30$ $I_{25}=40$	
$x_{17}=10$ $x_{19}=30$ $x_{22}=20$	$I_{26}=40$ $I_{27}=40$	
$x_{23}=30$ $x_{25}=20$ $x_{26}=20$	$I_{28}=40$ $I_{29}=40$	
$x_{27}=20$ $x_{28}=40$ $x_{29}=40$	$I_{35}=30$ $I_{36}=20$	
$x_{35}=30$ $x_{36}=20$ $x_{37}=20$	$I_{37}=20$ $I_{38}=20$	
$x_{38}=20$		

The result suggests that orchard farmers should take into account the constraints of labour and inventory capacity and it is not possible to sell all their oranges on the day of harvest, which allows for maximum revenue.

Moreover, Table 4.3 presents the optimal solution to the model, obtained according to the decay rate of the second possibility. The objective function value, i.e. the maximum revenue, is 450000 euros. In the eighth and ninth time periods, the oranges harvested at that time need to be sold directly. Of the 55 tonnes of oranges harvested in the second time period, 45 tonnes are sold on the day of harvest and the remaining 10 tonnes should be stored for one time period before being sold in the third time period. Some of the oranges harvested in the first, third, fourth, fifth, sixth and seventh time periods need to be stored for two time periods before they can be sold.

Table 4.3: Optimal solution of Fico Xpress for the second possibility

sell quantity x_{qt}	inventory level I_{qt}	revenue
$x_{11}=40$ $x_{12}=45$ $x_{13}=20$	$I_{22}=20$ $I_{23}=10$	450000 euros
$x_{14}=30$ $x_{15}=25$ $x_{16}=10$	$I_{24}=30$ $I_{25}=40$	
$x_{17}=10$ $x_{18}=40$ $x_{19}=30$	$I_{26}=20$ $I_{27}=40$	
$x_{23}=10$ $x_{27}=20$ $x_{33}=20$	$I_{28}=40$ $I_{33}=20$	
$x_{35}=30$ $x_{36}=40$ $x_{37}=20$	$I_{35}=30$ $I_{36}=40$	
$x_{38}=20$ $x_{39}=40$	$I_{37}=20$ $I_{38}=20$	
	$I_{39}=40$	

The second possibility has a greater maximum revenue than the first possibility. This is because, for the second possibility of formulating the quality decay function, navel oranges are sold at the same price in the first three quality levels, which are all zero. This does not matter in view of the assumption that the quality does not change in the first three quality levels. Without taking into account inventory costs, farmers in the orchard can store navel oranges for 1 or 2 time periods before selling them.

4.3 Sensitivity analysis of the optimal solution

Sensitivity analysis is a useful tool for determining the stability of the optimal solution (Claassen et al., 2007). If there is only a small change in one parameter of the model, but with a significant difference in the optimal solution, then the optimal solution can be considered sensitive to changes in that parameter; if not, it is robust. In this study, sensitivity analysis of the optimal solution refers to the analysis of the change in the coefficient of Function (3.6), which is the selling price for navel oranges of different quality level q. As mentioned earlier, the sale price of the navel orange depends on its decay rate. Therefore, the main purpose of this section is to examine the effect of changes in decay rate data on the optimal solution.

The results of sensitivity analysis of the optimal solution for the first possibility based on different decay rates are shown in Table 4.4 and Table 4.5. Whether the decay rate of navel oranges grows faster or slower over a range, the optimal point of the model remains unchanged. However, the optimal value changes due to changes in the selling price of navel oranges. In the first possibility of quality decay function, the optimal point is robust to changes in the decay rate of navel oranges.

Table 4.4: Scenario one of the sensitivity analysis for the first possibility

sell quantity x_{qt}	inventory level I_{qt}	revenue
x_{11}=40 x_{12}=25 x_{13}=20	I_{22}=20 I_{23}=30	446449.52 euros
x_{14}=30 x_{15}=5 x_{16}=10	I_{24}=30 I_{25}=40	
x_{17}=10 x_{19}=30 x_{22}=20	I_{26}=40 I_{27}=40	
x_{23}=30 x_{25}=20 x_{26}=20	I_{28}=40 I_{29}=40	
x_{27}=20 x_{28}=40 x_{29}=40	I_{35}=30 I_{36}=20	
x_{35}=30 x_{36}=20 x_{37}=20	I_{37}=20 I_{38}=20	
x_{38}=20		

Table 4.5: Scenario two of the sensitivity analysis for the first possibility

sell quantity x_{qt}	inventory level I_{qt}	revenue
$x_{11}=40$ $x_{12}=25$ $x_{13}=20$	$I_{22}=20$ $I_{23}=30$	443659.31 euros
$x_{14}=30$ $x_{15}=5$ $x_{16}=10$	$I_{24}=30$ $I_{25}=40$	
$x_{17}=10$ $x_{19}=30$ $x_{22}=20$	$I_{26}=40$ $I_{27}=40$	
$x_{23}=30$ $x_{25}=20$ $x_{26}=20$	$I_{28}=40$ $I_{29}=40$	
$x_{27}=20$ $x_{28}=40$ $x_{29}=40$	$I_{35}=30$ $I_{36}=20$	
$x_{35}=30$ $x_{36}=20$ $x_{37}=20$	$I_{37}=20$ $I_{38}=20$	
$x_{38}=20$		

The results of sensitivity analysis of the optimal solution for the second possibility based on different decay rates are shown in Table 4.6 and Table 4.7. This differs from the results of sensitivity analysis for the first possibility. When the decay rate of navel oranges grows faster within a certain range, both the optimal point and optimal value change (Table 4.6). Interestingly, this optimal point is the same as the optimal point of the first possibility. This is because navel oranges are only sold at the same price when they are in the first two quality levels.

Table 4.6: Scenario one of the sensitivity analysis for the second possibility

sell quantity x_{qt}	inventory level I_{qt}	revenue
$x_{11}=40$ $x_{12}=25$ $x_{13}=20$	$I_{22}=20$ $I_{23}=30$	449433.72 euros
$x_{14}=30$ $x_{15}=5$ $x_{16}=10$	$I_{24}=30$ $I_{25}=40$	
$x_{17}=10$ $x_{19}=30$ $x_{22}=20$	$I_{26}=40$ $I_{27}=40$	
$x_{23}=30$ $x_{25}=20$ $x_{26}=20$	$I_{28}=40$ $I_{29}=40$	
$x_{27}=20$ $x_{28}=40$ $x_{29}=40$	$I_{35}=30$ $I_{36}=20$	
$x_{35}=30$ $x_{36}=20$ $x_{37}=20$	$I_{37}=20$ $I_{38}=20$	
$x_{38}=20$		

The optimal point of the model also changes when the decay rate of navel oranges grows more slowly over a range, but the optimal value remains the same (Table 4.7). This is because navel oranges are sold at the same price in the first four quality levels. In summary, in the second possibility of quality decay function, the optimal solution is sensitive to changes in the decay rate of navel oranges.

Table 4.7: Scenario two of the sensitivity analysis for the second possibility

sell quantity x_{qt}	inventory level I_{qt}	revenue
x_{11}=40 x_{12}=45 x_{13}=30	I_{22}=20 I_{23}=10	450000 euros
x_{14}=30 x_{15}=45 x_{16}=10	I_{24}=20 I_{25}=40	
x_{17}=10 x_{18}=40 x_{19}=30	I_{27}=40 I_{28}=40	
x_{27}=20 x_{33}=20 x_{36}=20	I_{33}=20 I_{34}=10	
x_{38}=20 x_{39}=40 x_{45}=10	I_{35}=20 I_{36}=40	
x_{46}=20 x_{47}=20	I_{38}=20 I_{39}=40	
	I_{45}=10 I_{46}=20	
	I_{47}=20	

Chapter 5

Discussion

This chapter discusses the outputs of the research questions. The discussion is divided into two sections, the quality decay function of navel oranges (Section 5.1) and the application of the quality decay function to optimization models (Section 5.2).

5.1 Quality decay functions of navel oranges

Based on the literature review regarding quality decay functions and decay of navel oranges, it is known that the decay function of navel oranges is exponential. This is because the exponential function can be used to describe the dynamic process of food quality deterioration (Rong et al., 2011, Shrivastava et al., 2022, Van Boekel, 2008). Additionally, navel oranges are susceptible to *Penicillium digitatum* and *Penicillium italicum* during post-harvest storage, which is the main cause of quality decay (Costa et al., 2019, Du et al., 2021, Koyuncu et al., 2023, Tang et al., 2018). The growth rate of these fungal diseases in oranges is also considered to be exponential (Vilanova et al., 2012). However, this study focuses on the quality decay function based on the decay rate of navel oranges and does not consider other food attributes such as firmness, sugar content and vitamin C. These attributes also vary with the storage time of navel oranges (Gao et al., 2019). Decay functions based on these attributes are not necessarily exponential.

In some studies related to the deterioration of navel oranges, Shrivastava et al. (2022) employed the exponential decay function in their study on the cold chain of citrus fruits, because the researchers considered that most of the reactions associated with fruit decay (chemical, biochemical and microbiological) can be adequately modelled by the exponential function. However, since different quality attributes decay have different decay functions, Wu et al. (2018) used a linear quality decay function in addition to the exponential decay function when studying the citrus refrigerated supply chain.

In the methodology of this research, the exponential regression method using Excel Solver is applied to fit the exponential quality decay function to the observed data set of navel oranges. This is due to the fact that exponential regression is a desirable and commonly used method when fitting exponential quality decay functions in food industry (Goisser et al., 2020, Petrasch et al., 2022, Van Boekel, 2008). However, when using exponential regression in Excel, the data points with a value of zero need to be changed as the logarithm of zero is not defined. Ultimately, after analysis and comparison, the possibility of excluding the first four points is considered to be more appropriate to fit the exponential quality decay function using Excel Solver. In fact, the Nonlinear Least Squares (NLS) Regression Model using statistical software such as GraphPad Prism and RStudio can also be employed to estimate the parameter of the exponential quality decay function. By using those software, there is no difficulty with the zero-valued points because it is not necessary to take the logarithm of zero manually. For instance, Van Pham et al. (2007) applied nonlinear regression with the Least-Squares method in GraphPad Prism to model changes in apple firmness over time. The dataset of apple firmness was not changed or transformed during the study.

5.2 Optimization model

In order to test the performance of applying the exponential quality decay function to optimization problems, a simple model is developed. This model is constructed to maximize the revenue of the orchard while enabling retailers to purchase better quality navel oranges. The optimal solution to the model for the first possibility suggests that orchard farmers should take into account the constraints of labour and inventory capacity and do not need to sell all their oranges on the day of harvest, which will also allow for maximum revenue. The optimal solution to the model for the second possibility suggests that farmers in the orchard can store navel oranges for 1 or 2 time periods before selling them.

This simple optimisation model only considers the revenue and does not take into account harvesting costs and inventory costs. Caixeta-Filho (2006) developed an optimisation model with an objective function that was defined to maximize the total profit, taking into account both harvest and transport costs. Therefore, the optimisation model developed in this study can be extended and the objective function can be constructed to maximize the profit. In addition, the exponential quality decay function can be applied to optimization problems in other stages of the supply chain, such as transportation (Taşkıner and Bilgen, 2021). As an example, de Keizer et al. (2017) integrated product quality decay in a network design model. The proposed mixed integer linear model positions the inventory and allocates processes to maximize profits within quality constraints. By contrast, Caixeta-Filho (2006) focused on modelling the harvest scheduling of oranges. After all, there is no quantitative model that can cover all aspects in the food supply chain (Rong et al., 2011).

Chapter 6

Conclusion, limitation and further research

In conclusion, the literature review shows that the exponential quality decay function is suitable to describe the deterioration of navel oranges, as ***Penicillium digitatum*** and ***Penicillium italicum*** are the leading causes of quality decay in navel oranges, and they follow an exponential growth pattern. This study also demonstrates that the exponential quality decay function formulated by exponential regression method in Excel Solver can be applied into an optimization model. The optimal solution to the model, obtained according to the decay rate of the first possibility, suggests that farmers in the orchard should take into account the constraints of labour and inventory capacity and do not need to sell all their oranges on the day of harvest, which will also allow for maximum revenue. In the first possibility of exponential decay function, the optimal point is robust to changes in the decay rate of navel oranges. The optimal solution to the model for the second possibility suggests that farmers in the orchard can store navel oranges for 1 or 2 time periods before selling them. In the second possibility, the optimal solution is sensitive to changes in the decay rate of navel oranges. The exponential quality decay function of navel oranges formulated in this study can be widely applied in the citrus supply chain. Meanwhile, it can be used as a reference for formulating quality decay functions for other fruits.

The limitation of this study is that the exponential regression method using Excel Solver may not be the optimal method, although it can be employed to fit the exponential quality decay function of navel oranges. This is because the data points with a value of zero need to be changed, which to some extent affects the accuracy of the quality decay function. For the further research, nonlinear regression with Least-Squares using statistical software such as GraphPad Prism and RStudio can be used to fit the exponential quality decay function. The other limitation is the optimization model developed in this study is a simple one. In future research, this optimization model could be extended and take into account harvesting costs and inventory costs. The further research could even apply the quality decay function of navel oranges to the optimization model not only in the storage phase, but also in the transportation phase.

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Appendix A

Process of systematic literature review

This chapter describes the detailed process of systematic literature review, including searching, screening and search results.

A.1 Searching

Based on the first research question, core concepts are identified to search the literature. Table A.1 shows that the core concepts and their synonyms. The resulting research terms are used to generate strings with Boolean operators (AND, OR, AND NOT) for searching in Scopus. The search strategies are demonstrated in Table A.2. A total of 80 papers are found in Scopus. Meanwhile, the search on Google Scholar using core concepts produces a number of relevant articles.

Table A.1: Core concepts and synonyms

core concepts	synonyms
quality decay	quality loss, quality deterioration, rot*
function	model
food supply chain	food industry

Table A.2: Search strategies

search strings (TITLE-ABS-KEY)	database	hits	relevant
(”quality decay” OR ”quality loss” AND fruit* AND ”supply chain”)	Scopus	39	4
(”quality decay” OR ”quality loss” AND function OR model AND ”food industry”)	Scopus	17	1
(”quality decay” OR ”quality loss” OR deterioration AND ”navel orange*”)	Scopus	18	1
(”quality decay” OR ”quality loss” OR deterioration OR rot* AND function OR model AND ”navel orange*”)	Scopus	6	0

A.2 Screening

After searching, the determined papers are screened against certain criteria. The criteria for screening are:

1. Publications written in English can be included

2. Prefer newer publications after the year 2000

3. Studies about fruit supply chain management, especially quality decay in fruit supply chain

4. Studies about the quality decay functions in the food industry

5. Studies regarding the decay of navel oranges

After screening, six relevant papers in Scopus and fourteen relevant papers in Google Scholar are used for the literature review.

A.3 Search results

The search results of the papers from Scopus are demonstrated in Table A.3 and Table A.4. The main findings are reported in the literature review.

Table A.3: Search results of fruit supply chain

publication	research aim	main result
Shoji et al. (2022)	to assess the impact of potential measures and to improve the post-harvest supply chain	Optimising the fruit supply chain is essential to minimise food losses and ensure the availability of fruit worldwide. However, to date, stakeholders have been unable to assess where and how much of the quality of these fruits has been lost.
Ertan et al. (2019)	to determine the most suitable fresh fig products and demonstrate quality changes during storage and post-storage shelf life	Agricultural companies need to identify food losses and risk factors along the fruit supply chain and then take preventative measures to reduce these post-harvest losses. Fruit quality can not be improved after harvest.
Mahajan et al. (2017)	to highlight the impacts of different techniques on quality and safety of fresh horticultuiral commodities	Fruits are perishable after harvest because of the high moisture content and continued active metabolism, which requires coordinated action by growers, storage operators and retailers to reduce food losses. It is vital that the quality of the product can only be maintained, not improved, after the fruit has been harvested.
Glowacz and Rees (2016)	to assess the practical potential of jasmonates and salicylates as strategies to improve postharvest handling of fruit	The storability of fruit is usually limited and is determined by the initial quality of the fruit at the time of harvest. The difficulty of maintaining fruit quality is more significant than for other commodities due to the challenge of controlling the physiological processes of ripening.

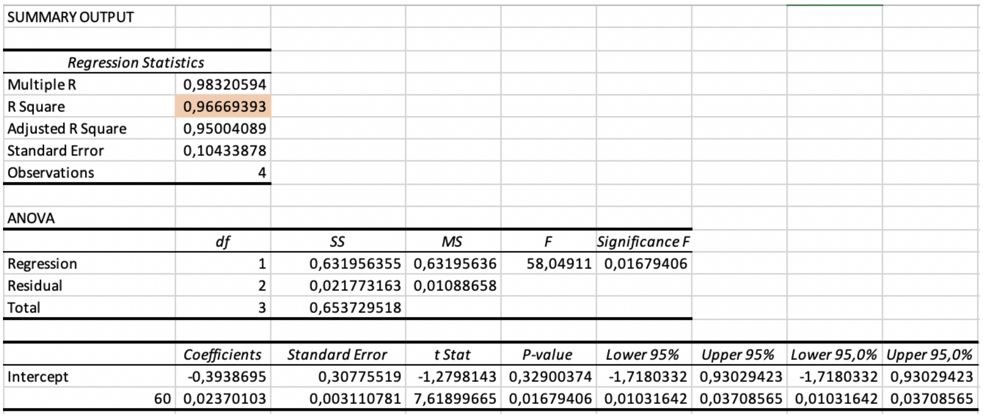
Table A.4: Search results of quality decay functions and decay of navel oranges

publication	research aim	main result
Torres-Sánchez et al. (2020)	to propose a method that can predict shelf-life losses of perishable commodities at different stages of the cold chain based on sensory and physico-chemical quality attributes	Food quality is often modelled using the Arrhenius equation. However, this generic approach is time consuming when many experiments need to be performed.
Koyuncu et al. (2023)	to study the effect of intermittent applications of ozone combined with low doses of fungicide and high doses of dissolved ozone in water on the storage life and quality of navel oranges	According to the latest data, 50% of world citrus production is oranges (FAO, 2022). Fungal diseases of oranges during storage are mainly caused by latent fungal infections on the surface of the fruit and by tissue wounds in the orchard during harvest and/or pre-harvest. The most common orange diseases during storage are *Penicillium digitatum* and *Penicillium italicum*.

Appendix B

Summary output of exponential regression

The summary output of exponential regression is presented in the following figures.



SUMMARY OUTPUT

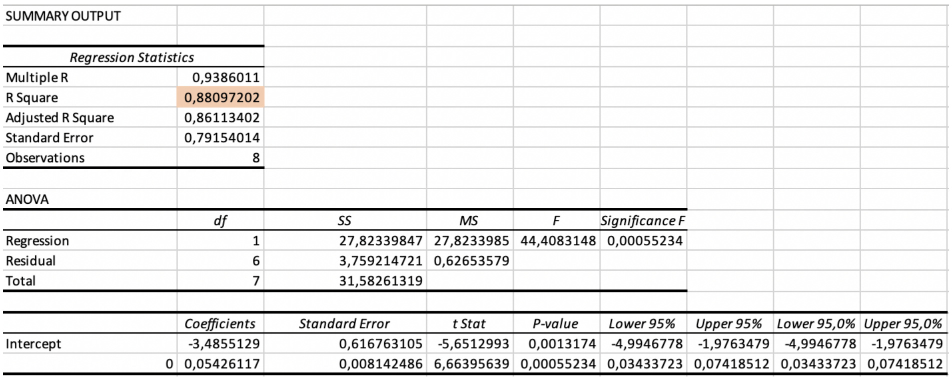
Regression Statistics	
Multiple R	0,98320594
R Square	0,96669393
Adjusted R Square	0,95004089
Standard Error	0,10433878
Observations	4

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0,631956355	0,63195636	58,04911	0,01679406
Residual	2	0,021773163	0,01088658		
Total	3	0,653729518			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	-0,3938695	0,30775519	-1,2798143	0,32900374	-1,7180332	0,93029423	-1,7180332	0,93029423
60	0,02370103	0,003110781	7,61899665	0,01679406	0,01031642	0,03708565	0,01031642	0,03708565

Figure B.1: The summary output of the first possibility



SUMMARY OUTPUT

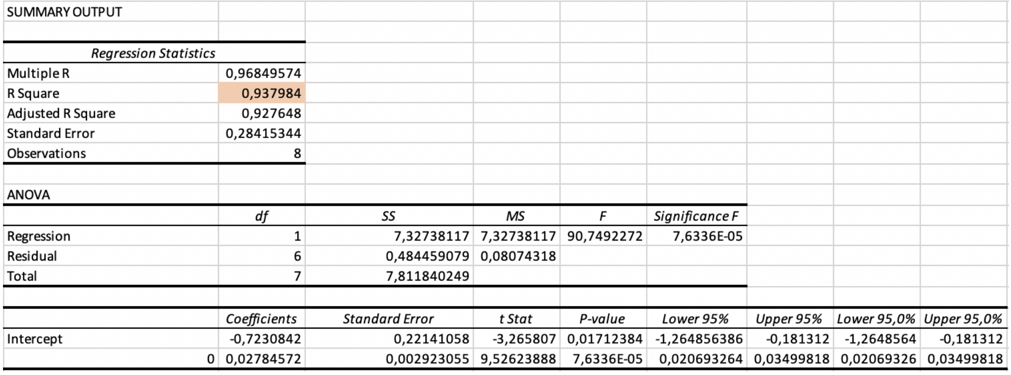
Regression Statistics	
Multiple R	0,9386011
R Square	0,88097202
Adjusted R Square	0,86113402
Standard Error	0,79154014
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	27,82339847	27,8233985	44,4083148	0,00055234
Residual	6	3,759214721	0,62653579		
Total	7	31,58261319			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	-3,4855129	0,616763105	-5,6512993	0,0013174	-4,9946778	-1,9763479	-4,9946778	-1,9763479
0	0,05426117	0,008142486	6,66395639	0,00055234	0,03433723	0,07418512	0,03433723	0,07418512

Figure B.2: The summary output of adding 0.1 in the second possibility



SUMMARY OUTPUT

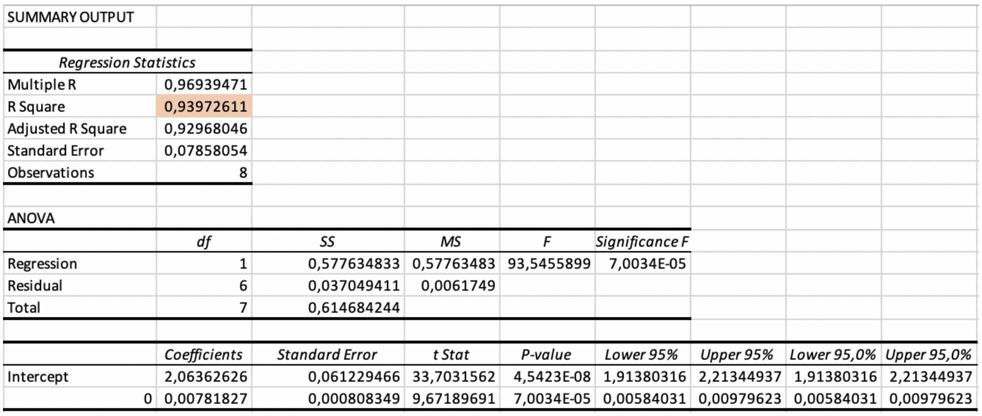
Regression Statistics	
Multiple R	0,96849574
R Square	0,937984
Adjusted R Square	0,927648
Standard Error	0,28415344
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7,32738117	7,32738117	90,7492272	7,6336E-05
Residual	6	0,484459079	0,08074318		
Total	7	7,811840249			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	-0,7230842	0,22141058	-3,265807	0,01712384	-1,264856386	-0,181312	-1,2648564	-0,181312
0	0,02784572	0,002923055	9,52623888	7,6336E-05	0,020693264	0,03499818	0,02069326	0,03499818

Figure B.3: The summary output of adding 1 in the second possibility



SUMMARY OUTPUT

Regression Statistics	
Multiple R	0,96939471
R Square	0,93972611
Adjusted R Square	0,92968046
Standard Error	0,07858054
Observations	8

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	0,577634833	0,57763483	93,5455899	7,0034E-05
Residual	6	0,037049411	0,0061749		
Total	7	0,614684244			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95,0%*	*Upper 95,0%*
Intercept	2,06362626	0,061229466	33,7031562	4,5423E-08	1,91380316	2,21344937	1,91380316	2,21344937
0	0,00781827	0,000808349	9,67189691	7,0034E-05	0,00584031	0,00979623	0,00584031	0,00979623

Figure B.4: The summary output of adding 10 in the second possibility