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Simulating Economic Impacts of Food Losses in Strawberry Supply Chains

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Abstract

Large volumes of fresh fruits and vegetables (FFVs) get wasted along postharvest logistics due to inefficient supply chain design. The quality of FFVs changes significantly over time with great impact of temperature and environmental conditions. Due to the inherent susceptibility and short postharvest life of strawberries, efficient supply chain design considering quality changes is of importance. In this thesis, a generic keeping quality model is implemented in a discrete event simulation to integrate quality losses of strawberries in supply chain modelling. The impacts of stock rotation schemes which consider product quality are compared to stock rotation schemes that operate isolated. Furthermore, the impacts of supply chain design and fleet configurations of producers and warehouses are tested and the economic impacts on food losses are analysed. The results show that the integration of product quality in stock rotation schemes can reduce food losses dramatically. Integrating cooling conditions at the producers' place as well as adequate truck capacities and fleet sizes can improve supply chain design and reduce food losses. Overall, if information to calculate shelf-life is available, it is recommendable to use it to adjust transport and chain processes before the qualities of FFVs drop below their acceptance limit.

Keywords:

Food Logistics, Keeping Quality, Simulation, Strawberry, Food Losses

Kurzfassung

Aufgrund ineffizienter Wertschöpfungsketten, welche nicht ausreichend auf die Bedürfnisse von frischen, leicht verderblichen Lebensmitteln eingehen, gehen große Mengen an wertvollen Ressourcen verloren. Es gilt, Methoden zu entwickeln, die es ermöglichen, die sich verändernden Qualitäten dynamisch in das Design von Wertschöpfungsketten zu integrieren. Dadurch können gute Qualitäten beim Endkunden garantiert und Verluste vermieden werden. Generische Haltbarkeits-modelle ermöglichen es, den Verlauf der Qualitätsveränderungen als Funktion aus Temperatur und Zeit von frischen Lebensmitteln nachzubilden. Erdbeeren sind sehr störanfällig und leicht verderblich, mit einer äußerst kurzen Haltbarkeit, die sehr stark durch Lagertemperaturen beeinflusst wird. Ein effizientes Design der Wertschöpfungs-ketten ist daher von großer Bedeutung. In dieser Arbeit wird ein Haltbarkeitsmodell, welches den Fäulnisverlauf der Erdbeere nachbildet, in eine ereignisgesteuerte Simulation integriert. Es werden isolierte Lagerdurchsatzstrategien mit solchen verglichen, die die Produktqualität in die Entscheidungen miteinbeziehen. Des Weiteren werden die ökonomischen Auswirkungen der Infrastruktur, der Wahl von Vertriebswegen sowie unterschiedlicher Temperaturen und Ausgangsqualitäten auf die Menge der Abfälle untersucht. Die Einbindung der Produktqualitäten in Lagerdurchsatzstrategien, Kühlmöglichkeiten beim Produzenten und adäquate Transportmöglichkeiten können die Entstehung von Abfällen deutlich verringern, daher sollten Haltbarkeitsberechnungen unbedingt in die Planung von Wertschöpfungsketten einbezogen werden.

Schlüsselwörter:

Lebensmittellogistik, Haltbarkeit, Simulation, Erdbeere, Lebensmittelabfälle

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Nomenclature and Abbreviations

Q	Quality (amount, intensity, percentage etc.)
Q_0	Initial Value of Q
Q_s	Current Quality
Q_{lim}	Quality Limit
t	Time
k	Quality Reaction Rate
KQ	Keeping Quality
KQ_{ref}	Keeping Quality at Reference Temperature (Shelf-life)
$f(Q)$	Quality Function
Ea	Energy of Activation [J/mol]
R	Gas Constant = 8.314 [J/mol/K]
T_{ref}	Reference Temperature [°C or K]
T_{abs}	Absolute Temperature [°C or K]

RH	Relative Humidity
FFVs	Fresh Fruits and Vegetables
FSC	Food Supply Chain
SRS	Stock Rotation Scheme
LSFO	"least shelf-life, first out"
FEFO	"first expired, first out"
FIFO	"first in, first out"
LIFO	"last in, first out"

In this work "food losses" and "food wastes" refer to the terminus "food loss" which means, per definition, the losses occurring at production, postharvest and processing stages (Parfitt et al., 2010).

1 Introduction

The world population is rising continuously, by 2050 over nine billion people are predicted to live on this planet, 66% of them in urban areas with higher income levels - 12% more than today (United Nations, 2014). The ongoing urbanization calls for extended food supply chains to transport the produces from rural production areas to the consumers in the urban environments. Simultaneously, with increasing incomes, peoples' food patterns change, as they ask for more fresh fruit and vegetables, dairy, meat and fish (Parfitt et al., 2010). This shift towards more perishable food causes an increase in food waste and losses due to the intrinsic behavior of perishables to deteriorate rapidly (Lundqvist et al., 2008). Large volumes of fresh fruits and vegetables are produced, requiring tremendous efforts and lots of resources (Hertog et al., 2015). In Europe, still 28% of these crops get lost along postharvest logistics, considering handling, storage, processing, packaging and distribution (Jedermann et al., 2014). Food consumption is linked to soil, air and water pollution as well as biodiversity losses. Hence, unconsumed food leads to avoidable CO_2 emissions and reduced economic values of produces (Gustavsson et al., 2011; Reynolds et al., 2014). Temperature control is one of the most important issues within food supply chains, since temperature mainly affects the rate of quality loss (Hertog et al., 2015). Therefore, well-managed cold chains gain more importance in the future to reduce food losses and improve the quality of products (Jedermann et al., 2014; Nunes et al., 2014). If compared to inedible products, the logistics of perishable ones is confronted with many uncertainties due to seasonable varying demand and supply, unpredictable weather conditions influencing harvesttime, quality and quantity of the produces. To achieve supply chains with low food losses and good qualities, it is important to adapt and develop solutions that fit the specific demands of food products (Fredriksson and Liljestrand, 2015). Most tools applied to model and improve food supply chains, however, wrongly assume that product quality does not influence and/or is not influenced by chain design (Van der Vorst et al., 2009). The challenge is to embed food quality models with logistic processes in discrete event simulation models, which are able to deal with uncertainties occurring in food supply chains (Van der Vorst et al., 2009). Moreover, variables like quality deterioration and wastage should be integrated in modelling these chains (Soto-Silva et al., 2016).

In this work a generic keeping quality model is integrated in a discrete event simulation to model a strawberry supply chain located in Lower Austria. Strawberries are one of the most perishable fruits worldwide, with a very short postharvest life of five to seven days, even under perfect storage conditions (Nunes, 2008a). Temperature mainly affects the quality and postharvest life of strawberries. The wrong temperature conditions after harvest can rapidly induce changes in the visual, eating and compositional quality (Nunes, 2008a). Due to the susceptibility and short postharvest life of strawberries, efficient chain design is of crucial importance for chain performance, improved qualities and reduced food losses. To analyse the impacts of infrastructure, temperature conditions and stock rotation schemes on the quality and wastage of strawberries, a generic keeping quality model adapted to strawberry decay is implemented in a discrete event simulation. Thereby, the underlying aim is to reduce food losses throughout the supply chain, starting at the producers and ending at the retailers.

This work firstly describes the characteristics of fresh fruits and vegetables (FFVs) that are of vital importance regarding their postharvest life. Furthermore, the special requirements of modelling supply chains of these crops are discussed. In addition, an approach (generic keeping quality model) to model the quality respectively the remaining shelf life of FFVs is introduced. Secondly, the biological behavior of strawberries under different temperatures is analysed in more detail followed by a description of the implemented model techniques. Afterwards, the results of the simulation model are presented and discussed. Finally, the main findings of this work are concluded and an outlook on future work is given.

2 Modelling Fresh Food Supply Chains

An effective food supply chain has the potential to minimize food and quality losses, to improve decision making and to gain operational efficiency (Kang et al., 2012). Overall, supply chains are defined as complex stochastic adaptive systems. They represent a network of business entities that are responsible to move a product from suppliers or producers to customers (Long and Zhang, 2014). Supply chain management (SCM) tries to efficiently integrate suppliers, producers, distributors and retailers, and plans, coordinates and controls logistic processes to deliver products on time at competitive prices (Long and Zhang, 2014; Van der Vorst et al., 2009). The supply chains of fresh fruits and vegetables differ from inedible products in that they have to deal with seasonal and perishable products, requiring climate control in storage and transit (Zhang and Wilhelm, 2011). Furthermore, changing qualities, long lead times, significant supply and demand uncertainties, and relatively thin margins challenge the management of food supply chains (Blackburn and Scudder, 2009; Soto-Silva et al., 2016). The following subsections expand on the special requirements of FFVs in postharvest handling and introduce modeling techniques of food supply chains. Furthermore, common warehouse strategies and stock rotation strategies that include product quality are described. To calculate the changes in quality occurring in FFVs a generic keeping quality model is explained.

2.1 Supply Chains of Fresh Fruits and Vegetables

The fresh fruit sector grew significantly over the last years (Reynolds et al., 2014). FFVs are perishable goods, characterized by a short shelf-life and varying product qualities along their supply chain. Nunes et al. (2014) define shelf-life as the period during which a fruit or vegetable maintains its desired quality attributes. These attributes of FFVs are traditionally defined by their visual appearance (freshness, color and absence of decay or physiological disorders) and texture (firmness, juiciness and crispness) (Ayala-Zavala et al., 2004) and depend on the grower, retailer and consumer perception (Nunes et al., 2014). Whereas, for example, the absence of defects and firmness are important for growers, retailers emphasize the suitability for purchase and the fruit's appearance. Uniform color, good eating quality and a reasonable remaining shelf-life are a major concern of consumers (Nunes et al., 2014). In general, shelf-life of FFVs is affected by specific storage temperatures and environmental conditions and is a highly dynamic variable (Hertog et al., 2014; Jedermann et al., 2014). Temperature dramatically effects the rates of biological reactions and microbial growth and, therefore, is seen as the most important factor concerning postharvest life of FFVs (Li and Kader, 1989). If the temperature is too low, chilling or freezing damages could occur. A too high temperature shortens shelf-life due to increasing respiration rate, which leads to a depletion of nutrient reserves and accelerated fruit deterioration (Nunes et al., 2014; Nunes, 2008a). For example, berries have a maximum shelf-life at storage temperatures of 0°C. If they are stored at 10°C, there will remain ~30% of their maximum shelf-life, whereas, stored at 30°C, there will only remain less than 10% of their maximum shelf-life (Nunes et al., 2014). Controlling relative humidity is another important factor to obtain good qualities. While too low levels can induces wilting and weight loss, too high levels can cause spoilage (Hertog et al., 2014). Furthermore, the right concentration of oxygen and carbon dioxide is able to induce a state of hibernation, causing extended shelf-life (Hertog et al., 2015). Postharvest handling cannot improve the quality of products, but it can delay the process of quality loss (Hertog et al., 2014).

Van der Vorst et al. (2009) treat the food supply chain as a “netchain”, where different actors cooperate to bring commodities to customers. These actors mainly are growers, auctions, importers and exporters, retailers and specialty shops and their logistics service providers. The main processes comprise the handling, stocking, packaging, transportation and distribution of the produces. Basically, these stages do not influence the intrinsic characteristics of the product grown or produced. Nevertheless, the environmental conditions do influence the quality of perishable products, hence, the quality decreases over time (Van der Vorst et al., 2009). Further improvement can be achieved, by controlling relative humidity and levels of oxygen and carbon dioxide in the surrounding air (Hertog et al., 2015). Various developments in controlling temperature, relative humidity and atmosphere enabled deliveries around the world in a chilled condition (James et al., 2006). Beside temperature and air control, the management of postharvest chains has to deal with major sources of uncertainties due to seasonable varying demand and supply, unpredictable weather conditions influencing harvesttime, quality and quantity of the produces (Fredriksson and Liljestrand, 2015; Hertog et al., 2007).

2.2 Modelling Supply Chains of Fresh Fruits and Vegetables

During the last years, supply chain management (SCM) has become a key concept in the fresh fruit sector to strengthen its competitiveness (Van der Vorst et al., 2009). An efficient planning of inventory management and stock rotation, transportation and distribution along fresh food supply chains is of vital importance for profitability (Soto-Silva et al., 2016). Due to the specific product and process characteristics and the underlying uncertainties along the entire supply chains of perishables, the integration of decision support systems is much more complicated than in supply chains of inedible products (Rong et al., 2011; Soto-Silva et al., 2016). To achieve systems with low rates of food losses and good qualities, it is important to adapt and develop solutions that fit the specific demands of food products (Fredriksson and Liljestrand, 2015). It generates a need for efficient management and new decision technology tools (Soto-Silva et al., 2016).

Since the late 1940s operation research has found its application to agricultural systems (Higgins et al., 2010). These methods present powerful decision support tools considering the growing complexity of the agricultural managerial problems (Borodin et al., 2016). Nevertheless, the adoption of operation research methods has been limited in improving planning and policy decisions along food supply chains (Higgins et al., 2010). Traditional analytical methods rely on mathematical formulizations, need simplified approximations, are restrictive and limited in time and are not suitable to effectively model supply chains (Long and Zhang, 2014). To represent supply chains in a better way and to consider risks and uncertainties, simulation models are commonly used as decision support tools for supply chain optimizations due to their inherent modelling flexibility (Long and Zhang, 2014; Van der Vorst et al., 2009). It enables an easier way to integrate and generate uncertainties while offering concrete solutions (Borodin et al., 2016). Over the last years, agent-based modeling and simulation has become a significant issue for supply chain modeling. These models are built to understand systems’ behavior over time, enable users to observe the operation of an entire supply chain and compare performances under different conditions (Long and Zhang, 2014; Tako and Robinson, 2012). Agents or agent groups represent supply chain entities, while their interactions represent the communication and coordination (Long and Zhang, 2014). In contrast, discrete event simulation methods focus on processes or activities as fundamental elements of simulation (Macal, 2016). They model systems of building blocks, consisting of queues and activities, changing their states at irregular discrete points of time. The entities are individually represented, with specific attributes, determining the behaviour of them throughout the simulation (Tako and Robinson, 2012). Discrete event simulation enables strong and realistic modeling and analysis capabilities (Long and Zhang, 2014) and it can quantify results and incorporate uncertainties (Van der Vorst et al., 2009). However, discrete event simulation models focus on logistic analysis rather than product quality. Product quality needs to be embedded in discrete event simulation models, thereby, the presence of attributes of model elements must be assumed. These attributes express the actual state of product quality. Furthermore, methods to model the quality change, depending on time and environmental conditions, must be defined. Finally, the methods should be able to deal with inhomogeneous product quality as well as other uncertainties (Van der Vorst et al., 2009).

Soto-Silva et al. (2016) reviewed research papers of the last decades concerning operational research models applied to the fresh fruit supply chain. From 28 papers, only 5 papers used simulation models to reproduce and design food supply chains. The predominant modeling technique (16 papers) used for food supply chains is linear programming. The rest of them used less popular techniques like non-linear programming and heuristic algorithms and metaheuristics. A combination of different methodologies was rarely employed. The most papers investigated decision variables in production (14), harvesting (12) and distribution (12). Only 6 of them focused on inventory managements and stock rotation schemes, and 4 of them on farming decisions. The authors call for new models and tools to improve food supply chains, integrating new variables like quality deterioration and food losses.

Before modelling the food supply chain, it is important to develop new approaches to improve handling steps that can be integrated in modeling techniques. Hertog et al. (2014) identified several international approaches focusing on various aspects to improve food supply chains. Some focus on sensor technology for monitoring logistic conditions as well as radio frequency identification (RFID) and GPS technologies for a fast communication throughout the supply chain. Furthermore, improvements in transport modalities enable better climate control. New developments regarding warehouse management approaches for perishable products occur as well as shelf-life models to estimate product's remaining shelf-life and behavior. The best solution to improve perishable food logistics combines all these approaches and shapes the supply chain around the product's requirements (Hertog et al., 2014). This work concentrates on different warehouse management strategies, explained in the following section, combined with generic models to calculate the remaining shelf-life of the produces.

2.3 Warehouse Management

Warehouse management strategies in food supply chains try to limit food losses by coordinating incoming and outgoing commodities. At best, these processes are accurately adapted to the individual product characteristics and requirements. This means that the product deterioration rate and the product demand are considered. The different warehouse management strategies have in common, that they try to deliver efficiencies along all handling steps, while reducing product lead times and quality losses. Furthermore, they aim to lower the costs of business operations. The focus is to facilitate the flow of information abreast product flow, while increasing the transparency of the supply chain. As in-house systems operate isolated and are often not compatible with systems of the company's stakeholders, this complicates the information transfers across the supply network and, therefore, precludes the determination of quality and integrity of incoming commodities (Hertog et al., 2014).

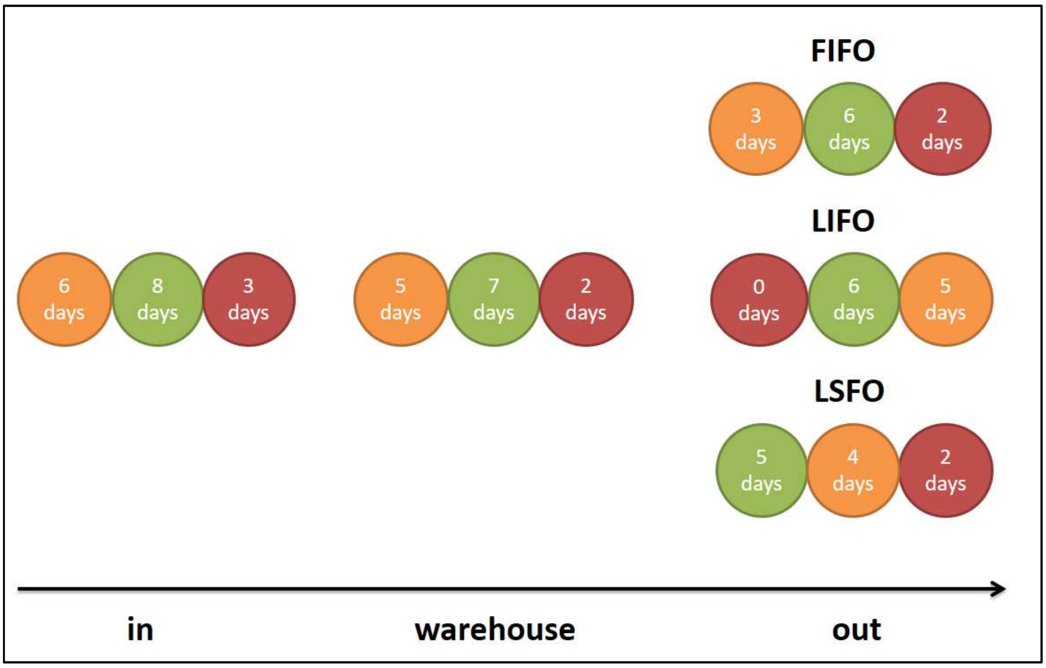

Figure 1 Stock Rotation Strategies

Common warehouse management strategies are "last in, first out" (LIFO) and "first in, first out" (FIFO) approaches. The LIFO strategy ships the last incoming goods first, whereas, the FIFO approach ensures a stock rotation, where the goods that entered the distribution center first, also get shipped first. Both approaches do not consider the products' remaining shelf-lives. These strategies misleadingly assume that all goods, arriving at the same time, have the same remaining shelf-life, however, it often becomes apparent to be not true (Hertog et al., 2014). To implement varying product quality and remaining shelf-life in warehouse management systems, Labuza and Taoukis (1990) suggested an approach, where the products with the least remaining shelf-lives are shipped first, called "least shelf-life – first out" (LSFO). Figure 1 plots the introduced stock rotation strategies, with the numbers displaying the remaining shelf-lives of the products. As shown, three perishable products with different remaining shelf-lives, due to, e.g., varying initial qualities and temperature conditions, enter one after another the warehouse. These products are stored for a certain time, depending on the applied stock rotation strategy, at specified environmental conditions leading to losses of quality and, therefore, shortened shelf-lives. The LSFO approach ships the product with the lowest remaining shelf-life (two days) first whereas the products with higher qualities are stored longer, able to remain higher qualities (still four and five days remaining shelf-life) during longer periods of storage. The LIFO approach ships the last incoming product (five days remaining shelf-life) first, whereas the FIFO strategy ships the first incoming product (two days remaining shelf-life) first. The other products are stored for longer periods. Hence, these products are more likely to become unacceptable during storage, as can be seen in Figure 1 LIFO approach. The product with the least shelf-life (two days at entering the warehouse) is the last one shipped. The product is stored for the longest period and drops below the acceptance limit (no remaining shelf-life).

To integrate product's requirements in warehouse management models, three approaches are suitable. The statistical process control (SPC) monitors and controls environmental conditions to stay within predefined limits by statistical concepts. It monitors process variables and ensures that the process stays constant within well-defined specifications. According to the supply chain of perishable goods Hertog et al. (2014, p. 6) refer the 'process' to 'climate control along the supply chain' whereas the 'variables' are the specific climate conditions realized (mostly temperature and humidity). The limits of control differ according to the targeted specifications (climate conditions). They could either be the optimal conditions based on product specific requirements or specifications based on economics (Hertog et al., 2014). SPC focuses less on quality control of products and more on controlling quality of the climate control process. The SPC approach is particularly beneficial when specific product knowledge is lacking and a strict climate control has to be guaranteed. This approach allows one to handle batches of food products according to their climate history. For example, those products, that were handled under extreme environmental conditions, supposed to be the first ones expired (Hertog et al., 2014). In contrast, the specific quality attribute model focuses on the changes of specific quality attributes induced by supply chain conditions. The assortment of these attributes depends on the different products studied. Thereby, the model tries to describe the relevant ongoing processes inside the product by observing the changes in quality. This approach can only provide a simplified model of the real processes in the product, but it is able to detect well known flaws of logic and provides an estimation of the quality of the supply chain. Afterwards, the impact of the logistic conditions can be translated on the product attributes. The main disadvantage of this model is its need for detailed expertise. The solutions are tailor-made and cannot be easily enlarged to other products (Hertog et al., 2014). Generic shelf-life models can be applied to a wider range of food products than the specific quality attribute model. Nevertheless, they also require product knowledge to calibrate (Hertog et al., 2015). The following subsection will introduce the principle of generic shelf-life/keeping quality models.

2.4 Generic Keeping Quality Model

Keeping quality is defined by van Beek et al. (1985), Fu and Labuza (1993) and Tijskens and Polderijk (1996) as the time until a commodity becomes unacceptable. The product's acceptability depends firstly on the product's quality defined by intrinsic properties like visual appearance, texture and rate of bacterial growth, and, secondly, on the consumer's attitudes defined by economical and psychological circumstances (Ayala-Zavala et al., 2004; Tijskens and Polderdijk, 1996). The keeping quality concept unites these two aspects and outputs a simple, attribute-unspecific index of product quality (Fu and Labuza, 1993; Tijskens and Polderdijk, 1996). The limiting product attributes can either be predefined or depending on circumstances, e.g., depending on which attribute first hits the acceptance limit. The keeping quality model can only provide information about the time until the product becomes unacceptable under defined conditions. It is not capable of providing information about the state of decay and the ongoing processes occurring in the product. However, to describe the dynamics of keeping quality, information about the processes leading to product decay is necessary (Tijskens and Polderdijk, 1996).

The basic generic keeping quality model from Tijskens and Polderijk (1996) considers the effects of temperature on the quality of perishable products as well as interrupted chilling conditions and different initial quality levels in conjunction with quality acceptance limits. It assumes that the keeping quality of FFVs depends, inversely proportional, on the sum of different reaction rates that lead to a decrease in product quality (Tijskens and Polderdijk, 1996). At constant storage temperatures and a given value of initial quality and quality limit, the attribute that becomes unacceptable first, will always be the same. The decrease of a single limiting quality attribute can approximately be described with one of the four following mechanisms introduced by Tijskens and Polderdijk (1996).

Zero order reactions (linear kinetics) are relatively rare, whereas the **Michaelis Menten kinetics** occur more frequently. This one can – under certain conditions, that most probably occur in the initial region of decay - be reduced to a linear or in some cases to exponential kinetics (Tijskens and Polderdijk, 1996). **First order reactions** (exponential kinetics) commonly appear in natural processes. The corresponding equations are listed in Table 1. Furthermore, there are natural processes, e.g., autocatalytic, diffusion controlled processes, complex growth kinetics that follow logistic behavior (**autocatalytic reactions**). These reactions can be described in many ways. For more information, refer to Tijskens and Polderdijk (1996).

Irrespective of the underlying kinetic mechanism of quality decrease, Tijskens and Polderdijk (1996) describe the keeping quality as proportional to the inverse of the reaction rate k. At constant environmental conditions with one single limiting quality attribute, Tijskens and Polderdijk (1996) represent the keeping quality as:

$$KQ = \frac{f(Q)}{k} \tag{1}$$

The quality function $f(Q)$ comprises the initial quality Q_0 and the limiting quality Q_{lim}. It depends on the underlying kinetic reactions of the decrease of the limiting quality attribute (Tijskens and Polderdijk, 1996). Table 1 gives the quality functions of the zero order (linear kinetics) and the first order (exponential kinetics) reactions.

To integrate the impacts of temperature on the behavior of keeping quality, the reaction rate k is calculated by Arrhenius' law. It describes the dependence of chemical, biochemical and enzymatic reaction rates on temperature as follows (Laidler, 1984):

$$k = k_{ref} e^{\frac{Ea}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_{abs}}\right)} \tag{2}$$

Kinetic Mechanism	Quality Decrease	Integration at Constant Temperatures	$f(Q)$
Linear	$\frac{dQ}{dt} = -k$	$Q_s = Q_0 - kt$	$Q_0 - Q_{lim}$
Exponential	$\frac{dQ}{dt} = -kQ$	$Q_s = Q_0 e^{-kt}$	$log_e(\frac{Q_0}{Q_{lim}})$

Table 1 Quality Functions (based on Tijskens and Polderdijk, 1996)

Considering multiple limiting quality attributes leading to quality decrease by non-interfering parallel processes, keeping quality at constant environmental conditions is described by Hertog et al. (2015) as:

$$KQ = \frac{f(Q_0, Q_{lim})}{\sum_{i=1}^{n} k_i} \quad (3)$$

k_i describes the rate constants which affect the quality attributes, with generally i≤3. Hertog et al. (2015) as well as Tijskens and Polderdijk (1996) indicate that for the concept of keeping quality the underlying reaction mechanism does not play an important role, particularly not for comparison of supply chains. Hertog et al. (2015), therefore, assume simple zero-order reaction kinetics (see Table 1 linear kinetic mechanism). Extended to multiple limiting quality attributes the equation by Hertog et al. (2015) is:

$$\frac{dQ}{dt} = -\sum_{i=1}^{n} k_{i,dyn} \quad (4)$$

$k_{i \ldots n}$ is a function of dynamically changing storage conditions.

To compare different time temperature combinations, e.g., along supply chains, the remaining keeping quality (with its current quality Q_s) has to be calculated at appropriate standard temperatures and conditions. In this scenario, the remaining keeping quality is then called shelf-life (Hertog et al., 2015; Tijskens and Polderdijk, 1996). Assuming zero order reaction kinetics the expected remaining shelf-life KQ_{ref} at any time point during the transport phase is calculated according to Hertog et al. (2015):

$$KQ_{ref} = \frac{Q_s - Q_{lim}}{\sum_{i=1}^{n} k_{i,ref}} \quad (5)$$

$k_{i \ldots n}$ represents a function of constant shelf-life conditions.

Hertog and Tijskens (1998), further, developed an equation to calculate the remaining shelf-life during a product's lifetime under changing temperature conditions.

$$KQ_{st} = \frac{KQ_{ref} - \int_0^t \sum_{i=1}^{n} k_{i,dyn} * dt}{\sum_{i=1}^{n} k_{i,ref}} \qquad (6)$$

This equation calculates the remaining shelf-life at arbitrary chosen reference temperatures, suitable for multiple limiting attributes: The parameter $k_{i,ref}$ stands for the rate constant at reference temperature T_{ref} (Hertog and Tijskens, 1998). KQ_{ref} includes the quality function divided by the constant rate $k_{i,ref}$ at arbitrary chosen reference temperature (see Equation 5). The integral describes the decrease of quality over time during a dynamically changing scenario with $k_{i,dyn}$ as a function of changing temperatures (Hertog et al., 1999).

Hertog and Tijskens (1998) extended the earlier published formulation from Tijskens and Polderdijk (1996) for multiple limiting attributes and integrated the effects of O_2 and CO_2 on quality in the formulation. During the PASTEUR project (Hertog et al., 2015) the effects of relative humidity on product quality are included as well. For further information, please refer to the cited articles. In this work the generic keeping quality model is applied to the quality changes of strawberries. To understand the behavior of strawberries and the dependence on temperature, the following section enlarges on the biological decay of strawberries.

3 Biological Decay of Strawberries

The strawberry fruit (*Fragaria ananassa*) is one of the most widely consumed fruits worldwide (Ménager et al., 2004). Strawberry plants belong to the *Rosacea* family and *Fragaria* genus. The plant is perennial with root runners and usually bears red fruits. It is classified as an aggregate accessory fruit, that consists of an enlarged receptacle with one-seeded fruits or achenes embedded on the surface (Bordonaba and Terry, 2011; Ménager et al., 2004). The fruit contains an average of 92% water (Nunes, 2008a) and consists of large cells and thin cell walls (Kader, 1991). This contributes to a high level of susceptibility to physical damages (Kader, 1991). Appearance (color intensity and distribution, fruit shape and size, freedom from defects and decay), firmness, fruit flavor and nutritional value mostly determine the quality of strawberries. The amounts of sugars, phenolics, characteristic aroma volatiles and the primary organic acids, namely citric (~90% of the total acid contents) and malic acids, are responsible for the flavor of the fruits (Kader, 1991; Nunes, 2008a). Sucrose, glucose and fructose account for more than 99% of the total sugars in ripe fruits, however, the content of sugars in strawberries differs due to environmental differences and cultivar characteristics (Nunes, 2008a). Furthermore, strawberries are an important provider of Vitamin C (ascorbic acid) with on average 40-90 mg per 100g of strawberries (Nunes et al., 1998; Nunes, 2008a). According to the FAO (2004), the recommended nutrient intake for vitamin C lies about 45 mg per adult and day and can be covered by eating five to ten strawberries a day (Nunes, 2008a). The main pigments responsible for the color of strawberries, are anthocyanins, carotenoids, and chlorophyll (Nunes, 2008a). Pelargonidin-3-glucoside (80% - orange color) and cyanidin-3-glucoside (orange-red color) are the main anthocyanins of strawberries (Bakker et al., 1994). Different compositions of these two pigments determine the differences in color among fruit maturity and strawberry cultivars (Nunes, 2008a). Furthermore, Spayd and Morris (1981) state that the content of anthocyanin is determined by cultivar, storage time, and storage temperature. Table 2 shows the average composition of strawberry fruits with large genotypic variations.

Constituent (unit)	**Range**
Total Solids (%)	7.0-12.7
Total Soluble Solids (%)	4.6-11.9
Total Sugars (%)	4.1-6.6
Reducing Sugars (%)	3.7-5.2
Sucrose (%)	0.2-2.5
Fructose (%)	1.7-3.5
Glucose (%)	1.4-3.1
Total Pectins (%)	0.2-0.9
pH	3.18-4.10
Titratable Acidity (%)	0.50-1.87
Citric Acid (%)	0.42-1.24
Malic Acid(%)	0.09-0.68
Total Ascorbic Acid (mg/100g)	26-120
Total Phenolics (mg/100g)	58-210
Total Anthocyanins (mg/100g)	55-145

Table 2 Composition of Strawberry Fruits (based on Kader, 1991)

During strawberry development and the ripening process of strawberries, several biochemical changes occur (Moing et al., 2001). For example, the anthocyanin content increases whereas the content of chlorophyll decreases, which contributes to changes in color (Nunes, 2008a). An increasing content of simple sugars contributes to sweetness, whereas an increase in organic acids and phenolics cause acidity and astringency. In addition, the ripening process increases the content of aroma volatiles. This contributes to the typical flavor of the fruits (Nunes, 2008a; Salunkhe et al., 1991). Furthermore, soluble solids and total sugars tend to increase, but in the overripe fruit a slight decrease in soluble solids may occur (Nunes, 2008a). Acidity reaches the maximum content in the mature green fruit, from that point forward the acidity decreases (Nunes, 2008a). The pH decreases in the early stages of ripening (green to red) and then hardly changes (Nunes, 2008a). At proceeded stages of the ripening process the content of vitamins, proteins, lipids and other carbohydrates degrades (Salunkhe et al., 1991), while the content of total ascorbic acid rises (Nunes, 2008a). Due to the loss of cell wall material either during ripening in the field or during storage, firmness decreases when the fruit matures. The outermost fragility of ripe fruits is caused by the characteristic structure of strawberries; large cells and thin cell walls (Szczesniak and Smith 1969, Nunes, 2008a).

Scores	Color, Firmness and Shriveling	Appearance
(1) very poor	Very dark purplish-red; extremely overripe or senescent, extremely soft and deteriorated; extremely wilted and dry	
(2) poor	overripe; very dark red; soft and leaky; fruit is shriveled and calyx is wilted and dry	
(3) acceptable	fully red; minor signs of softness; fruit and calyx show evident signs of moisture loss	
(4) good	Fully light red; firm but less turgid; minor signs of shriveling, calyx slightly wilted	
(5) excellent	three-quarter to fully light red; very firm and turgid; field-fresh, fruit and calyx appear very fresh and turgid	

Table 3: Visual Quality Scores and Descriptors for Strawberries (based on Nunes, 2015)

To assess harvested strawberries, a visual quality score system with descriptors was constructed by Nunes et al. (2015). Strawberries with a score of less than three are considered to be unmarketable. Table 3 shows the visual quality scores and descriptors for strawberries with corresponding pictures.

The strawberry is one of the most perishable fruits (Nunes et al., 1995b). Even under perfect storage conditions, strawberries can only be stored for five to seven days (Nunes, 2008a). To obtain good product qualities along the entire strawberry supply chain and to extend their postharvest life, several factors must be considered. The ripeness stage at harvest, and, first and foremost, storage temperature affect the quality and postharvest life of strawberries (Forney et al., 1998; Kader, 1991; Nunes et al., 1995b). Furthermore, a relative humidity of about 90-95% of the storage environment avoids water loss of the fruits and prohibits moisture condensation on the surface of the fruits, which leads to heightened growth of surface mold and development of decay (Nunes, 2008a). Fluctuating temperatures during handling can also cause water condensations on the berries and therefore should be avoided (Nunes et al., 2003). A controlled atmosphere with lower rates of O_2 and/or higher rates of CO_2 can also extend postharvest life of strawberries due to controlled postharvest decay, reduced rates of respiration and ethylene production, retarded softening and increased accumulation of volatiles (Li and Kader, 1989). Overall, nearly every aspect affecting keeping quality is directly or indirectly influenced by the temperature of the environment (Hertog and Tijskens, 1998). The next subsections expand on the impacts of different harvest times and storage temperatures on the quality of strawberries.

3.1 Effect of Harvest Time on Quality

The quality and postharvest life of strawberries are amongst others affected by the ripeness stage of the fruits at harvest (Forney et al., 1998). The best eating qualities are gained when strawberries are harvested at or near the full ripe stage. In contrast, less mature fruits are firmer, less susceptible to fungal decay and less accident-sensitive while shipping than fully ripe fruits (Forney et al., 1998; Kader, 1991).
The ripeness stage at harvest substantially affects the quality and shelf-life of the fruits. Therefore, Nunes et al. (2006) compare changes in physical and chemical characteristics of strawberries, that are harvested at four different stages of color development (color break, half-colored, three-quarters-colored and full red colored), during eight days of storage at 1°C. Full red colored strawberries are less firm than those picked at earlier stages of color development. Regarding the color development of the strawberries, the fruits harvested at color break or half-colored stages indeed change their color, turn brighter and red color intensity increases, but the color never reaches the same level as those harvested at three-quarter-colored or full red colored stages. Strawberries can accumulate anthocyanin pigments off the plant and, therefore, can change their color during storage. But in fact, only the more advanced three-quarter-colored and full red colored strawberries continue ripening in storage and undergo sufficient changes in sugar and acid content to be suitable for fresh consumption (Kalt et al., 1993; Nunes et al., 2006). Strawberries, that are harvested at the three-quarter-colored stage develop pH, acidity, soluble solids concentration (SSC), total ascorbic acid (TAA) and total soluble phenolics (TSP) similar to those harvested at the full red color stage.
Overall, to obtain the best eating qualities, they should be harvested at or near the fully ripe stage (Forney et al., 1998; Nunes et al., 2006). The three-quarter-colored strawberries develop normally during storage and can be stored for a longer period without losses of firmness and color (Nunes et al., 2006).

3.2 Temperature Effects on Quality

Temperature mainly affects the quality and postharvest life of strawberries. The wrong temperature conditions after harvest can rapidly induce changes in the visual, eating and compositional quality (Nunes, 2008a). As the temperature rises, the respiration rate increases, leading to a depletion of nutrient reserves and accelerated fruit senescence. For example, the respiration rate of strawberries stored at 0°C is about 18 mg CO2/kg/h, whereas, of those fruits stored at 27°C it is about 211 mg CO2/kg/h (Nunes et al., 1995b). Storage temperatures higher than 0°C can shorten postharvest life of strawberries, due to the fact, that for each 10°C rise in temperature the rate of deterioration increases two- to four-fold (Mitchell et al., 1996). Nunes et al. (1995a) assert in their study, that berries with delayed cooling for six hours at 30°C show significant losses in quality compared to those fruits that are more quickly cooled. Therefore, the strawberries should be pre-cooled to, e.g., 1-5°C immediately or not more than two to three hours after harvest, to reduce decay and loss of quality and to increase shelf-life (Mitchell et al., 1996; Nunes et al., 1995a, 1995b; Nunes, 2008a). Ayala-Zavala et al. (2004) tested the effects of storage temperatures on strawberries. Therefore, they stored strawberries at different storage temperatures (0, 5 and 10°C) and assessed their behavior and appearance over time. Besides changes in biochemical contents, they evaluated the overall quality on a one to five scale according to percentage of surface affected by decay:

- (1) 50% surface affected (unacceptable)
- (2) 20-50% surface affected (bad)
- (3) 5-20% surface affected (acceptable)
- (4) up to 5% surface affected (good)
- (5) excellent

Figure 2 shows the overall quality index of the strawberries stored at 0°C, 5°C and 10°C. As can be seen, the overall quality maintains the highest at storage temperature of 0°C. The overall quality index continuously decreases at higher rates in those fruits stored at 5°C or 10°C.

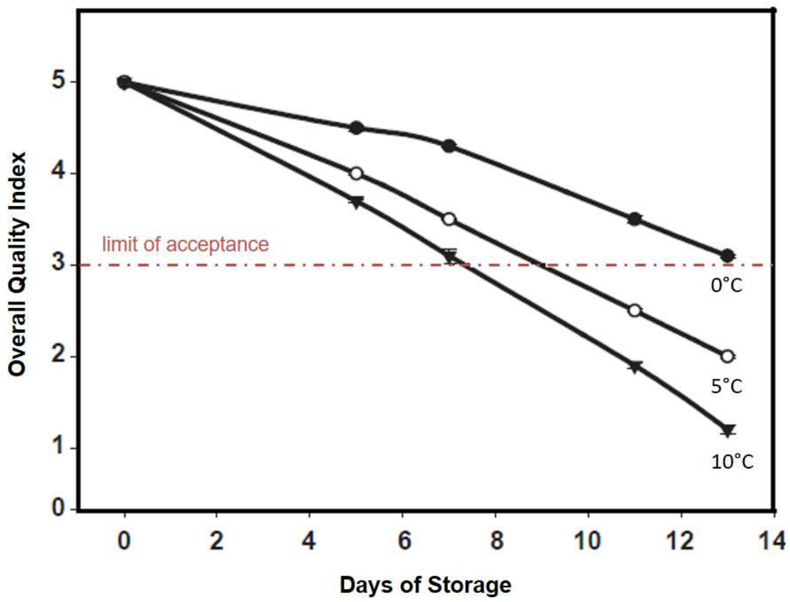

Figure 2 Overall Quality Index of Strawberries (based on Ayala-Zavala et al., 2004)

3.2.1 **Visual Quality**

As previously discussed, the color of strawberries depends on the content of anthocyanins, carotenoids and chlorophyll (Nunes, 2008a). Strawberries are able to accumulate anthocyanin pigments after harvest (Kalt et al., 1993). The anthocyanin content is mainly affected by cultivar, storage time and temperature (Spayd and Morris, 1981). Encymatic or nonencymatic reactions during storage can cause a decrease of red-pigmented anthocyanin and an increase of red-brown pigments, which is accompanied by color degradation from dark red to brownish-red (Nunes, 2008a). This rate of color loss may increase two- to three-fold for each 5°C rise in storage temperatures above 0°C (Collins and Perkins-Veazie, 1993). Overall, the changes in color and the development of visible decay are the main attributes to determine visual quality during storage. When storage time and storage temperature increase, these changes occur more rapidly (Nunes, 2008b).

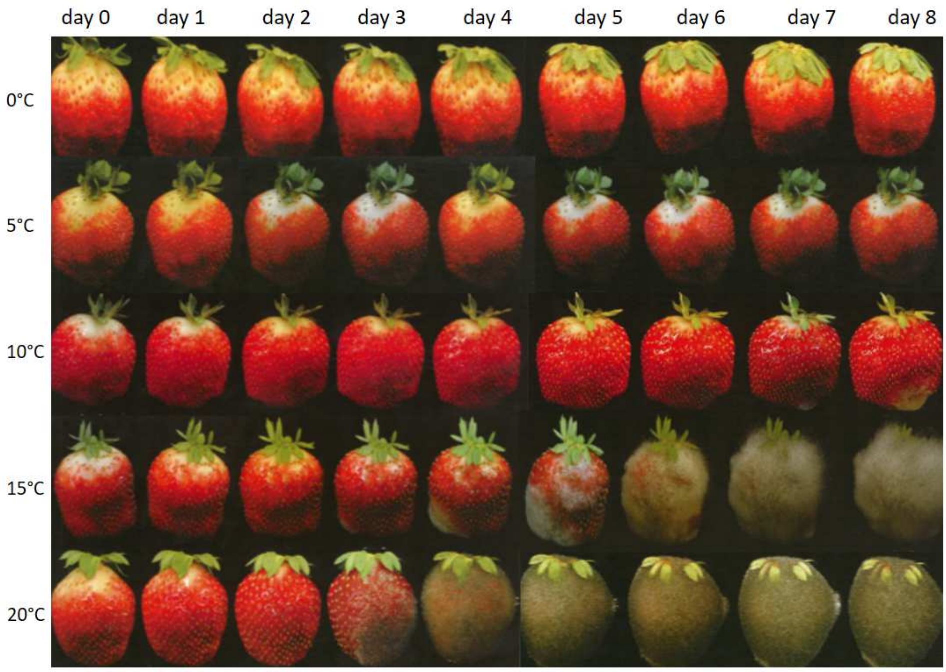

Figure 3 Visual Appearance of Strawberries (based on Nunes, 2008a)

To observe the time and temperature effects on the visual quality of strawberries, Nunes (2008a) harvested 'Seascape' strawberries at the three-quarters-colored stage and stored them immediately after harvest at five different temperatures (0°C, 5°C, 10°C, 15°C and 20°C) with 95-98% relative humidity for eight days (Figure 3). The fruits developed red color after harvest, whereas those stored at temperatures above 0°C developed color faster. The strawberries stored at 0°C changed their color slightly to red, while the whitish surface area on the strawberry shoulders marginally decreased after eight days of storage. Overall, the strawberries stored at 0°C maintained their acceptable visual appearance during seven to eight days of storage. The strawberries stored at 5°C maintained their acceptable visual appearance for six days, then the fruit quality started to deteriorate. The strawberries darkened slightly after four days, and after eight days the whitish surface diminished and became reddish. After three days minor defects occurred and increased after eight days. The strawberries stored at 10°C became full-red, but appeared overripe within eight days of storage with gray mold on the lower part of the fruit. They developed decay on the fruit surface after six days and maintained acceptable visual appearance for five days.

The color of those strawberries stored at 15°C developed red color on white areas in only four days. Decay increased to 75% of the fruit after five days and to 100% after eight days. The strawberries stored at 20°C changed their color rapidly after two days and after three days decay has spread to the half of the fruit surface and by day four the fruit is completely covered with gray mold. Those berries stored at 15°C and 20°C maintained their acceptable visual appearance only for one day.

3.2.2 **Firmness**

The firmness of strawberries decreases, as the fruit matures (Nunes, 2008a). Firmness decreases from white to half-red and then nearly stabilizes from the three-quarters to the full and dark red stages. At harvest, the firmness of full-red or dark red strawberries is 20% lower than the firmness of half-red strawberries (Forney et al., 1998; Ménager et al., 2004; Nunes, 2008a). Regardless of the storage temperature, strawberry firmness decreases during storage. In any case, the firmness of fruits stored at 20°C for two days considers unacceptable, while fruits stored at 15°C become more soft than firm after three days, and strawberries stored at 0°C and 5°C maintain a still acceptable firmness after seven days (Nunes, 2008a). Furthermore, strawberries should not be transferred from low temperature storage to higher temperatures. This causes condensation of the surface of the strawberries and, consequently, the firmness decreases (Luoto, 1985).

3.2.3 **Fungal Decay**

The fungal decay (*Botrytis infection*) of strawberries is significantly determined by storage temperature (Nunes, 2008a). Takeda et al. (1990) show that strawberries stored at 18°C and 95% relative humidity rapidly develop fruit rot. More than 35% of the fruits show decay after already two days in storage. Furthermore, Shin et al. (2007) show that decay quickly increases after seven days of storage at 10°C, whereas slight fungal decay arise at storage temperatures of 5°C after 13 days. Fungal decay causes the deterioration of the fruits after three days of storage at 20°C and after four days at 10°C. In contrast, Ayala-Zavala et al. (2004) proof that storage temperatures of 0°C suppress decay in strawberries. Beside temperature conditions, maturity stage of the fruits can also influence the development of decay, thus, strawberries harvested with white tips have a lower decay development than fully red harvested strawberries (Pritts et al., 1987). Nevertheless, the main criterion concerning infection of *Botrytis* is the presence or absence of spoilage, rather than the degree of decay (Hertog et al., 1999). The spoilage rate of strawberry packages follows a sigmoidal pattern from 0-100% strawberries affected in a consumer package of 20 strawberries with an initial exponential increase that later diminishes to zero until all strawberries are affected (Figure 4). In those packages, stored at 4°C the percentage of strawberries affected is significantly lower and increases more slowly than in those packages stored at 16°C, 12°C or 8°C (Hertog et al., 1999).

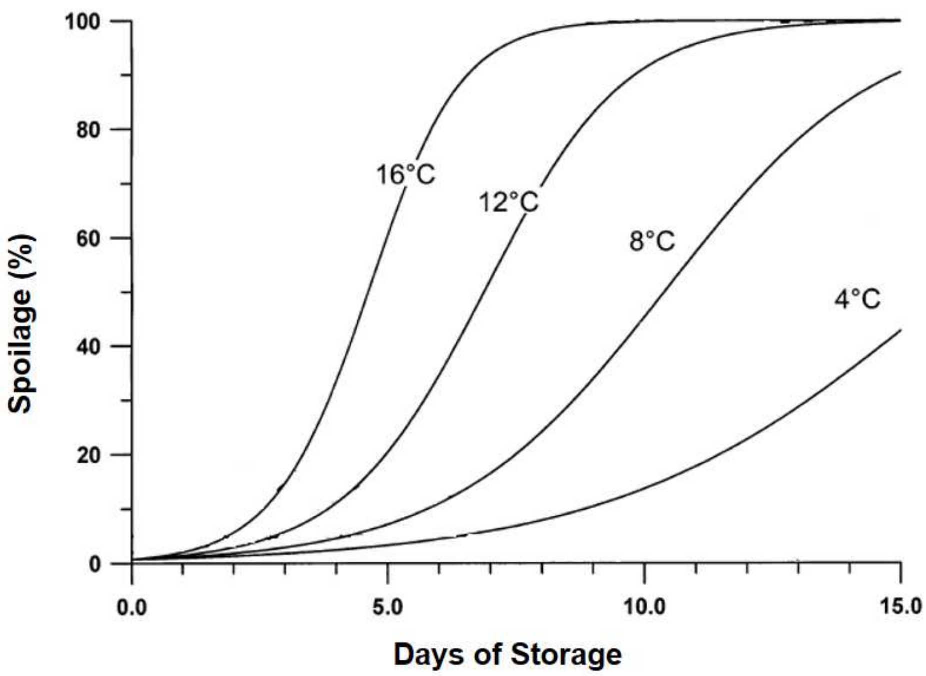

Figure 4 Spoilage of Strawberries (based on Hertog et al., 1999)

3.2.4 **Loss of Aroma Volatiles and Taste**

Aroma and taste of fruits are defined by special compilations of different metabolites. Sugars and acids define sweetness and tartness, whereas different combinations of volatile molecules determine the aroma of fruits. A complex mixture of esters, aldehydes, alcohols, and sulfur compounds account for the characteristic flavor of cultivated strawberries (Ayala-Zavala et al., 2004). Storage time and temperature markedly influence the aroma compounds. Strawberries that are stored at 5°C or 10°C generally produce higher levels of aroma volatiles than those strawberries stored at 0°C (Ayala-Zavala et al., 2004). In contrast, Nunes (2008a) indicates that the loss of aroma of ‘Seascape’ strawberries is faster when stored at temperatures above 0°C, those berries stored at 15°C and 20°C develop off-flavors and therefore are considered to be unacceptable after one to two days, whereas those fruits stored at 0°C, 5°C and 10°C maintain an acceptable aroma for six, five and four days. Péneau et al. (2007) observed that the freshness of strawberries decreases during storage at 0°C after nine days, showing fermented and sour odor and flavor.

3.2.5 **Weight Loss and Other Changes**

Water loss is one of the main causes affecting deterioration due to losses of salable weight, appearance (wilting and shriveling), texture and nutritional quality (Kader, 1986). A maximum water loss (measured as weight loss) of 6% is considered to be acceptable for salability of strawberries (Robinson et al., 1975). Furthermore, morphological changes affecting color quality can occur (Kalt et al., 1993). The loss of water also affects the vitamin stability. The weight loss increases over time and is significantly affected by storage temperatures (Shin et al., 2007). Low temperatures and high humidity during storage can positively influence vitamin stability and therefore delay degradation of ascorbic acids (Nunes et al., 1998). An immediate precooling after harvest is essential to avoid great weight losses (Nunes et al., 1995a). Strawberries stored at 0°C, 5°C, 10°C and 15°C lose at an average 3% of their initial weight, whereas those stored at 20°C lose 6% after two days only (Nunes, 2008a). The weight losses over two days are similar at all temperatures (0.5°C,10°C and 20°C), but increase afterwards at 10°C in the lowest RH (75%) and increase rapidly from day three at 20°C especially with lower RH (Shin et al., 2007). Nunes et al.(1998) stated that with increasing temperature, the strawberries lose more weight and the ascorbic acid degradation increases. Low storage temperatures of 1°C extend postharvest life and reduce losses of ascorbic acid by an average of 7.5-fold. In another study, Nunes et al. (2003) assert that the ascorbic acid losses of strawberries are slightly higher when handled under fluctuating temperatures than those handled under constant temperatures. Furthermore, if bruising occurs, the strawberries easily tend to lose their content of ascorbic acid rapidly due to the fact that the enzyme ascorbate oxidase, located in the cells, releases and oxidizes vitamin C when the cell walls get damaged (Nunes, 2008a). The content of total soluble solids (TSS) is significantly influenced by storage temperature and storage time. TSS of strawberries decreases at storage temperatures of 0°C, 5°C as well as 10°C over time, whereas those fruits stored at 10°C have the lowest content after 11 days. (Ayala-Zavala et al., 2004). Total titratable acidity (TA) and pH do not show significant changes affected by temperature or storage time (Ayala-Zavala et al., 2004; Nunes et al., 1995b; Shin et al., 2007). Table 4 summarizes the most important changes affected by storage temperature.

Storage Temperature	Loss of Firmness	Color Development	Fungal Decay	Loss of Aroma Volatiles	Weight Loss
	(Nunes and Emond, 2002)	(Nunes et al., 2006)		(Nunes and Emond, 2002)	(Nunes and Emond, 2002)
0°C	7	7-8	very effective in suppressing decay (Ayala - Zavala et al. 2004)	6	average loss 3%
5°C	7	6	after 6 days fruit starts to deteriorate (Nunes et al., 2006) slight fungal decay after 13 days (Shin et al. 2007)	5	average loss 3%
10°C	no data available	5	major cause of fruit deterioration after 4 days, 11.7% of surface affected (Shin et al. 2007)	4	moderate shriveling after 6 days and 2-3% weight loss
15°C	3	1	no data available	1-2	moderate shriveling after 4 days and 2-3% weight loss
20°C	2	1	major cause of fruit deterioration after 3 days, 39.7% of surface affected (Shin et al. 2007)	1-2	after 2 days maximum weight loss 6%

Table 4 Effects of Storage Temperature

4 Methods

This work integrates a keeping quality model in the simulation of strawberry supply chains. The following subsections describe the employed methods. Starting with the applied model to calculate the quality changes in strawberries, followed by the simulation framework.

4.1 Modelling Quality Losses of Strawberries

Botrytis infection is a major limiting factor concerning the keeping quality of strawberries (Hertog et al., 1999). Moreover, Schouten et al. (2002) claim that the keeping quality of strawberries solely depends on *Botrytis* pressure. Also, since spoilage is one of the first quality attributes the consumer can notice and assess, keeping quality is limited by it. The main criterion concerning infection of *Botrytis* is the presence or absence of spoilage, rather than the degree of decay (Hertog et al., 1999). The method for calculating keeping quality of strawberries is based on Hertog et al. (1999) and Schouten et al. (2002). They define the keeping quality as batch keeping quality which gives the percentage of strawberries affected in one single batch. The quality limit describes the time until the first strawberry in a defined batch becomes rotten. Therefore, they set the limit of acceptance to 5% (one affected strawberry per consumer size pack of 20 strawberries).

To reproduce the spoilage rate k_i affected by absolute temperature T_{abs}, the formulization of Arrhenius' law is used (Equation 7). Thereby, the value of k_{ref} represents the spoilage rate of strawberries at reference temperature (10°C).

$$k_i = k_{ref} e^{\frac{Ea}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T_{abs}}\right)} \quad (7)$$

As mentioned in subsection 2.4, there are several kinetic mechanisms in generic keeping quality models, complex or simple, determining the decrease of quality (zero order reactions, first order reactions or autocatalytic reactions). Tijskens and Polderdijk (1996) pointed out that the type of kinetic mechanism of quality decrease is important for the quality attribute itself, but, for reason of comparison, the keeping quality can be calculated without concrete information about the reaction kinetics involved (Tijskens and Polderdijk, 1996).

Assuming zero order reaction kinetics and an initial batch quality Q_0 of nearly 100%, the current quality of the batch Q_s is measured as the initial quality Q_0 minus the spoilage rate k_i at absolute temperature T_{abs} (Equation 7) and the time period t.

$$Q_s = Q_0 - k_i t \quad (8)$$

Furthermore, the expected remaining shelf-life is calculated by the following formula:

$$KQ_{ref} = \frac{Q_s - Q_{lim}}{k_{ref}} \quad (9)$$

The quality limit $Q_{\lim}$ describes the time until the first strawberry in a consumer pack rots. It is subtracted from the current quality of the batch Q_s and divided by the spoilage rate at reference temperature (10°C) k_{ref} to enable comparable results.

4.2 Modelling Food Losses in Strawberry Supply Chains

Agent-based modelling is a simulation and modelling technique which is able to model real world systems of various scientific disciplines ranging from natural to social research areas (Macal, 2016). The simulation of supply chains enables the observation of operations throughout entire supply chains and compares the effects of multiple scenarios. The agent-based simulation approach uses agents to represent entities of supply chains like, e.g., producers, vehicles, products and pallets (Long and Zhang, 2014). Grigoryev (2016) states that it is beneficial to use a discrete event approach with a process flowchart to represent the agent's internal dynamics. Discrete event modeling represents a system as a process, where agents perform sequences of operations (Grigoryev, 2016). The states/ operation sequences of these agents change at irregular discrete time steps. Discrete event simulation models are stochastic with statistical distributions generating randomness (Tako and Robinson, 2012).

To represent the supply chain of strawberries a discrete event simulation method was applied. The supply chain structure assumed in this work, illustrated in Figure 5, starts with the harvest of the strawberries at the producers' fields. Afterwards, the strawberries get picked up by trucks and transported to the warehouse where the strawberries get sorted and consolidated, and then, transported to the retailers.

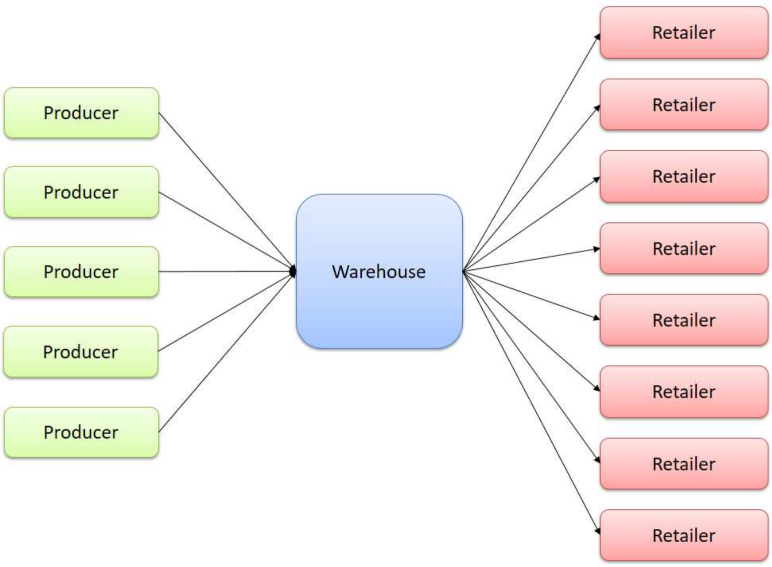

Figure 5 Supply Chain Structure

Table 5 lists the agents implemented to reproduce the entities in this strawberry supply chain. The following sections describe the employed agents and process flows in more detail.

Agents	Representation
Strawberry	perishable product with implemented specific quality attribute
Producer	produces strawberries with biological variations in quality
Strawberry Batch	implemented to collect strawberries for one truck load
Truck	climate controlled truck (producers)
Warehouse	cooled warehouse
Warehouse Truck	climate controlled truck (warehouse)
Retailer	end destination of strawberries

Table 5 Agents

4.2.1 **Strawberry Agent**

One strawberry agent is representing one consumer package. At harvest, an initial batch quality is assigned to each strawberry agent. To reproduce uncertainties along the supply chain, the loading and unloading time, the spoilage rate at reference temperature and the activation energy for calculating quality decay are normally distributed and individually for each strawberry agent. During the process, various temperatures in different process steps (field (producer), transport (truck), warehouse, retailer) are assumed. To calculate quality decay as a function of temperature and time (see Equation 8), the duration of every process step by constant temperatures is measured. If the temperature conditions change, the current quality and the current remaining shelf-life are calculated. As shown in Figure 6, the quality and the remaining shelf-life of one strawberry agent decreases (linearly) over time influenced by temperature. In this example, the quality firstly drops dramatically due to high temperatures on the field, during storage at warehouse the quality decreases more slowly.

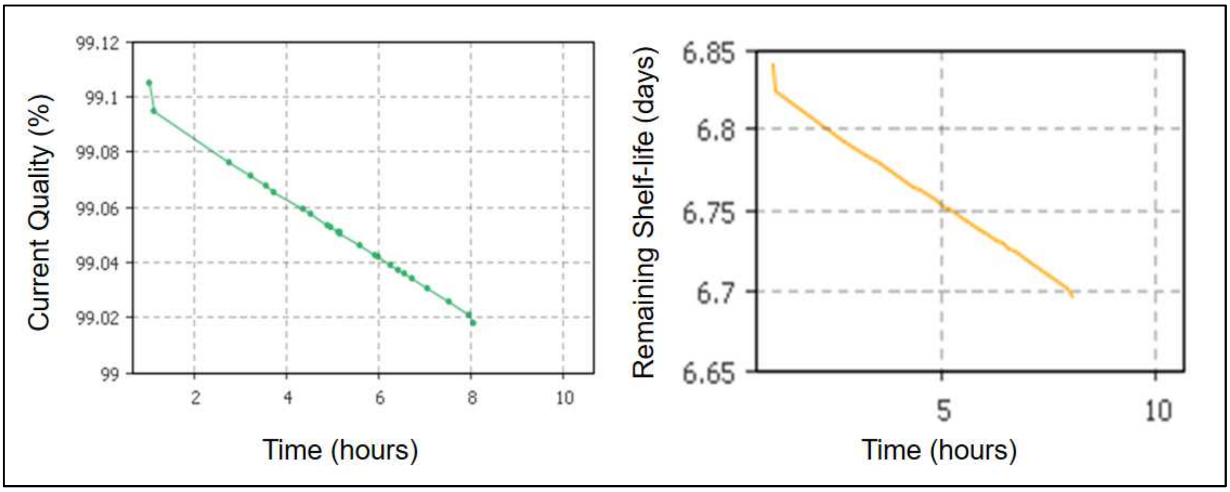

Figure 6 Current Quality and Shelf-life Loss

4.2.2 **Producer Agent**

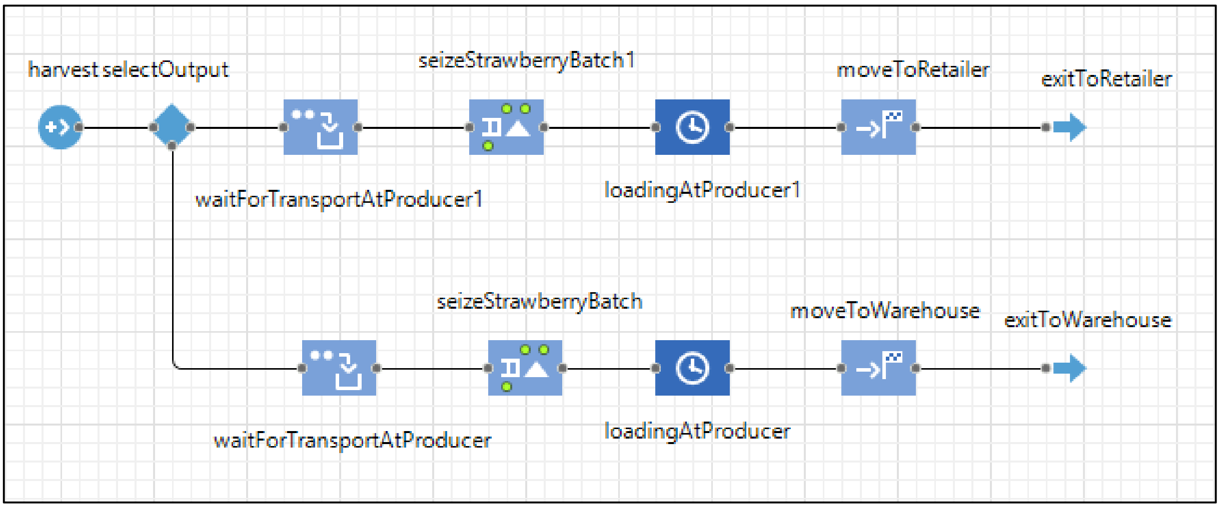

Figure 7 Process Chart Producer

The supply chain starts at the producer's field. Figure 7 illustrates the process steps operated at the producers. First of all, the strawberries are harvested at a specified harvest rate with uniform distributed initial qualities. Then, the strawberries get shipped directly or indirectly, over a warehouse, to the retailers. In both cases the strawberries wait until enough strawberries are available to fill a truck. Therefore, the "Strawberry Batch" agent is implemented which collects the strawberries and then seizes an available truck of the resource pool. Afterwards, the strawberries in each strawberry batch agent get loaded. The loaded truck moves to either one randomly defined retailer (direct deliveries) or the warehouse. The truck agents represent trucks with a previously defined average speed. Every producer has a resource pool of a limited number of trucks. The capacity as well as the temperature of the trucks can separately be defined.

4.2.3 Warehouse Agent

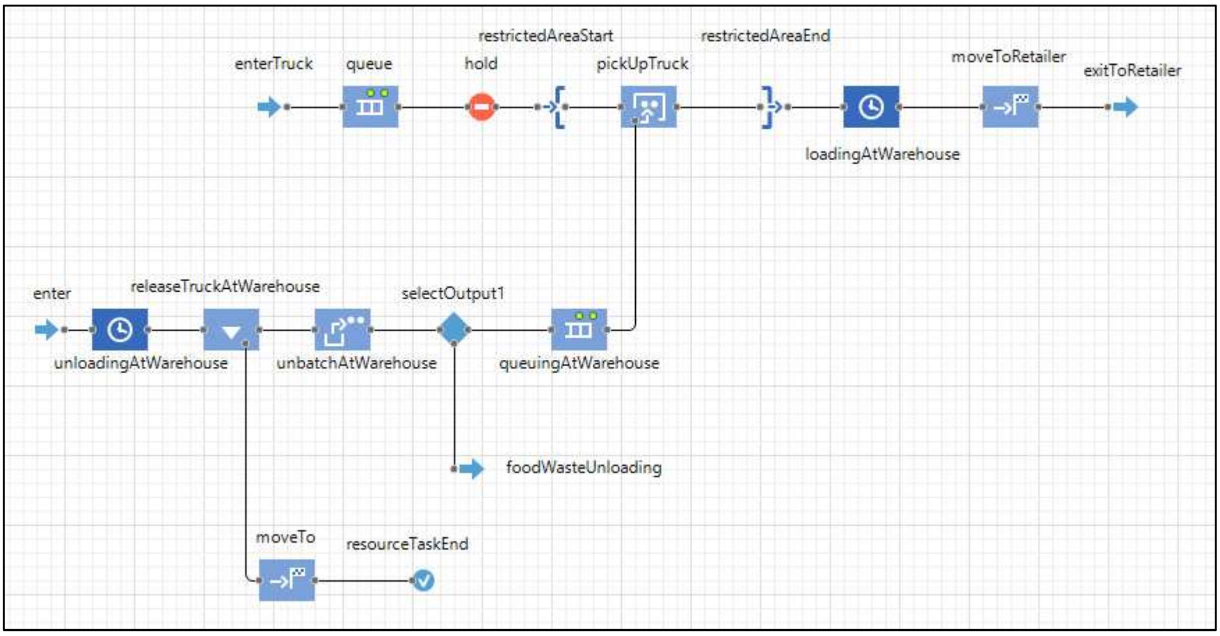

Figure 8 Process Chart Warehouse

If the strawberries are not sent directly to the retailers, they get consolidated in the warehouse. Figure 8 presents the process flow at the warehouse. When one producer's truck enters the warehouse, the strawberries get unloaded and the truck is released and sent back to its home location (producer). Afterwards, the quality of the strawberry agents get tested. If the quality of one strawberry agent is below the quality limit, it gets removed from the process. To count the amount of food losses and to assign the losses to the occurring location, the rejected strawberry agents are added to collection lists called "Food Waste Warehouse Unloading", "Food Waste Storage Warehouse" and "Food Waste Retailer". The strawberry agents with qualities higher than the quality limit are stored and wait until enough strawberry agents are available for further transport to the retailers. As mentioned before, the quality of the strawberry agents is calculated after every step as a function of time and temperature in these steps.

This model is primarily implemented to check the impacts of different stock rotation strategies, as mentioned in subsection 2.3. To enable the LSFO strategy, the quality of each strawberry agent is updated, if enough strawberry agents for one truck load are available. Then, the queue (storage) gets newly sorted, with the strawberries with low qualities leaving the queue first. For FIFO and LIFO stock rotation schemes, the time is measured, when the strawberry agents enter the queue, and then get sorted, regarding the time of entrance.

Every strawberry agent that drops below the quality limit during storage, gets removed from the process and added to the collection list "Food Waste Storage Warehouse". To simulate infinite demand, a truck is called, whenever the batch size of a warehouse truck is reached. Like the producers' trucks, the warehouse trucks have an average speed, and a limited number of trucks is available. The capacity as well as the temperature of the trucks can separately be defined. If a truck is available, it enters the loading zone, picks up the strawberry agents and moves them to a randomly chosen retailer based on implemented street network data. Based on the implemented road maps the travel durations are calculated.

4.2.4 **Retailer Agent**

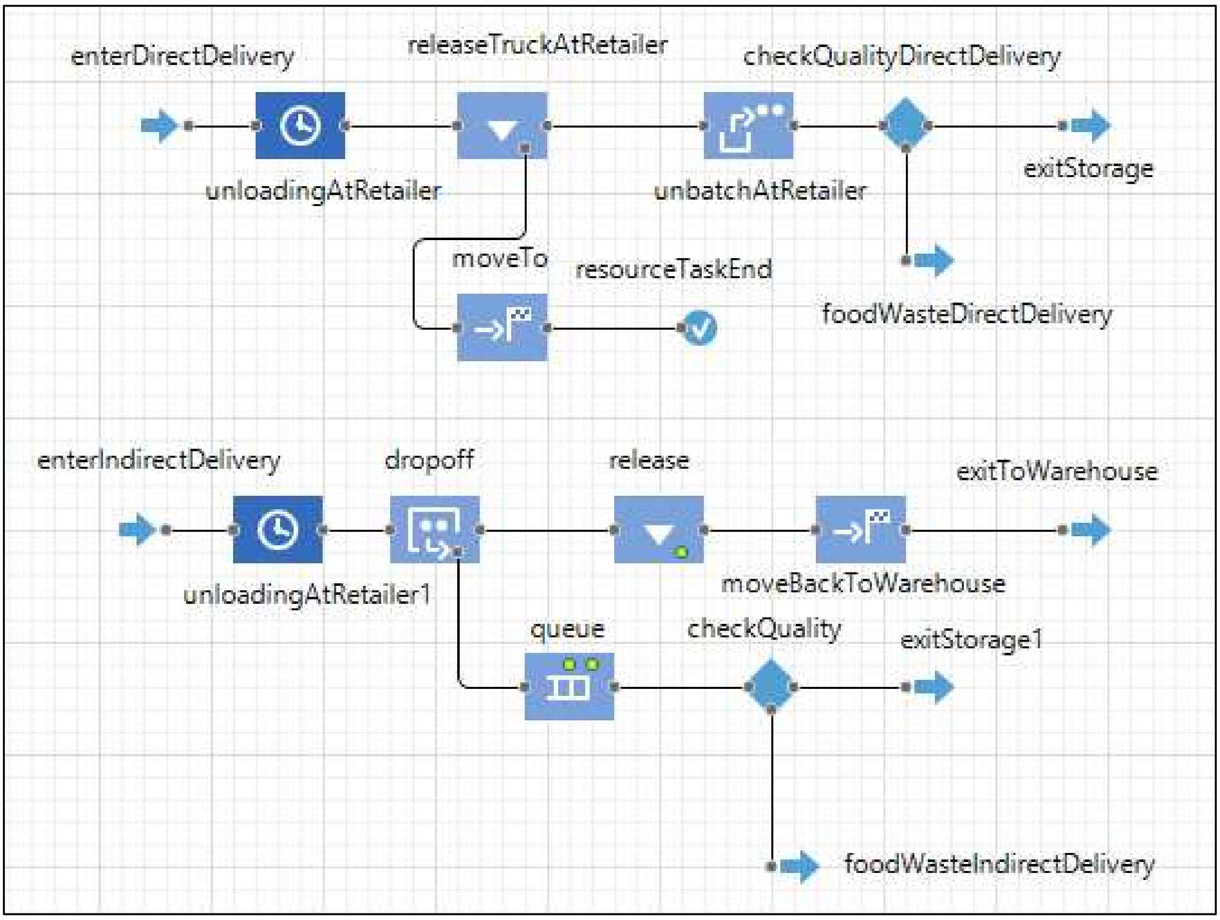

Figure 9 Process Chart Retailer

The supply chain assumed in this work ends at the retailer's store. Figure 9 illustrates the last process steps along the assumed strawberry supply chain. The strawberry agents get unloaded and their qualities are checked for the last time. If their quality is less than the quality limit, they are added to the collection list "Food Waste Retailer". Otherwise, they exit the process.

4.3 Modelling Parameter and Assumptions

In this work, one single limiting attribute namely spoilage depending on temperature is considered as Schouten et al. (2002) claim that the keeping quality of strawberries solely depends on the rate of spoilage. Furthermore, Nunes (2008a) states that the decay of strawberries is significantly determined by storage temperatures. For reasons of comparison, it is convenient to assume zero-order reaction kinetics (Hertog et al., 2014; Tijskens and Polderdijk, 1996), as it is done in this work. Constant temperatures in the different process steps are assumed as well. For adapting the keeping quality model of Tijskens and Polderdijk (1996) to calculate quality losses of strawberries, the initial quality represents the quality of one consumer pack of 20 strawberries (one strawberry agent). Schouten et al. (2002) and Hertog et al. (Hertog et al., 2015, 1999) applied this method in their studies as well. Strawberries that do not satisfy the consumer acceptance on field/at harvest are not considered in this study. The simulation horizon is set to two weeks during the main strawberry season. Due to major demand throughout this season, constantly high demand is assumed. Hence, every produced strawberry is in demand, if not considered to be unacceptable. Furthermore, the harvest rate is assumed to be constant during this time horizon. All producers are supposed to have at least one available cooled truck for delivery. The warehouse is big enough to store all incoming strawberries in chilled conditions, and owns cooled trucks for deliveries to the retailers. The retailers get randomly delivered, with no specified demand. The simulation and analyzation of various impacts on food waste ends at the retail stores. Losses at the retail stores after unloading are not considered in the framework of this thesis.

4.4 Limitations

First and foremost, this work is limited due to a lack of available data concerning producers and production rates. Nevertheless, if data are available, they can be easily implemented in the model environment. Due to hardly ascertainable conditions of relative humidity and levels of O_2 and CO_2 throughout the entire supply chains of strawberries, this work does not consider these aspects in calculating quality losses. Nevertheless, the impacts of temperature on quality loss are representative and with some adaptions on the calculation of quality loss and recorded data, the calculation can be extended. Furthermore, fluctuating temperatures during the processing steps and out-of-bound temperatures at loading and unloading were not considered. Even though an exact prediction of shelf-life due to lacking data is not possible, the model can help to improve strawberry supply chains by analyzing the effects various decisions along the supply chain without biological accuracy. In the framework of this master thesis, the implementation of algorithms for routing optimizations was not considered, nevertheless, it provides a solid base for further improvements.

5 Simulation Data

The following subsections describe the study region and the used parameter values as well as the experimental design in more detail.

5.1 Study Region and Data

This work focuses on the strawberry production in Lower Austria. In Austria, more than 1.100 ha are used to grow strawberries. The most important production areas are Lower Austria (Marchfeld), Upper Austria (Eferdinger Becken), East- and Southeast-Styria and Burgenland (AMA, 2017). In Lower Austria, more than 47% of the Austrian strawberry crops were harvested in 2015 (Statistik Austria, 2015). Furthermore, on an area of nearly 400 ha (in Lower Austria), over 100 farms produced more than 6,000 tons of strawberries (Statistik Austria, 2014) during the harvest season from the middle of May until the end of July, 2013 (AMA, 2017).

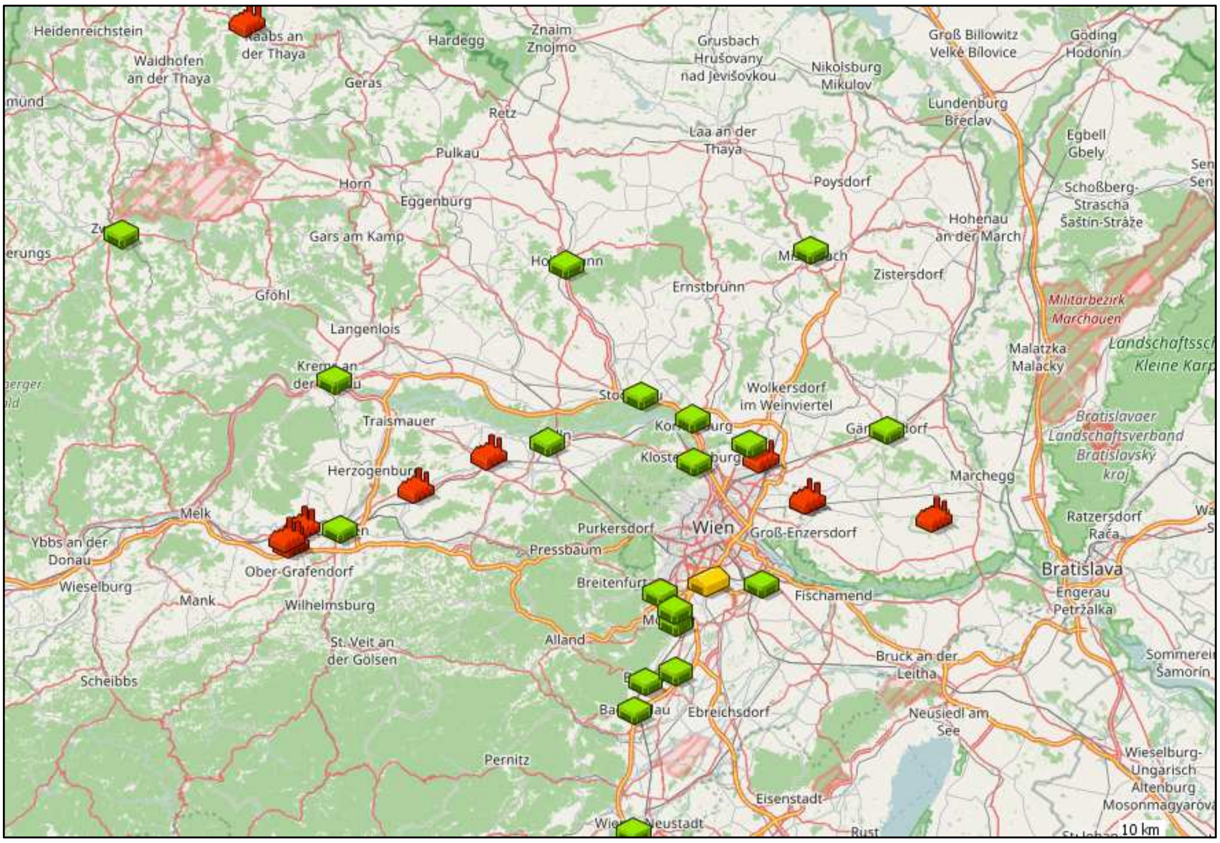

Figure 10 Study Region Lower Austria

To simulate the Lower Austrian supply chain of strawberries, 10 producers certified with the AMA-Gütesiegel were chosen. These data were taken from the GLOBALG.A.P. database (GLOBALG.A.P, 2017). All publicly available data of strawberry producers in Lower Austria were implemented in the model. The red factory icons in Figure 10 show the chosen strawberry producers' head offices. In this work, the head offices are assumed to be the production place (field) as well. The supply chain was based on the fresh supply chain of a major Austrian grocery chain. Therefore, the distribution center, located in the South of Vienna, was selected as the warehouse location in the simulation model (yellow icon). For the biggest (23) cities in

Lower Austria, with a population size over 10,000 people in the year 2011 (CityPopulation, 2017), one existing retail store (green icon) in each city, was chosen. Figure 10 illustrates the simulation are and the implemented producers, the warehouse and the retailers.

To replicate the production rate during the harvest season in Austria, the production output of 2013 (14,946 tons) (AMA, 2015) was converted to a production volume per farm (420 strawberry farms in 2013), assuming that every farm produces the same amount (Statistik Austria, 2014). This results in a production volume of 35.59 tons per farm and year. Further converted, assuming a three months lasting harvest season (AMA, 2017), this results in a production rate of 0.40 tons per farm and day (16,475 gram per hour). One consumer size pack is assumed to contain 20 strawberries (Hertog et al., 1999) with an average weight of 500 gram. Considering these calculations, the harvest rate is rounded up to 33 (32.95) packages per hour and farm.

5.2 Parameters for Calculating Keeping Quality

To calculate the spoilage rate k_i at the different temperature levels, Equation (7) is used. Table 6 lists the, therefore, required parameters. The spoilage rate constant at reference temperature 10°C (283 K) and the activation energy as well as the initial percentage of spoilage, measured by Hertog et al. (1999), are chosen. To reproduce biological variance, the parameters are normally distributed. Their standards errors are listed in Table 6. The initial batch quality is assumed as the maximum initial quality of 100% minus the percentage of initially spoiled strawberry batches. Uniform distributed initial qualities between 96.78 and 99.92 are assigned to the strawberries at harvest.

Hertog et al. (1999) set the limit of acceptance to 5% (one affected strawberry per consumer size pack of 20 strawberries). The same limit is applied in this work. Therefore, the quality limit is subtracted from the maximum quality (100%) and results in a quality limit of 95%.

Parameter	**Hertog et al., 1999**	
	Value	**Standard Error**
Gas Constant (J mol-1 K-1)	8.314	
Activation Energy (J mol-1)	70108	7056
Spoilage rate constant (day-1) at Reference Temperature 283K (10°C)	0.6	0.045
Initial spoilage of batch (%)	0.08-3.22	
Initial Batch Quality (%)	96.78 - 99.92	
Quality Limit for Shelf-Life (%)	95	
Quality Limit Retailer (%)	96.2	

Table 6 Parameters for Calculating Keeping Quality

To guarantee a remaining shelf-life of at least two days at the retail store, the minimum quality at the retailer should be 96.2% (calculated with the mean value of spoilage rate at reference temperature (0.6) and a quality limit of 95%, implemented in Equation (9)).

5.3 Temperatures

Along entire food supply chains different temperatures occur. Table 7 lists the assumed temperatures by different authors throughout the supply chain of strawberries. The only reference found concerning temperatures on field was chosen. It is assumed, that the harvested strawberries wait on the field (temperature field) for further transportation. To analyse the impact of chilling possibilities of the producers, the temperatures get varied from 4°C (temperature producer with chilling possibilities) to 24°C (temperature field). Transport conditions are supposed to be constant at temperatures of 4°C. The temperature in the distribution center is 3°C, which is suitable for different fresh fruits and vegetables (Kader, 1991). To measure the remaining shelf-life of the strawberries entering the retail stores and to make them comparable, the temperature at the retail stores is the reference temperature (10°C).

	Temperature (°C)				
	Hertog et al., 1999	Hertog et al., 1999	Nunes et al., 2004	Nunes et al., 2003	**in this work**
Location		(closed cold chain)	(blackberries)		
Field	---	---	**23.9**	**---**	23.9°C (297.05 K)
Grower/Producer	12	**4**	---	3	4 °C (277.15 K)
DistributionCenter	4	4	1.1	**3**	3°C (276.15 K)
Transport	10	**4**	0.6-1.7	3	4°C (277.15 K)
Retail	16	4	6.7	20	10°C (283.15 K)

Table 7 Handling Temperatures along Strawberry Supply Chains

5.4 Batch and Fleet Size Trucks

It is assumed that the producers use refrigerated trucks that are typically smaller ones, than those used by distribution centers. Hertog et al. (1999) assumed consumer size packages of 20-50 strawberries with 200-300 strawberries per pallet, in this work, packages of 20 strawberries are assumed with 300 strawberries per pallet. This results in 15 packages per pallet. Assuming a maximum producer's truck capacity (producer batch size) of three pallets it results in a producer batch size of maximum 45 strawberry agents. Considering that, under normal conditions, one warehouse truck is not filled with strawberries only, the batch size of the warehouse truck is at maximum 30% loaded with strawberries, assuming a maximum warehouse truck capacity of 33 pallets (495 strawberry agents) this results in a maximum batch size of nearly 150 strawberry agents.

5.5 Experimental Design

The model is implemented with the simulation software AnyLogic 7.3.6. To reproduce realistic transportation routes, data from the OpenStreetMap are integrated in the model and an average truck speed of 80 km/h is stated. The simulation run time is set to two weeks. Several experiments with varying parameters were tested. For each parameter, the simulation was replicated 100 times. Table 8 represents the boundary conditions defined by the listed parameters. The experimental runs vary either one or two parameters at the same time.

Parameter	Value
Task Priority	1
Speed of Trucks	80
Fleet Size Producer	1
Batch Size Producer	45
Temperature Field in Kelvin	297.05
Temperature Transport in Kelvin	277.15
Temperature Warehouse in Kelvin	276.15
Temperature Retailer in Kelvin	283.15
Fleet Size Warehouse	1
Batch Size Warehouse	140
Quality Limit Retailer	96.2
Quality Limit Warehouse	96.2
Enable Direct Deliveries	false
Run Time Minutes	20160
Run Time Hours	336
Harvest Rate	33

Table 8 Boundary Condition Parameters

The amount of food waste occurred at the different process steps are measured, displayed and analysed.

- Strawberries that are rejected immediately after entering the warehouse (Food Waste Warehouse Unloading)
- Strawberries that are rejected during storage at warehouse (Food Waste Storage Warehouse)
- Strawberries that are rejected immediately after entering the retail store (Food Waste Retailer)
- Losses that are influenced by the applied stock rotation scheme (Food Waste Influenced by Stock Rotation Scheme (SRS) = Food Waste Storage Warehouse + Food Waste Retailer). For example, if the LSFO approach is applied the strawberries with the lowest remaining shelf-life are shipped first, hence, they are less likely to drop below the acceptance limit during storage at warehouse, and, at best, arrive the retailer with a still acceptable quality.
- Total Food Waste = Food Waste Warehouse Unloading + Food Waste Influenced by SRS

The next sections describe the experimental runs with the varied parameters.

5.5.1 **Stock Rotation Scheme**

In this experimental run four different stock rotation schemes (Parameter: Task Priority) namely LSFO (Task Priority = 1), FIFO (Task Priority = 2); LIFO (Task Priority = 3) and RANDOM (Task Priority = 4) are tested. Subsection 2.3 expands on the main principles of the LSFO, FIFO and LIFO stock rotation strategies. The RANDOM stock rotation scheme orders and ships the strawberries randomly. To measure the impacts of stock rotation schemes on food waste, the amounts of “Food Waste Storage Warehouse”, “Food Waste Retailer” and “Food Waste Influenced by SRS” are displayed and analysed. In this experimental setting, the food losses occurring at entering the warehouse are not considered.

5.5.2 **Infrastructure, Quality, Temperature and Supply Chain Design**

The waiting time for batching on field influences the quality of the strawberries due to high temperatures. The producer’s batch size as well as the fleet size determine the waiting time. Therefore, the batch size and fleet size of the producers get varied simultaneously. The batch size is tested in the range of five to 45 with a step of five, whereas the fleet size ranges from one to five with a step of one.

The batch and fleet size of the warehouse affect the waiting times and, therefore, the quality of the strawberries as well. The parameters batch size and fleet size of the warehouse get varied simultaneously. The batch size is tested in range of 50 to 150 with a step of 10, whereas the fleet size ranges from one to two with a step of one.

To determine the quality at which it is not possible to deliver the strawberries to the retailer without dropping below the acceptance limit, the initial quality get varied. Therefore, a parameter describing the minimum level of the uniformly distributed initial quality (maximum level as mentioned in subsection 5.2. is 99.92) gets implemented and ranges from 96.2 to 98.4 with a step of one.

To analyse the impacts of chilling possibilities of the producers, the parameter “Temperature on Field In Kelvin” gets varied from 4°C (277.15 K) to 24°C (297.15 K) with a step of one.

Every temperature parameter is set to 4°C (277.15 K) to represent a closed cold chain and to analyse its impact on food losses.

The impact of direct deliveries with the initial batch and fleet size of the producer on food waste are measured in another experiment. Therefore, all deliveries are sent directly from the producers to the retailers.

6 Results and Discussion

The following sections present the results of the applied simulation model and the experimental runs and the impacts of the different stock rotation strategies, supply chain designs and infrastructures on food losses are discussed.

6.1 Impacts of Stock Rotation Scheme

The results show that the stock rotation scheme mainly affects the amount of food losses. The LSFO approach produces the lowest amount of total food waste, the second best SRS regarding food losses is the FIFO approach. The highest level of food losses occurs by applying the LIFO approach while the RANDOM SRS ranges between FIFO and LIFO (Table 9). The result is more significant regarding the food losses influenced by the chosen stock rotation scheme. Compared to the LIFO approach, the LSFO approach reduces food losses influenced by SRS of more than 92%. Furthermore, the food losses occurring with the application of the LSFO strategy are less than 12% of the food losses occurring by applying the FIFO strategy.

	Food Waste			
Stock Rotation Scheme	**Storage Warehouse**	**Retailer**	**influenced by SRS**	**Total**
LSFO	398	548	946	36989
FIFO	8039	115	8154	44197
LIFO	12307	25	12332	48376
RANDOM	11268	46	11314	47357

Table 9 Food Waste Stock Rotation Schemes

To better visualize the results Figure 11 illustrates the amount of food losses occurring by applying the four stock rotation schemes. The orange bars represent the total food losses, the blue bars represent the food losses occurring at storage at warehouse, whereas the red bats represent the food losses occurring at the retailers. The last two values are summarized in the amount of food waste influenced by SRS, illustrated by the grey bars.

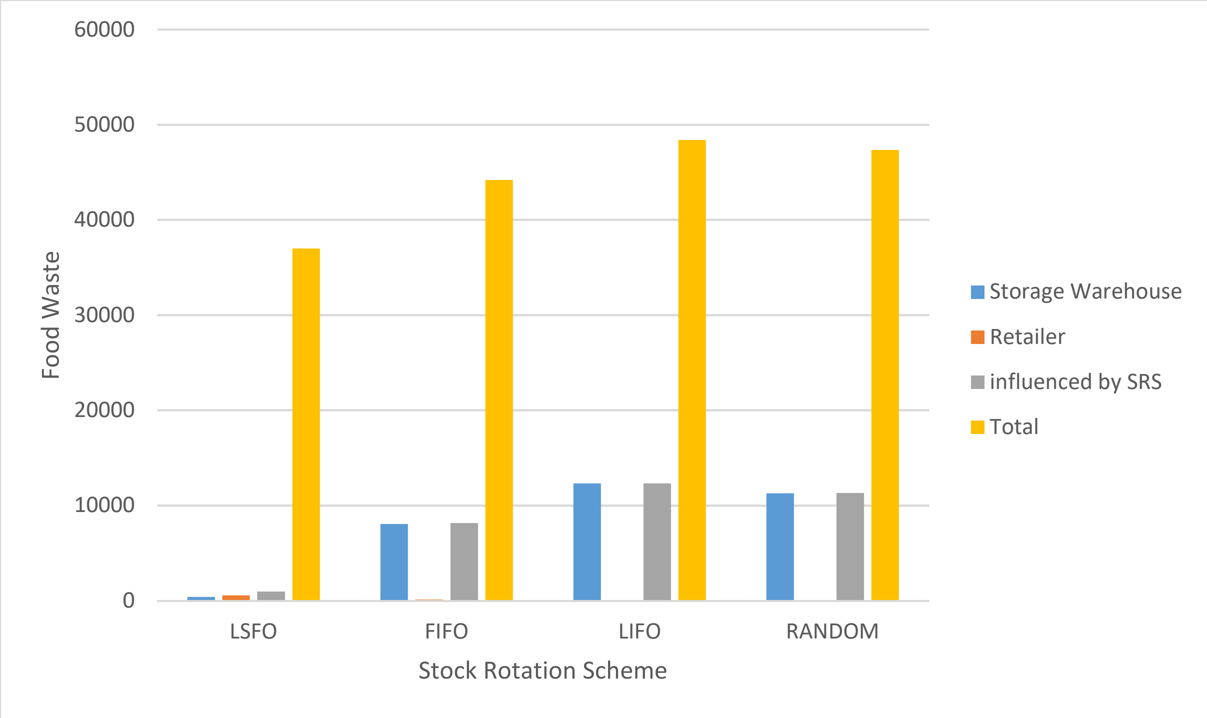

Figure 11 Food Waste Stock Rotation Schemes

The results conform with the statement of Jedermann et al. (2014) that sending out products by applying the FIFO approach can and does create waste that could be avoided by applying the LSFO strategy considering product quality. They also state that it is wasteful to send products with lower shelf-life on longer transport routes, whereas pallets with higher shelf-life are sent on short supply chains. The results of this work show that the food waste occurring at the retailers is minimal higher using the LSFO approach since the destination of the goods is randomly chosen. If information to calculate shelf-life is available, it should be used to adjust transport and chain processes before the quality of the produces drops below the acceptance limit. Products with critical remaining shelf-life, therefore, should be sent on shorter supply chains while products with higher remaining shelf-life can be assigned to longer transport routes, this approach is then called FEFO (Jedermann et al., 2014). The FEFO approach ships only those goods with known expiry date. This ensures high qualities at arrival and eliminates food losses during transport. To apply the FEFO strategy, all trading partners across the supply chains must share their information. Thus, the distribution center manager has more information about the shelf-life potentials of all incoming commodities and, therefore, can adapt the distribution. The manager will coordinate the remaining shelf-life of the goods with the duration of transport. Hence, information about primary production, secondary processing and distribution must be available (Hertog et al., 2014). It homogenizes quality by intelligent stock rotation, nevertheless, it is not able to increase the average product quality at delivery (Jedermann et al., 2014). In contrast, Van der Vorst (2009) mention, that the homogenization of product quality might not be the most efficient strategy to reduce food losses. They suggest to split product lines, in segments with the highest qualities and higher prices, and specific outlets with lower prices for lower qualities, considering that product quality has different importance for varying customer groups. Nevertheless, the implementation of the FEFO approach calls for various elaborate steps and the collaboration of different scientific disciplines, but it has a high potential in avoiding food losses (Jedermann et al., 2014).

6.2 Impacts of Batch and Fleet Size Producer

The infrastructure of the producers influence the amount of occurring food losses at warehouse unloading. The results show that with increasing batch and fleet size, the food waste at unloading at the warehouse decreases (Table 10). In more detail, if the composition of batch and fleet size is able to transport more strawberries than harvested in one hour (33 per hour), the food losses decrease by increasing batch and fleet size. This might be due to the fact that more berries can be transported at the same time and less of them have to wait on the field at high temperatures. A second truck with the same capacity (batch size 45) can reduce the losses at warehouse unloading to a sixth, whereas a third truck with a batch size of 45 diminishes the food losses to zero. If it is not possible to transport more strawberries than harvested in one hour, with bigger batch size, more food waste occurs at warehouse unloading. Regarding the total food losses, no unambiguous trend can be deduced. If less strawberries get wasted entering the warehouse, more strawberries get wasted afterwards.

Food Waste Warehouse Unloading	**Fleet Size**					
Batch Size	**1**	**2**	**3**	**4**	**5**	**Total**
5	8583	17001	25178	32901	39881	**24708**
10	17004	32922	**44906**	33657	35143	**32726**
15	25179	**44932**	35876	28839	21363	**31238**
20	32930	33664	28872	13324	5956	**22949**
25	39925	35232	21382	5981	28	**20510**
30	**44958**	28902	6093	991	0	**16189**
35	41827	27097	5529	0	0	**14891**
40	33715	13598	1102	0	0	**9683**
45	36032	6116	0	0	0	**8430**
Total	**31128**	**26607**	**18771**	**12855**	**11375**	**20147**

Table 10 Food Waste Batch and Fleet Size Producer

6.3 Impacts of Batch and Fleet Size Warehouse

The experiment of varying batch and fleet size of warehouse trucks results in a more distinct trend than the variation of batch and fleet size of the producer trucks. With an increasing batch size and an increased fleet size of one additional truck, the food waste can be significantly reduced (Table 11). Choosing a fleet size of two trucks, a bigger batch size than 80 or an additional truck cannot further improve the result. This experiment must be seen in a critical way. In this work, no specialized demand is assumed. The retail stores that get delivered are randomly chosen with no specified quantity of demand. One loaded truck (with always the same amount of strawberries) delivers only one retailer. This does not correlate with the reality.

Food Waste Influenced by SRS	Fleet Size		
Batch Size	**1**	**2**	**Total**
50	21637	14121	**17879**
60	20435	8633	**14534**
70	19002	987	**9994**
80	17307	99	**8703**
90	15354	99	**7727**
100	13004	99	**6551**
110	10411	99	**5255**
120	7462	99	**3781**
130	4056	99	**2078**
140	946	99	**523**
150	126	99	**113**
Total	**11795**	**2230**	**7012**

Table 11 Food Waste Batch and Fleet Size Warehouse

Nevertheless, this experiment might demonstrate that efficient routing positively influences the amount of food losses. In the way that one delivery in the simulation model represents one efficiently chosen transport route. If the distribution of the products and the corresponding demands are managed well (in means, that less strawberries must wait in the warehouse for further transport), food losses can be reduced.

6.4 Impacts of Initial Quality

With decreasing initial qualities, the amount of total food losses rises (Figure 12). The first markedly rise in the amount of food waste occurs at qualities under 98.2 percent. The food losses occurring at unloading at warehouse increase more rapidly than the food losses influenced by SRS. It seems that a lot of berries with initial qualities under 98.2 percent drop under the acceptance level during transport to warehouse. The more strawberries are rejected at the warehouse, the less are rejected at the retail stores, this might explain the peaks of the food waste influenced by SRS (Figure 12 orange line). The second markedly rise starts at qualities under 97.5 percent. It can be observed that the amount of food waste influenced by SRS rises and then diminishes again, whereas the food waste at warehouse unloading rises continuously. It can be assumed that those strawberries with initial qualities between 97.5 and 96.9 percent are likely to deteriorate on the way from warehouse to the retail stores. The most strawberries with an initial quality under 96.7 percent are unacceptable already at arrival at the warehouse. Hence, it is not recommendable to send strawberries with initial qualities under 97.5 percent on long supply chains. These berries are still acceptable at the producer or, at best, at the warehouse and lose their acceptance during transport. To avoid losses, they could be sent on short transport routes, sold locally or further processed to jam or other by-products like juice, compote or liquors.

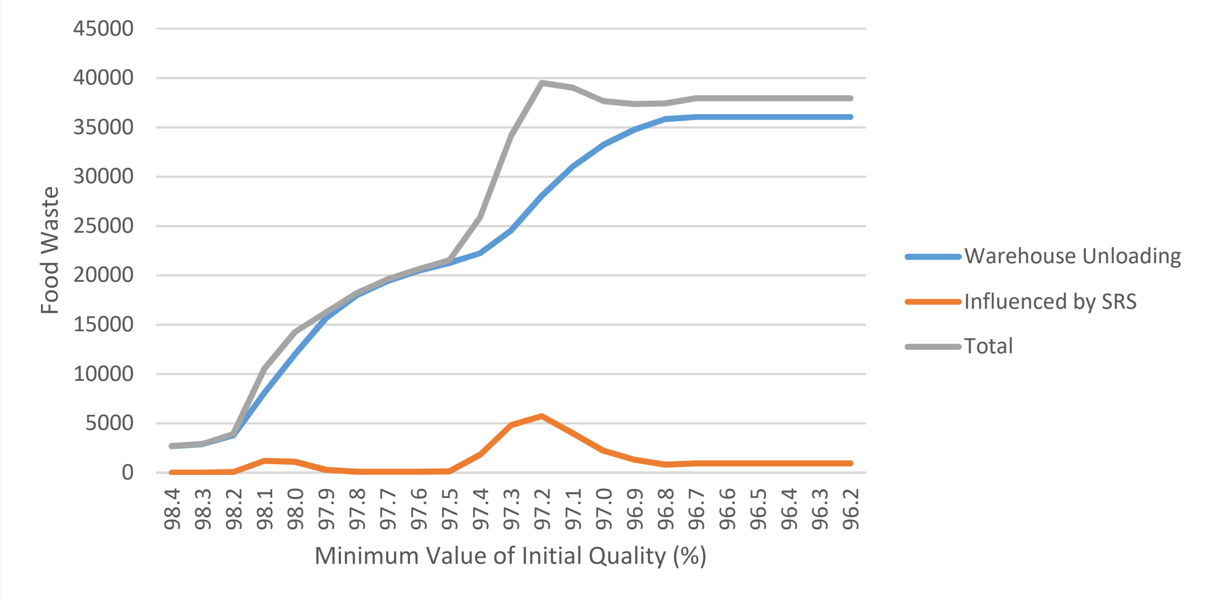

Figure 12 Food Waste Initial Quality

Jedermann et al. (2014) conclude that the consolidation of products in warehouses or distribution centers reduces the overall transport costs and, as mentioned before, it enables the application of the FEFO strategy. However, the consolidation process negatively affects the shelf-life of products due to increased transport durations. Furthermore, warehouses hardly store only one product. Considering the different requirements of every fresh fruit, it is not possible to adapt optimal temperature and storage conditions for all produces.

6.5 Impacts of Temperature Producer

Nunes et al. (1995b) studied the effects of delays to cooling and pointed out that prompt removal from field heat can slow down undesired quality changes and increase the remaining shelf-life of strawberries. The results of this study show that the producer can significantly reduce food wastage by immediately cooling the strawberries after harvest (Figure 13). If the producers immediately cool the strawberries to 4°C the total food waste can be reduced to 78% compared to food wastes occurring at temperatures of 24°C at the producer. By storing the strawberries between 4°C and 12°C more strawberries are rejected at the retailer than at entering the warehouse, whereas storage temperatures over 12°C induce more food waste occurring at the warehouse.

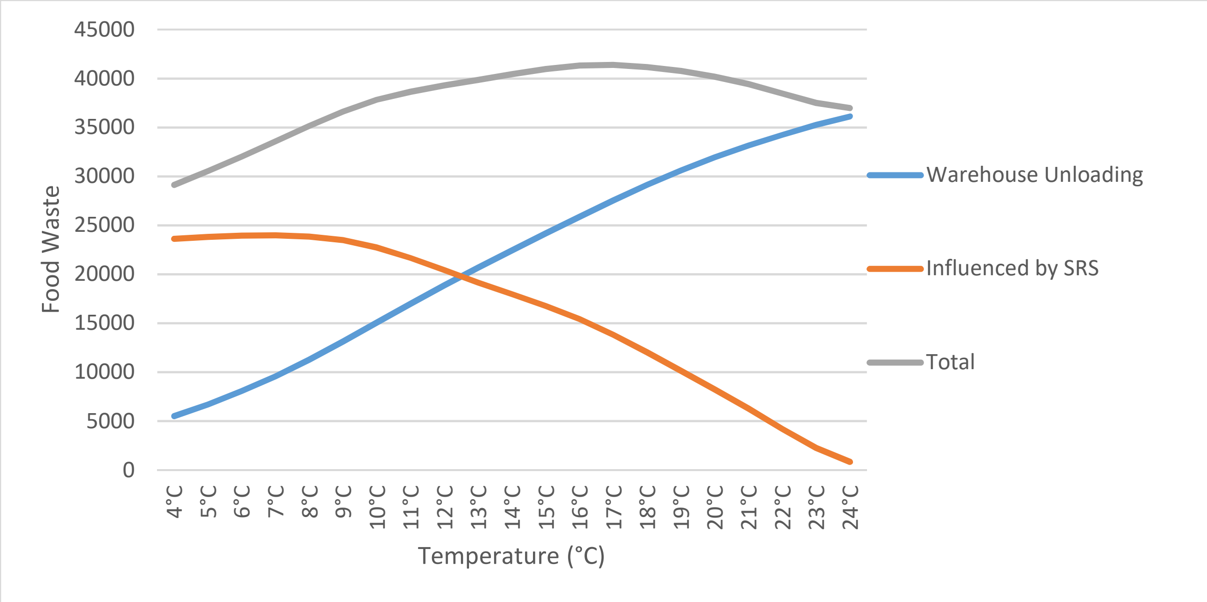

Figure 13 Food Waste Temperature Producer

Furthermore, Jedermann et al. (2014) state that immediate postharvest processes like pre-cooling and packaging might bring better benefits than the implementation of LSFO or FEFO approaches. Regarding the food losses by immediate pre-cooling possibilities of the producer, the total food losses are significantly lower by producer temperatures of less than 9°C than food losses occurring by applying the LSFO strategy. However, this study shows that producer temperatures between 10°C and 23°C raise the amount of total food losses.

6.6 Impacts of Closed Cold Chain and Direct Deliveries

Figure 14 visualizes the impacts of different supply chain designs on food waste. The normal supply chain is described in the experimental design, assuming LSFO stock rotation strategy and temperatures of 23.9°C (producer), 4°C (transport), 3°C (warehouse) and 10°C (retailer) as well as a batch and fleet size according to Table 8. The normal chain shows a very high amount of food waste by unloading at the warehouse, most likely due to the high temperatures at the producers. The direct delivery chain assumes that all deliveries are taken by the producers themselves with the same batch and fleet size as assumed in the normal chain. It shows to be the most inefficient strategy. The closed cold chain design assumes temperatures of 4°C throughout the entire supply chain by applying the LSFO stock rotation scheme. The amount of food waste at unloading the warehouse is significantly lower compared to the normal chain. However, the food waste occurring during storage at warehouse and at the retailers are higher compared to the normal chain. In contrast, the supply chain design named “Temp Prod” assumes the normal chain designed with cooling possibilities of the producers. Therefore, the temperature of the producer is set to 4°C. This chain design produces the lowest amount of food losses. A rise of 1°C (from 3° to 4°C) at the warehouse causes nearly the same amount of food waste as cooling the strawberries after harvest to 7°C.

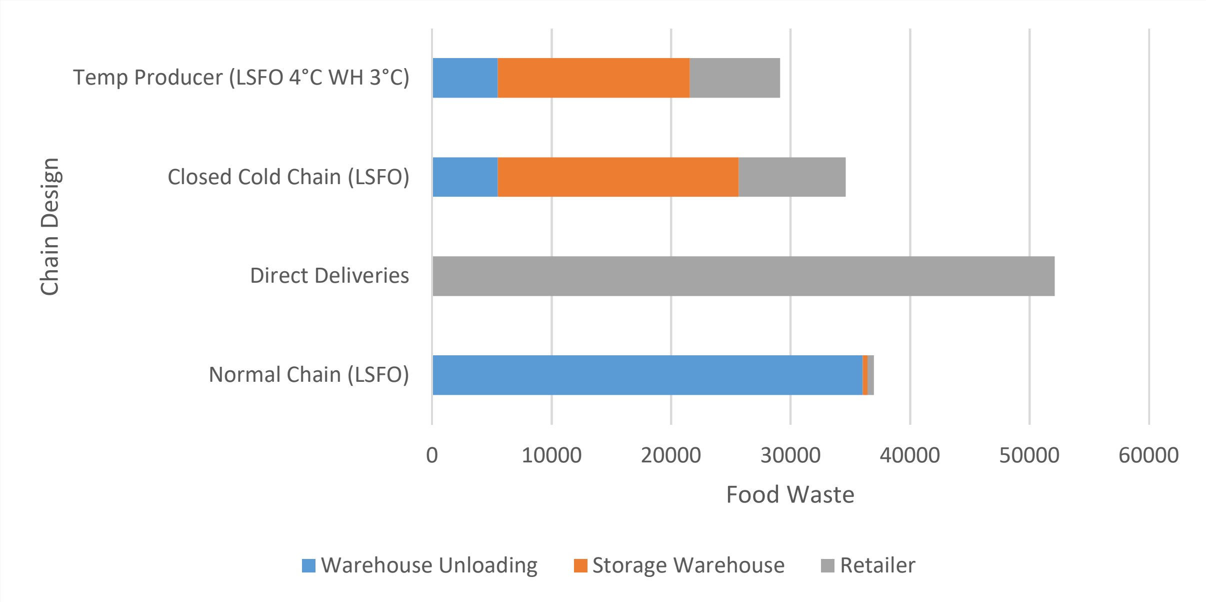

Figure 14 Food Waste Chain Design

Regarding direct deliveries, Table 12 shows that with increasing batch size, the total food waste can be reduced. Using three small trucks with a batch size of 45 or two trucks with a batch size of 75, the food losses diminish to zero. Nevertheless, this might induce higher transport costs and CO_2 emissions.

Total Food Waste	**Fleet Size**			
Batch Size	**1**	**2**	**3**	**Total**
45	52080	6159	0	**19413**
55	57714	4843	0	**20852**
65	47210	33	0	**15748**
75	26413	0	0	**8804**
85	9291	0	0	**3097**
95	6231	0	0	**2077**
105	5872	0	0	**1958**
115	3613	1	1	**1205**
125	781	3	3	**262**
135	42	9	9	**20**
145	24	22	22	**22**
Total	**19025**	**1006**	**3**	**6678**

Table 12 Food Waste Batch and Fleet Size Producer Direct Delivery

Jedermann et al. (2014, p. 11) state that 'the first step in creating minimum-loss cold chains is to avoid faulty and/or careless handling of goods'. Nonetheless, typical cold chains have to deal with less than perfect conditions, e.g., significantly varying temperatures, hardly pre-cooling, turned off cooling units of trucks overnight and different understandings of ideal temperature conditions at various points along the supply chains (Jedermann et al., 2014). However, the implementation of predicting keeping qualities of FFVs in decision support systems is of great importance, even if exact predictions are not possible. It enables to compare different scenarios. Hence, the best solutions can be derived and implemented.

Obviously, there is a trade-off between investing in the food supply chain and occurring food losses. To minimise overall food losses various, more or less, expensive investments in infrastructure, like bigger and/or more trucks with better chilling units and refrigerated storage houses at the producers, improved information management systems and sensor technologies for monitoring logistics conditions to better calculate shelf-lives are required.

7 Conclusion and Outlook

This work gives an example on how to integrate generic keeping quality models in simulation models to consider food quality and losses in redesigning fresh food supply chains. The strawberry fruit is one of the most perishable fruits worldwide with a very short shelf-life, even under perfect storage conditions. The shelf-life of strawberries is mainly affected by temperature as high temperatures increase the rate of fungal decay and lead to shriveling, color degradation, loss of aroma and taste. Along the strawberry supply chain, many of the fruits deteriorate before they reach consumers' plates. Considering the amount of resources implemented to grow the fruits, every wasted strawberry caused by inefficient chain design is one too much. Designing supply chains of perishables requires special considerations due to varying qualities and seasonable changing demand and supply. To integrate these uncertainties in redesigning strawberry supply chains, generic keeping quality models offer the possibility to calculate the remaining shelf-life as a function of time and temperature conditions. Within this thesis, the decay of strawberries is calculated as a function of the spoilage rate depending on time and temperature. Assuming linear reaction kinetics, this calculation is integrated in a discrete event simulation of the strawberry supply chain, beginning at the producers' fields (harvest), consolidating the strawberries in a warehouse and ending at the retail stores. By means of this study, different stock rotation schemes, chain designs and chilling possibilities as well as the infrastructures of producers and warehouses are tested and theeconomis impacts on food losses are analysed. The results show that the LSFO approach significantly reduces food losses compared to the FIFO and LIFO approach. Integrating cooling conditions at the producers' place as well as adequate batch and fleet sizes at producer or warehouse level can improve chain design and reduce overall food losses. Direct deliveries only make sense if the producers expand their batch and/or fleet size. However, they are likely to increase transport costs and CO_2 emissions. Nevertheless, the consolidation of FFVs in warehouses mostly lowers the qualities of FFVs due to longer transport durations. Furthermore, this study analyses the impacts of varying initial qualities of strawberries on the performance along the supply chain. Strawberries with already low qualities at the field are likely to become unacceptable on the way to the retailers. Therefore, local distribution or other purposes, e.g. further processing to juice, jam, compote or liquor should be considered. Further processing of fruits with low remaining shelf-life or low qualities can improve efficiency and reduce food losses.

Future works could expand the integration of generic keeping quality models in supply chain simulations to other fresh fruits and vegetables, using the same or other kinetic reactions. Additionally, with more detailed data, the generic keeping quality model can be expanded by implementing the impacts of relative humidity and levels of O_2 and CO_2. The effects of interrupted cold chains and varying temperatures during loading and unloading, could also be integrated in simulation models of fresh food supply chains. Furthermore, the LSFO approach should be extended and combined with routing optimization algorithms that assign FFVs with lower qualities to shorter routes and consider multiple stops. The integration of economic models allows to analyse the trade-offs between costs and reduced food wastage. The investigatory horizon could be extended to consider fluctuating demand and seasonable varying crops. Drawing attention on reducing food losses at the retail stores and at the consumers' place might also be a worthy aspect of future investigations.

Tables

Figures

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