Introduction

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Reducing food losses by intelligent food logistics

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The need to feed an ever-increasing world population makes it obligatory to reduce the millions of tons of avoidable perishable waste along the food supply chain. A considerable share of these losses is caused by non-optimal cold chain processes and management. This Theme Issue focuses on technologies, models and applications to monitor changes in the product shelf life, defined as the time remaining until the quality of a food product drops below an acceptance limit, and to plan successive chain processes and logistics accordingly to uncover and prevent invisible or latent losses in product quality, especially following the first-expired-first-out strategy for optimized matching between the remaining shelf life and the expected transport duration. This introductory article summarizes the key findings of this Theme Issue, which brings together research study results from around the world to promote intelligent food logistics. The articles include three case studies on the cold chain for berries, bananas and meat and an overview of different post-harvest treatments. Further contributions focus on the required technical solutions, such as the wireless sensor and communication system for remote quality supervision, gas sensors to detect ethylene as an indicator of unwanted ripening and volatile components to indicate mould infections. The final section of this introduction discusses how improvements in food quality can be targeted by strategic changes in the food chain.

1. Summary

Roughly one-third of global fresh fruits and vegetables (FFVs) are thrown away because their quality has dropped below an acceptance limit [1]. In the face of an increasing world population, this is totally unacceptable. A high share of these losses is related to non-optimized handling during supply chain processes. 'Shelf life' is a common term that relates to the number of days that a food product has left to be of 'acceptable quality' and safe to consume. The shelf life depends on the optimal temperature and transportation conditions of the FFV.

One concept for a better supply chain management solution is first-expired-first-out (FEFO), which was first introduced at the end of the 1980s. The basic idea is to apply stock rotation in such a way that the remaining shelf life of each item is best matched to the remaining transport duration options, to reduce product waste during transportation and provide product consistency at the store.

Variations in food quality and the remaining shelf life are calculated automatically from accumulated environmental condition data, such as temperature; the shelf life variations are then used by warehouse management software to match the shelf life variation to inventory rotation, routing and special handling. Owing to the lack of automated data capture and shelf life calculation systems to perform this task, FEFO has found very little practical application so far.

The current quality state of packed food is often hard to measure and is not visible from the outside. For example, a 'red' tomato might last for two more weeks in good condition or it might change to an unacceptable colour and texture the next day. In general, the remaining shelf life cannot be measured directly, yet it may be predicted by biological models calculating the effect of accumulated temperature and other influences.

The challenge in providing such an automated food quality supervision system requires a holistic approach. Experts from the fields of sensor systems, communication science, predictive biology and food technology have to cooperate with transport operators and managers of supply chains. In order to meet this challenge, projects such as the 'intelligent container' (§5*a*) have been initiated within the last decade. In this Theme Issue, we combine the results of implementing this prototype system with worldwide research by experts from various disciplines.

We start our discussion with an article providing a general overview of how the relationship between food quality losses and transport conditions can be modelled and how this information can be used to optimize the management of the supply chain [2]. The centrepieces of this Theme Issue are three case studies on how to reduce losses and improve quality by using better quality monitoring, biological modelling of the shelf life and FEFO adjustments:

— the first case study focuses on berries to illustrate how losses can be avoided by more effective pre-cooling management, shelf life modelling and stock rotation (FEFO in real operations), as well as accurate mapping and estimation of the product temperature [3];
— the quality changes of bananas during trans-ocean transportation can be described by the concept of green life, giving the time span until an unwanted ripening process takes place; in the second case study, we present models for green life and temperature prediction inside a loaded container and show how cooling can be improved by better packing [4]; and
— although most of the work is concentrated on FFVs, the same principles apply to the supply chain for meat products; in this case study, we present the application of a shelf life model covering the supervision of a chain, including four different truck transports and three distribution centres (DCs) [5].

Our combined research found that focusing only on shelf-life-dependent stock rotation is too narrow. Correct temperature management is a basic requirement that is often not met in practice. Product packing is often not optimized with regard to airflow and thus hinders the efficient cooling of the product, as we found in one of our case studies [4]. Furthermore, it should be verified whether the shelf life of the product could be extended by adequate post-harvest treatments. A review paper summarizes the current and emerging post-harvest technologies [6].

Finally, in the last four articles of this Theme Issue we focus on the communication and sensing systems required for remote quality supervision. Two of these articles focus on how sensing data can be wirelessly transmitted effectively. The first one introduces the overall technical system of the 'intelligent container' and communication protocols and discusses the problems and limitations, such as the high attenuation of radio waves by the high water content of FFVs and the limited lifetime of battery-powered sensors [7]. The second one focuses on how radio frequency identification (RFID) technologies ranging from passive to semi-passive to active can reduce energy consumption and provide cost-efficient solutions for wireless sensing [8].

For most environmental parameters, such as temperature, humidity, and CO_2 and O_2 concentrations, there are standard sensing devices at hand. However, an adequate solution, suited to online monitoring under the conditions of a packed food container, is still missing for some. In the last two articles of the Theme Issue, we look at two environmental factors not commonly seen in monitoring devices and applications. The gas ethylene is an important indicator of unwanted ripening and decay processes for many FFVs. In the related article, we present new approaches to mobile ethylene-sensing systems [9].

Finally, an opinion piece [10] discusses mould and acceleration as new sensory tasks. In contrast to the case of 'ethylene' with sensor systems available as prototypes or in the close-to-market state, there has been hardly any research on mobile detection systems for fungal infections. The article reviews new developments and thereby proves the general feasibility of mould detection by autonomous and miniaturized sensor systems.

Although sensors for shock and vibration are available, there is very little research to determine their quantitative effect on the shelf life. The article presents the first research results on how vibrations can be related to the quality attributes of beverages, for example.

In this introductory article, we summarize the key findings of the contributions to this Theme Issue and provide some more background information on the FEFO strategy and different approaches to shelf life modelling. Strategic supply chain management has received significant attention in other industries, such as the automotive and non-food supply chains, in recent years. Before we close with our conclusions, we discuss—as an outlook on future developments—how a food quality view of strategic management might be applied.

2. The challenge to avoid losses in the food chain

Malnutrition in many countries and the increasing world population demand better solutions to avoid food waste. According to a rule of thumb given by Gustavsson *et al.* [1], *roughly one-third of food produced for human consumption is lost or wasted globally*, based on an analysis of the data from the *FAO statistical yearbook* [11]. Studies related to single countries show a large variation in food losses, but their sum supports the rule of thumb given by Gustavsson. The total food losses in the USA sum up to 40% [12]; losses of grain were estimated at 19% in China [13]. Parfitt *et al.* [14] listed seven studies on the losses of FFVs indicating average losses between 14% and 70% per product.

Food losses can be attributed to two main factors: (i) waste owing to oversupply and (ii) losses owing to the natural decay of food products, which cannot be stopped but are accelerated especially by lacking or poor temperature management or unhygienic conditions.

Oversupply plays an important role in affluent economies [14], where people can afford to throw food away. This relates to producers, retailers and consumers:

— products of perfect nutritional quality, but with cosmetic defects, such as bent carrots, are sorted out during production; to avoid being 'delisted', food manufacturers will often overproduce in case extra quantities are required at short notice [14];

— retailers conduct no forecasting of their demand and aim to have overstocked product displays [12]; and

— consumers purchase, cook and serve more than they actually need or eat [14]; consumer losses are in the magnitude of between 8% and 28% for FFVs, meat and fish [1].

Unnecessary losses of shelf life can also be found in any part of the chain, especially with regard to temperature management:

— farmers do not pre-cool after harvest; the 'cut-to-cool' time is recognized as being very important for many commodities [3] but is typically not monitored effectively;
— the actual temperature conditions during transport and storage often do not meet the optimal product-specific values; and
— customers keep fresh products for hours in the warm boot of their car or set the temperature of their fridge to achieve minimal power consumption, thus ignoring the recommended storage temperatures.

Several initiatives have been taken to remedy the first problem, especially in the UK by the waste reduction action plan. This initiative worked on improving the consumer's discernment of 'use-by' and 'best-before' labels to avoid unnecessary waste [15]. A further programme was set up to foster information exchange between retailers and suppliers with the aim of providing more accurate and timely demand forecasting [16]. The effect of such vertical information exchange was also evaluated by Kaipia *et al.* [17] in three case studies in Nordic countries. They showed that losses at retailers could be largely reduced by an automated demand forecast based on a better information flow.

However, the second problem of accelerated shelf life loss, which is related to this issue, has been paid insufficient attention. The cold chain will become more important in the future owing to two factors given by Parfitt *et al.* [14]: (i) as people's income grows, they diversify their diet to less 'dry' starchy products, such as rice, potatoes and cereals, to more FFVs, fish and meat, requiring chilled transportation and (ii) whereas food is often sold the same day at local markets in rural societies, urbanization requires longer and more complex supply chains.

Problems arising from long transport distances will require increased attention in the future, owing to the globalization of the food supply chain with distant production locations, especially during the consuming country's winter season, as production comes from locations in the opposite hemisphere.

The cold chain, as defined for the purpose of this Theme Issue, ideally starts directly after picking from the field or at slaughter and ends in the retail cabinet of the local supermarket. Cold chain ruptures can have a dramatic effect on food quality and losses, as Huelsmann & Brenner [18] showed in a literature survey. They found more than 100 reports related to problems during storage (e.g. wrong temperature management) and transport on the ground (e.g. blocking of the airflow by wrong pallet positioning), by ship (e.g. a reefer container requires two weeks to reach the temperature set point) and by air (e.g. high temperature variation during flight operations).

Nevertheless, a quantification of the average losses along the cold chain is hard to find. Gustavsson *et al.* [1] split losses in the supply chain into five categories. Losses during distribution vary between 4% and 15% for FFVs, meat and fish depending on the region and product group. However, they did not list cool chain losses as a separate category. So part of the category called 'post-harvest handling and storage' with losses of between 0.5% and 10% should be added to the distribution losses in order to obtain a raw estimation of the total cool chain losses.

Furthermore, the problem of hidden shelf life losses has to be considered: the effect of poor handling might only become visible in the next stage of the chain; shelf life losses are often not visible from the outside. Therefore, if the customer buys tomatoes planned to last for one week but throws them away after 2 days because they have become unsightly, the blame should lie with the cold chain partners, not the customer.

3. Making use of shelf life information for supply chain planning

The basic idea behind this Theme Issue, of how the unacceptable amount of food losses can be reduced by intelligent food logistics, is rather simple. Information about shelf life losses based on monitored environmental data, such as temperature, should be used to adjust transport and chain processes, as long as it is still possible to take action before the food quality drops below
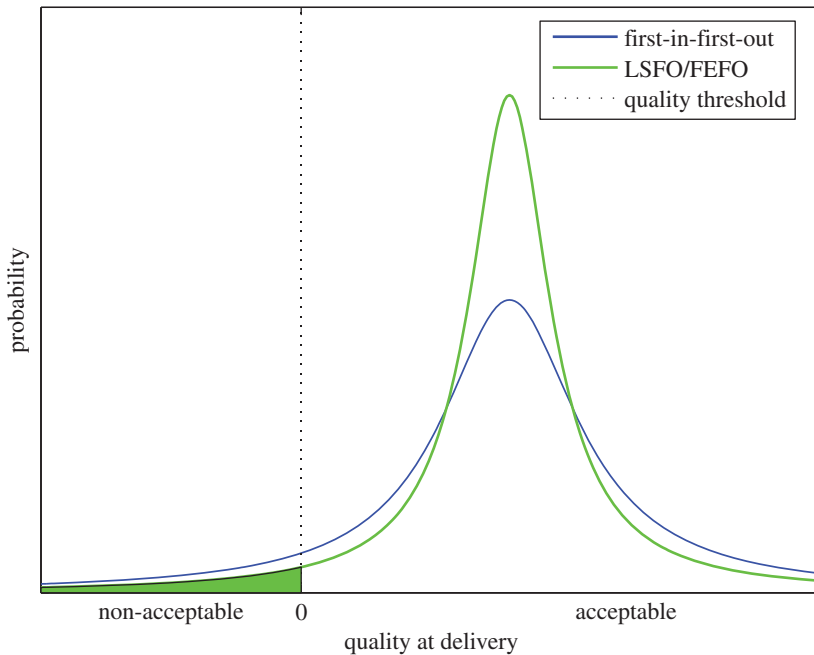
Figure 1. Effect of quality-based schemes for stock rotation (schematic, axis not to scale). The share of non-acceptable products at delivery can be reduced by the LSFO or the FEFO strategy according to Labuza & Taoukis [22]. (Online version in colour.)

an acceptance threshold. Items in a critical state can be assigned to shorter transport routes to prevent losses and to provide consistent quality to customers. However, the implementation of this concept requires several elaborate steps and the cooperation of scientists from different fields.

The shelf life mainly depends on temperature deviations during transport and storage [2]. Simply knowing the maximum or peak temperature as measured in most commercial supply chains is not particularly helpful. A short peak of a few minutes during loading hardly affects the shelf life, whereas a deviation of 1–2°C lasting over several days does. Time temperature integrators (TTIs), dating back to the 1970s [19] and earlier, were the first devices to give a visual indication of temperature-related shelf life losses. TTIs are usually provided as stickers that can be attached to perishable products. The surface shows a colour indicator and a reference scale. One current TTI, the Blue Dot [20], uses a colour pigment that is decomposed by a chemical reaction depending on time and temperature similar to the product to which it is attached. TTIs were originally only used to verify that the product had not been exposed to the wrong temperatures over a longer period.

To our knowledge, the idea of using this type of shelf life information to improve warehouse management was first proposed by Taoukis & Labuza [21] at end of the 1980s and is explained in more detail in [22], as follows.

Standard inventory management and stock rotation schemes assume that *all products have gone through uniform handling, thus their quality is basically a function of time alone*. The oldest products, which came in first, should be sold first (FIFO). Labuza & Taoukis [22] suggested a strategy in which the products with the shortest remaining shelf life are sold first. They coded their approach as 'least shelf life, first out' (LSFO).

It is not possible to increase the average product quality at the point of time of delivery by changing the sequence of delivery, but the variation in quality can be reduced (figure 1). In the ideal case, orders are organized in such a way that all the items of one type of product are delivered with almost identical quality states.

This approach reduces the share of products for which the quality state has dropped below the acceptance threshold before delivery (the shaded area in figure 1). The shape of the curve and

the reduction of losses by decision-making based on shelf life information were experimentally verified by Koutsoumanis *et al.* [23] in 2002 in a study on the delivery quality of sea bream. A quantification of the advantages of FEFO management by the percentage of avoided losses is unfortunately not as straightforward as some might assume. A later study by the same group [24] showed how several parameters of the cold chain, as well as their statistical variation, have to be taken into consideration.

Owing to the limited technical capabilities of TTIs, the LSFO approach required more than 10 years to reach its first practical applications. TTIs have an inherent limited accuracy because it is extremely difficult to match exactly the temperature dependency of the chemical reaction for decolourization of the tag with the reactions that are responsible for the quality decay of the real food product. TTIs can only report the current quality state, not when and where temperature abuse has happened. Furthermore, they have to be read manually and can therefore not be integrated into automated planning systems.

The advent of wireless sensor nodes at the beginning of this century gave a new push to shelf-life-based strategies. Similar concepts were published by Emond & Nicometo [25] and Scheer [26] under the term FEFO to stress the difference from standard FIFO planning. The term 'dynamic FEFO' was introduced by Lang *et al.* [27] to stress the point that delivery assignment is not fixed, but can be modified at any time according to new information on shelf life deviations. Besides arranging the order of deliveries based on the current shelf life, the expected duration of succeeding transport processes was also taken into consideration. The relation between shelf life and structural changes in the supply chain has hardly been the focus of research so far. Some general ideas will be discussed in the last section of this article.

In the following, we will take a closer look at the previously mentioned study on cooked ham [24] and compare it with other studies about the benefits of FEFO. Two decision points in a supply chain for cooked ham were considered in a Monte Carlo simulation study. Products from the initial shipment are split in half at the first decision point and forwarded to different retail markets, either close by or further afield as exports requiring longer transportation. The second decision point is installed in the retail stores. Packets are placed in retail cabinets immediately or after 12 or 24 h. The probability distributions of the chain parameters were estimated by field studies. During the simulation, variations of parameters, such as the initial bacterial load after production, transport duration on different routes, temperature variations in different steps and distribution of time and temperature in domestic fridges, were considered. If decisions at the two points are made based on the product's time–temperature history, the share of product with a critical bacterial load could be reduced from 16% to 8%, compared with an assignment that is solely based on product age (FIFO). This approach not only increases the shelf life, but also reduces the risk of food pathogen-related illness.

A later similar study [28] showed that the share of gilthead sea bream with a non-acceptable bacterial load could be reduced from 15% to 5%.

A study by the University of Florida, USA, and Ingersoll Rand, USA, analysed the effect of shelf-life-based decisions at a DC for strawberries [25,29]. The operator decides whether the strawberries are sold immediately or forwarded to local or remote customers. Compared with a random delivery, in the case of absence of quality information, losses could be reduced from 37% to 23%.

Tromp *et al.* [30] calculated in a simulation study that the sum of losses resulting from an unacceptable bacterial load, necessary price discounts and out-of-stock losses could be reduced from 17.1% to 3.8%, if the fixed expiry date is replaced with a dynamic one. These four studies are summarized in figure 2.

4. Definition and selection of the shelf life model

The term 'shelf life' may be confused with 'best-before' or 'use-by' dates. The latter give a fixed date as guaranteed by the producer, whereas the shelf life is a dynamic value related to the actual quality and environmental condition history. The shelf life gives the time span for which the
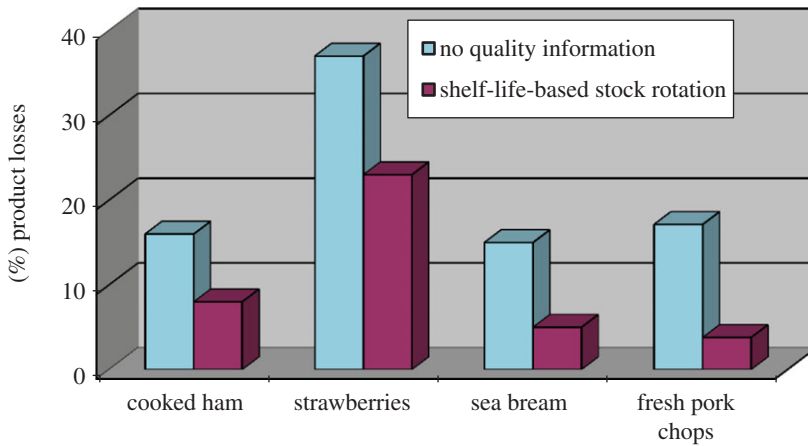
Figure 2. Comparison of the share of product losses for cooked ham [24], strawberries [25], sea bream [28] and fresh pork chops [30] with (i) random delivery owing to a lack of quality information and (ii) shelf-life-based stock rotation according to the FEFO approach. (Online version in colour.)

product can be stored at a certain reference temperature until (i) it is no longer suitable for human consumption, (ii) the customer would refrain from buying it in the store or (iii) the customer will no longer use it at home and will throw it away. The acceptance threshold depends on local preferences and might change over time. A product with reduced quality that is accepted in most parts of the world might be rejected in high-income countries.

The acceptance threshold must be defined in a product- and consumer-specific way. It can be based on biochemical or physical properties such as colour or loss of chlorophyll, firmness, bacterial growth or nutrition content, or it can be defined from a consumer perspective on properties such as appearance, texture and taste.

The aim of a shelf life model is to predict the time span that is left in total for transport, storage, display in the shop and storage in domestic fridges as a function of the environmental conditions to which the product was, or may be, exposed if such information is available.

There has been a vast array of research on shelf life models in the past two decades. For example, Tijskens & Polderdijk [31] published a list of model parameters for 60 FFVs in 1996. A review of the existing shelf life models for berries, for example, can be found in [3].

Although most of the models presented in this Theme Issue [2–5] include factors such as humidity and atmospheric gas concentrations, they all agree on the point that temperature is the most critical factor influencing quality. The spread of models presented in this Theme Issue shows that there is no unique approach.

One common approach is to relate shelf life to respiration activity [3]. It is assumed that the speed of ageing processes increases proportionally to the increase in the CO_2 production rate at higher temperatures. The temperature dependency can then be modelled by an exponential function with the Q_{10} value as the key parameter, such that, for every $10°C$ increment in temperature, the product's shelf life is reduced by a factor given by the Q_{10} parameter. From a more general standpoint, the Q_{10} parameter can either be defined by the measured CO_2 rates or by measurement of a quality attribute [4] at different temperatures.

The temperature dependency can be modelled more accurately using the law of Arrhenius for reaction kinetics [2]. The model can contain differential equations or common functions for bacterial growth [3]. A shelf life model can be based on a single attribute only. However, in order to cover a wide range of environmental conditions, multiple quality factors should be considered. Depending on the conditions, different factors, such as colour, firmness or taste, can limit the shelf life [3]. Similarly, the model can be based on sensory evaluations of quality attributes by trained tasters [5].

More complex models can provide better accuracy, but in general they contain more parameters that have to be evaluated experimentally. The selection of a model is therefore also a question of the amount of available data or the budget to carry out laboratory tests as well as the technical capabilities of the monitoring hardware for recording and processing of environmental data. For example, if no product-specific model is available, the Q_{10} model can serve as a starting point with only two required parameters for the initial shelf life at the reference temperature and the Q_{10} value for temperature dependency.

It is important to note that different pre-harvest conditions influence factors that could not be measured and biological variance causes a certain amount of uncertainties in the shelf life prediction, which even complex models cannot remove. Whereas for some products quite accurate shelf life prediction is possible [3,5], the model for bananas is overlaid with uncertainty of several days [4]. Nonetheless, even if an exact prediction is not possible, the models are of great importance for organizing stock rotation and prioritizing containers in a critical state for unloading. For example, should a container with a temperature deviation of 1°C lasting over 10 days or a container with a deviation of 5°C over 2 days be handled first, or do both deviations have the same effect? A predictive model can calculate the shelf life for both scenarios and thereby evaluate which of them is the most harmful. This comparison does not require absolute accuracy and will be possible even if the model uncertainties are too high to predict the exact date and hour when the product will pass the quality acceptance threshold.

Accumulated exposure to higher than optimal, or planned, temperatures results in 'physically invisible' advanced shelf life loss. Common, hands-on visual inspection does not show the accumulated shelf life loss, so a product that looks good is treated on a FIFO basis. When time and temperature data are captured from the point of harvest or production, using even the simplest forms of shelf life modelling, the normally invisible variations in advanced shelf life loss are exposed, empowering logistics systems and managers to adjust the remaining transport time for products, matching products with a shorter shelf life to shorter routes and holding products with a longer shelf life in inventory or sending them on longer transport routes. In effect, assigning deliveries based on a shelf life prediction overlaid with uncertainties is always better than performing the same job with two blind eyes by ignoring the temperature history because either no record or no method to compare and evaluate the data is available.

(a) Key findings of the article on shelf life modelling for warehouse management

The second article in this Theme Issue investigates the components required for the integration of shelf life modelling into supply chain management [2]. It introduces a generic shelf life model for multiple environmental influence factors. FEFO is discussed from the perspective of information flow. The FEFO approach is extended to the problem of finding an optimal distribution solution for a particular FFV in a typical commercial supply chain consisting of multiple DCs and customers. The authors analysed the complexity of this problem and showed that an exhaustive search of the cost function, such as the total waste percentage or the average quality of products delivered to the stores, is computationally feasible and is reduced to a combinatorial optimization problem.

5. Projects on remote sensing of food quality

RFID tags have already found a wide application for the tracking and tracing (T&T) of non-food items, such as apparel, in the retail industry [32]. The extension of RFID from pure identification to sensing devices, as well as the application of biological models to food chain supervision, has been in the scope of several research projects during recent years.

The Pasteur project, funded from 2009 to 2012 within the European CATRENE framework, had the goal of developing a smart sensor tag, containing temperature, pH, humidity and gas sensors. The tag could be wirelessly read out by RFID functionality. Models for food quality prediction were developed and translated into algorithms that can be implemented on an RFID chip [33].

The European project CHILL-ON, funded from 2006 to 2010, focused on the avoidance, detection and prediction of food safety hazards in fish and poultry supply chains. Improved chilling technologies, rapid microbial detection techniques and a remote temperature monitoring system were applied to achieve these goals. An assessment of shelf life and food safety risks was conducted (i) by decision support tools based on mathematical models to calculate the growth of relevant food pathogens and (ii) by combining a TTI label with an RFID interface for automated, wireless readout [34].

Other projects have focused on active wireless sensor technologies, mainly because of their greater communication range. For example, a discussion of telematics systems for trucks and containers with additional sensing capabilities can be found in [7] in this Theme Issue. The topic of shelf-life-based supply chain management is still of great interest, as recent research articles on the economic [35], biological [36] and technical [37] aspects show.

(a) The 'intelligent container'

A parallel approach for integration of all the required electronics and the decision system into a reefer container has been under development at the University of Bremen, Germany, since 2004 [27,38]. The first field tests of this concept for an 'intelligent container' started in 2008. A new project, funded by the Federal Ministry of Education and Research in Germany, with an extended consortium of six research and 22 industrial partners, was initiated in 2010 and completed in June 2013 with the aim of providing a full-scale prototype and carrying out field tests for different food products.

The overall system of the 'intelligent container' consists of (i) a network of wireless sensors, installed inside or on the surface of food pallets to monitor deviations of temperature and other parameters, (ii) a freight supervision unit, installed inside the container, to evaluate the measured data and to calculate a shelf life prediction for the transported commodities, (iii) a telematics unit for external communication by the global system for mobile communications (GSM) or satellite networks, and (iv) a remote server for web access and integration into company databases [7].

The consortium included institutes from the fields of microelectronics, communication science, operational research, agricultural technology and animal science. The industrial partners included transport operators, fruit importers, delicacy retailers and providers of database services, embedded software, wireless sensor systems and communication and telematics systems.

The case studies on the supply chains for bananas [4] and meat [5] and the article on communication techniques and challenges [7] originated from this project. In addition, the article on ethylene sensing [9] was written by a cooperation of researchers from this project and other leading groups in gas sensing. To complete the full spectrum of articles included in this Theme Issue, we invited international experts from the USA, Belgium, Sweden, France, South Africa and Australia to participate.

6. Case studies

In addition to shelf life modelling research and technology development, case studies, in which such knowledge is applied to different commodities, are equally important as the advantages and potential of quality supervision can be clearly demonstrated. In this Theme Issue, we discuss the following three case studies on the supply chains for berries, bananas and vacuum-packed lamb.

(a) Key findings of the case study on berries

The first case study is based on an analysis of temperature and shelf life variations in a supply chain for blackberries [3]. The authors showed that the differences in pre-cooling, transport temperatures and the position in the truck led to tremendous variations in quality, resulting in 57% of the berries arriving at a packing house without sufficient remaining shelf life for the

longest transport routes. If the affected pallets are not reassigned to shorter routes according to the FEFO approach, there are significant avoidable losses.

The authors compared the benefits of some different shelf life prediction models. Especially for berries, it is necessary to include multiple quality attributes, such as colour, weight, taste and odour, to achieve a good level of accuracy. Furthermore, in order to make accurate shelf life predictions based on the temperature history for all the products, the sensors need to be placed in a variety of locations inside the shipping pallet. However, placing temperature loggers inside the centre of the pallet is often not possible in commercial supply chain processes for a number of reasons. The authors showed that an accurate temperature prediction can be calculated by an artificial neural network approach with the measurements of ambient or surface sensors as inputs.

(b) Key findings of the case study on bananas

The prototype of the 'intelligent container' was tested for the supervision of the transportation of bananas from Central America to Europe [4] in the second case study. Bananas have the characteristic feature of continuing to produce large amounts of heat by respiration processes after being harvested. The balance between the generated respiration heat and the amount of heat removed by cooling was calculated based on a mathematical model for individual pallets equipped with wireless sensors. The model predicts which pallets are at risk of turning into a hot spot, from which the generated heat can no longer be removed by cooling.

The second important finding was that less than 10% of the available cooling capacity of the unit actually arrives at the bananas in the centre of a pallet load. The cooling efficiency could be improved by as much as 50% with better packing and loading schemes.

Bananas turned out to be a very stable product as long as the peel colour remains fully green. A direct measurement of the remaining days of green life, until unwanted ripening starts, is not possible. A green life prediction based on the temperature history can only be calculated with an uncertainty of a few days. Based on the prediction of the hot spot risk and green life, containers can be prioritized for unloading. If no risk is detected, further processing steps can take place directly in the same container. The general feasibility of container ripening was verified during three field tests.

(c) Key findings of the case study on meat

The third case study focused on a supply chain for vacuum-packed lamb within Europe [5]. This type of shelf life model depends very much on the product and packing. Under vacuum-packed conditions, no specific spoilage organism could be identified. Therefore, the bacterial growth model had to be excluded. Quality changes in regard to product age and storage temperature were evaluated by trained testers. Fitting with a linear model for time and Arrhenius-type temperature dependency resulted in a model with quite a high degree of accuracy (with a coefficient of determination R^2 between 0.88 and 0.93).

This case study is an example of a networked supply chain, including cross-docking, deconsolidation and consolidation processes by three DCs and a total of four truck transports. Possible decision points were identified during a process analysis.

The presented sensor solution provides 'online' and 'offline' modes depending on the available infrastructure inside trucks and warehouses. Temperature data and a shelf life prediction can be read out by a handheld device or transferred to a decision support tool on a remote server depending on the network availability.

7. Side effects of first-expired-first-out analysis and additional measures

The implementation of smart distribution practices, such as FEFO, should start with a complete analysis of the supply chain process and environmental conditions. The analysis should include the monitoring of deviations of the product temperature along the chain by data loggers or

wireless sensors as the first step. The second step is the evaluation of the related effects by biological models. The results of the analysis will reveal where most of the shelf life is lost in the chain.

Critical processes should be addressed directly with the goal of providing the best product handling and treatment practices for the best quality. Often, a large share of the shelf life is lost owing to poor temperature management, as discussed in the following section. As mentioned in the case study on bananas [4], further measures can be taken, such as extending the shelf life by adequate post-harvest treatments, in this case transport in a controlled atmosphere (CA). An analysis of the dynamic temperature inside the pallets showed that a large amount of cooling capacity is 'lost' by inefficient packing. Simple modifications of the box design improved cooling by approximately 10%.

(a) Verify temperature management

The first step in creating a minimum-loss cold chain is to avoid faulty and/or careless handling of goods. In a typical chain monitored by environmental loggers, one can observe a combination of less than ideal situations, such as significant temperature variations, little to no pre-cooling prior to loading the product in the shipping container, truck drivers turning off the cooling unit overnight to save fuel and different personnel at various points in the cold chain (such as harbour crew versus ship crew) having different instructions about the ideal temperature set points for the product.

Continuous temperature monitoring from producer to retailer is a pre-condition for FEFO, but it will also reveal such obvious mistakes. A systematic analysis of the performance of the chain processes can be performed by evaluating it according to a standardized index, such as the cool chain quality indicator (CCQI) [39]. The CCQI includes factors such as the instruction and training of personnel, the age of the equipment, the existence and suitability of maintenance schedules, hygienic maintenance, manual or automated temperature measurement and recording, and the existence of emergency response plans.

(b) Key findings of the article on post-harvest treatments

Various means of post-harvest treatments are available to extend the shelf life, depending on the type of product [6]. They include one-time treatments such as heat, irradiation, chemicals and gassing with ethylene or its antagonist 1-MCP to initiate or block ripening processes. The authors also included emerging technologies, such as ozone and plasma treatment.

Gaseous treatments especially are applied continuously by maintaining modified or controlled atmospheric conditions with CO_2 increased (fruits) and O_2 either reduced (e.g. fruits) or increased (e.g. meat) by specially equipped containers or warehouses. Packing the fruit in films with determined gas permeability can also be applied to create the desired atmosphere, either by self-respiration or by introducing the atmosphere into the package headspace before sealing. These treatments in combination with an appropriate temperature control are the basis for maintaining quality and reducing decay incidence.

(c) The need for continuous temperature and quality supervision

Improving the immediate post-harvest processes, such as pre-cooling and packaging, based on one-time temperature mapping, might bring higher benefits in the end than the more sophisticated implementation of shelf-life-based stock rotation.

However, it needs to be noted that, even when the best practices are identified and implemented, there are unavoidable variations in post-harvest handling, owing to weather, peak supply with limited manpower, etc. Because of the unavoidable variations in some of the cold chain processes, time and temperature data collection, coupled with automated calculation of shelf life loss variation, will continue to generate significant process benefits in real time while

reducing the avoidable shelf life loss. In order to keep the process as efficient and effective as possible, a continuous audit, based on both current and past temperature and quality data, is necessary.

Furthermore, shelf life variations by natural biological variance cannot be avoided. For example, for bananas we found variations of several days in the green life. These unavoidable deviations should be handled by dynamic measures, i.e. smart quality supervision, intelligent stock rotation or the reassignment of deliveries according to the FEFO strategy. In the final section of this article, we return to this issue and present an outlook on how the improvements of chain processes can be examined from a strategic management perspective.

8. The technical system: sensors and communication

For all the shelf life models, FEFO strategies and case studies described above, the crucial first step is the selection of the front-end system to remotely monitor the environmental conditions. The communication system for wireless and remote access to the sensors has to be adapted to the generally more difficult requirements of densely packed food products. Furthermore, for some products it is necessary to extend the sensory capabilities because even though temperature and humidity stand out as the most important external factors affecting the product quality and remaining shelf life, the monitoring of other environmental factors, such as ethylene gas concentration [9] and mould [10], can be just as crucial.

(a) Single or multi-hop communication?

We start our consideration with a look into the general design considerations for the communication system. The choice of the first tier of the communication system depends basically on whether the sensors attached to freight can be communicated with directly or only via forwarding over multiple hops, e.g. for sending their measurements to a data collection unit mounted inside a truck or container.

If reliable data transfer can be guaranteed by direct single-hop communication, this method should clearly be preferred. Simpler radio protocols lead to lower energy requirements and thus longer battery lifetime at lower costs. Even battery-less systems by passive RFID technologies are possible for this type of communication [8]. But, unfortunately, the radio links are often too weak for reliable direct communication, owing to the high water content of food products. In fact, an important first step, to test radio link quality before system application, is often left out, and system planning directly jumps into either a cost-efficient RFID system or an elaborate system providing multi-hop communication. A well-founded decision should be based on an analysis of radio signal attenuation in the target set-up [7], depending on radio frequency, product, packing, water content and sensor placement.

(b) Surface or core measurement?

Because shelf life is related to product core temperature, sensors should ideally be placed in the centre of boxes or packing units. On the other hand, sensors on the surface of pallets or boxes are easier to install and less affected by signal attenuation. do Nascimento Nunes *et al.* [3] present an approach to predict the centre temperature by surface measurements. However, for some fruits which produce a significantly varying amount of heat by respiration activity, a prediction cannot provide the required accuracy and a direct measurement inside the box centre is preferred, resulting in the need for multi-hop communication.

(c) Key findings of the article on communication techniques and challenges

Jedermann *et al.* [7] described a remote environmental monitoring system with the example of the 'intelligent container'. They highlighted the challenges owing to the physics of how radio

frequency waves interact with FFVs that are naturally high in water content. A model calculation for signal attenuation shows that the commonly used 2.4 GHz frequency range is less suitable for FFVs and lower frequencies should be preferred. Network protocols should be based on open standards in order to avoid confusion by proprietary solutions. Special attention has to be paid to the radio uptime for multi-hop protocols, giving the time span during which the radio chip has to be powered to transmit or listen for incoming messages. With the example of a wireless IPv6 protocol, they showed how the radio uptime and thereby the energy consumption can be analysed and further optimized.

(d) Key findings of the article on radio frequency identification-enabled wireless sensing

Similarly, Zou *et al.* [8] considered a complete internet-of-things platform and discussed different RFID technologies, such as passive, semi-passive and active, based on their cost, frequency of operation, power consumption and communication range. The article reviews the existing state-of-the-art technologies in the RFID domain and the future trends for wireless sensor systems specifically for monitoring perishables in the cold chain. They concluded that the biggest obstacle facing wide-scale adoption of monitoring technologies in the food chain is the cost and they showed that there are existing, though not yet completely developed, RFID technologies that can enable wireless monitoring systems at a much lower cost, e.g. by integration of ultrawide-band communication. The ultimate solution will have extended functionalities, such as on-tag algorithm processing or multiple environmental sensors for a reduced cost, and instead of a single prevailing technology, a combination of passive, semi-passive and active RFID will be needed based on the requirements of each application.

(e) Key findings of the article on ethylene sensing

The detection of a low concentration of ethylene in the parts per billion range will give crucial information about the quality state of climacteric fruits, such as bananas, and help to improve the accuracy of shelf life prediction. However, high-resolution measurement is currently restricted to stationary and expensive laboratory equipment.

The article on ethylene detection in fruit supply chains [9] summarizes the research of three independent groups on high-resolution ethylene-sensing systems suitable for mobile applications. Future systems for installation inside reefer containers or transportable systems for detection in harbours or warehouses can be based on infrared, electrochemical or miniaturized gas chromatography systems. The systems' costs will be far below those of stationary gas chromatography or photo-acoustic systems.

(f) Key findings of the opinion piece on the detection of mould and effects of vibrations

The detection of fungal infections in an early state is currently possible only by using offline laboratory tests. The last paper in this Theme Issue [10] identifies two candidate technologies for a mobile system, which can be either applied as handheld equipment or installed inside a container. The first approach is based on a miniaturized device for automated sample taking on a culture medium. An alternative solution combines the measurements of microbial volatile organic compounds with a combined set of micro-fabricated gas sensors. Both technologies are still at the beginning of development and require further research efforts. Mechanical shocks can have a direct effect through packaging breakage or mechanical damage to food products. However, persistent vibrations of lower amplitude can also have a less obvious but also negative effect on quality, e.g. red cells in blackberries and pink rips on lettuces. The final article focuses on presenting the first research results on vibration-related changes in the quality attributes of beverages as an example.

9. The next steps

So far, we have considered the supply chain as a static network with multiple suppliers and routing paths, by which customer needs can be served. Hertog *et al.* [2], in this Theme Issue, show that in this case the FEFO approach can be reduced to a *combinatorial optimization problem* of moderate complexity for typical supply chain scenarios. The FEFO management can be included in the existing delivery planning software. The shelf life at the time of delivery can be seen as an additional key performance indicator for the optimization process.

The planning of deliveries is often related to time windows: customers have to be served within an individual time frame given by the retailer's working hours. Existing algorithms can also easily be extended to include the shelf life because the shelf life is just another time window during which the product has to be delivered in an acceptable state.

However, we can take one step further and ask what happens if we change the links of the supply chain itself, for example if another transport operator might provide a better quality of service at a higher cost. Alternative transport modes will need to be considered, e.g. replacing expensive air freight with sea transportation under CA conditions. Additionally, DCs can be replaced by direct deliveries or vice versa. In such a scenario, the structure of the network becomes part of the optimization problem.

(a) Strategic supply chain management

Similar questions have been handled under the term 'strategic supply chain management' but in a non-food-specific context. The availability of enterprise resource planning (ERP) systems, providing the tools to monitor and control the chain better, has triggered a revolution in supply chain management since the 1990s.

In particular, the automotive industry promoted new strategies, such as just-in-time deliveries and make-to-order. Strategic supply chain management is an umbrella term, including several methods, with no clear definition, especially in the case of perishable products.

According to Cohen & Roussel [40], one of the key methods is to comprehend the supply chain not just as something to transport items from A to B at the lowest possible price, but also as a strategic asset. Having a better supply chain than one's competitors is an opportunity to gain a higher market share, for example, by being able to provide new products to the market faster, being able to produce and deliver customer-specific products with lower lead times or just being able to deliver better quality products.

(b) Price or quality leadership?

According to Cohen & Roussel [40], companies should decide on a single primary basis of competition with their supply chain. Among the four listed targets of competition, quality and cost leadership are the most relevant to food chains.

Although the food market is said to be facing a severe price war, with retailers operating on extremely high revenues but low profit margins, there are several examples to prove that striving for cost leadership is not the only option.

— The increasing market for organic food shows that customers are willing to pay a higher price for better quality.
— The British retailers Tesco and Sainsbury's started in 1992 to give a 7 day vase life guarantee for their flowers. Because of the guarantee to replace the purchase if the flowers wilted earlier, they were able to increase their market share from 18% to 60% over 15 years, while the total flower consumption in the UK doubled in this period.
— The company Barlean's managed to achieve an increase in turnover of organic oils of 40% per annum at the end of the 1990s by identifying 'freshness' as the key competitive differentiator in the market [41]. Its linseed oil is only pressed on demand and delivered

by express. Owing to this fast handling, it was able to provide only slightly processed oil, resulting in a higher freshness level but a lower maximum shelf life of only four months, whereas their competitors cannot provide a similar degree of freshness because their distribution processes take up to five months.

The most important observation is that independent of the company's priorities in leadership, whether low cost or high quality, FEFO can be applied in both cases either to reduce costs by avoiding waste or to make sure that only adequate and consistent quality is delivered.

(c) Simulation studies

There have been various attempts to calculate the effects of changes in the supply chain by simulation studies [24,42–44]. The supply chain scenario can be described as a series of events, such as incoming new orders, the arrival of a truck at a warehouse or the expiration of the shelf life for a certain item. A decision-making agent assigns orders according to a predefined strategy. The simulation has to include the movement of physical objects (pallets and trucks) as well as the information flow (who is informed at which point of time).

The agro-logistic analysis and design instrument (ALADIN) simulator [43] embeds food quality models with logistic processes. It also provides the feature of including the uncertainties of shelf life models caused by biological variance and varying temperatures inside one pallet. In an example case study, ALADIN simulated the impact on the shelf life, the percentage of fruits arriving at the customer in poor quality, the transport costs and the CO_2 emissions for alternative chains for pineapples.

However, a simulation can only be as good as its input data. The application to a concrete supply chain requires the capturing of statistical data on several components. The previously quoted study on cooked ham [24] used average and variance data for the initial bacterial load after production, transport duration on different routes, temperature variations in different steps and distribution of time and temperature in domestic fridges. The product-specific parameters are often neglected in simulation studies, e.g. [42] and [44], which presented a detailed study on the supply chain of apples and bananas, respectively, but included only general assumptions on the transport temperature and its relation to the shelf life.

(d) Suggestions for strategic food chain management

Strategic management can be seen from the perspective of cost reduction only by avoiding losses owing to quality decay and waste owing to overstock. However, more benefits can be achieved if planning is considered from the quality point of view instead. The ability of the chain to deliver perishable food products faster and in better quality can be seen as a strategic asset to gain market shares in the competition.

Unfortunately, the implementation of such strategies in a specific food chain has hardly been the object of scientific research. A detailed costs and benefits analysis would require the publication of confidential company internal information, such as order quantities and the exact percentage of losses. If a company gives full details of its strategy for a certain product, it might lose its advantage over its competitors. For this reason, we can only summarize studies and recommendations that consider food chain strategies in general.

(i) Selection of logistic service providers

Parts of the transport and chain processes might be subcontracted to logistic service providers (LSPs). The selection of an LSP should be based on several questions in regard to temperature and quality management: (i) Does the LSP have an awareness of the temperature sensitivity of the product? (ii) Is the technical equipment up to date and maintained regularly and does it have sufficient cooling capacity? and (iii) Are the staff trained to take care of the correct adjustment of

the set point? Based on such an analysis of temperature and quality management, the CCQI [39] can serve as an index to evaluate and compare LSPs.

The willingness of the LSP to share data and to give transparent access to the temperature sensors and loggers installed to monitor the transport process is a crucial pre-condition for implementing FEFO strategies. Does the LSP provide adequate software interfaces? Are data provided in real time or only on demand after a claim for transport damage has been raised?

(ii) Number of hubs and decision points

The consolidation of products in hubs or DCs reduces the amount of transport of 'less than a truck load' [5] and thereby the costs. Increasing the number of hubs in the chain can have negative or positive effects as well in relation to quality aspects. Consolidation processes have a negative effect on the shelf life because they increase the total transport duration and it is not possible to adjust the set point to the optimal temperature for all the products in a mixed container load. On the other hand, though, each hub provides the option to install a decision point, at which orders can be reassigned according to the FEFO strategy.

(iii) Demand and supply chain management

Demand and supply have to be tied very closely together owing to the limited shelf life of food products. Traditionally, undersupply will result in out-of-stock, while oversupply will result in product loss. Although food is a daily necessity, changing weather conditions can lead to an abrupt change in the demand. For example, nobody buys watermelons if the weather is cold, and a good weather forecast for the weekend can drive a tremendous demand in barbeque meat.

Beside the work on demand forecasting [16,17] mentioned in §2, Scheer [26] focused on the integration of such aspects with quality tracing and FEFO planning. He suggested a self-learning demand and supply chain management system at the retailer level that gives advice on recommended order quantities, based on reported daily sales and waste owing to overstock. This approach requires accurate data capturing at the point of sale and fast response and short lead times of the supply chain.

He suggested further that products with a shorter shelf life should be sent to high-turnover outlets, at which the products are sold faster, before reaching their due date. In this regard, a FEFO-enabled supply chain can provide the necessary information for such distribution.

(iv) Diversification of quality

Management according to the basic FEFO strategy tries to homogenize quality by intelligent stock rotation. However, this might not be the most efficient approach. Van der Vorst *et al*. [45, p. 96] suggested that 'variability can also be strategically exploited through the flexible management of quality differences for specific market outlets'. Hence, the product line can be split into quality segments, providing premium customers with the highest quality by focusing investments on related chain processes and by prioritizing based on the actual or predicted shelf life. Before these investments are made, 'quality' should be considered from the customer's perspective by answering questions related to such issues as the degree of importance that quality has for different groups of customers who are willing to pay more or less for higher or lower quality.

(v) Harvesting 'green' versus 'ready-to-eat' fruits

Tropical fruits, such as mangos, are often harvested in a 'green', unripe state in order to prolong their shelf life. The customer might lack the patience to wait until the fruit is fully ripe, and being dissatisfied with the taste, remains a low-frequency user [46]. The implementation of better control mechanisms and FEFO management can be seen as a strategic decision to remove the need for long shelf life buffers in the chain and thus enable a higher harvest age, which presents fruits in a more 'ready-to-eat' state, achieving higher consumer acceptance.

(vi) Shifting transportation modes

Alternative modes of transportation might be enabled by better control of post-harvest conditions. The short shelf life of fruits such as blueberries prevents sea transportation lasting for one or two weeks, which leaves air transportation as the only option for transcontinental exports of fresh fruits. Transportation in CA containers prolongs the shelf life sufficiently to enable sea transportation with lower costs and less ecological impact.

The second example is given by the decision to be made between different modes of sea transportation. The transport capacity in specialized reefer vessels has been declining since 1994, whereas the containerized fleet has increased by a factor of 10 and is now providing 90% of the overall reefer capacity [47]. Bananas are still the product with the highest share of bulk transport of 65% but they are gradually moving towards containers.

If the decision on bulk or container mode is seen from the viewpoint of capacity utilization, containerized transport on third-party vessels has a clear cost advantage because it allows more reactive flexibility in a market with changing order quantities every week, whereas a specialized reefer vessel can operate cost-efficiently only if it is fully loaded [4].

Nevertheless, the shift from bulk to container also brings new opportunities: containers can be shipped door-to-door. Without the need for cross-docking, costs and time are saved. A longer shelf life is made possible by faster delivery. However, door-to-door shipments will only be possible with a system for remote quality supervision because manual quality inspection is no longer possible in cross-docking depots. Without increasing the transparency of chain processes, the shift from bulk to container is rather disadvantageous from a quality point of view because the control and performance of cooling equipment is less reliable than that on company-owned vessels.

10. Conclusion

The main purpose of this Theme Issue is to make the case that reducing losses through better quality supervision and prediction models, using more advanced technology, is not only possible but also mandatory today. With the current rate of population growth and developing countries requesting a larger share of limited resources, the world can neither afford nor sustain food loss caused by inefficient cold chains.

To this effect, each of the articles included in this Theme Issue either provides the necessary information on how to use technology to enable better quality monitoring or control different products and environmental factors or discusses the case studies in which the application, benefits and true potential for such oversight are clearly demonstrated.

T&T became mandatory by legislation in the European Union in 2005 [48, p. 15, Article 3 Point 15], as 'the ability to trace and follow a food, feed, food-producing animal or substance through all stages of production and distribution'. Scheer [26] argued that the cost of an automated T&T system will bring added value for the companies in the food chain only if the food quality is traced along with identification and location data, thus forming a quality-oriented T&T system. As shown in the technical articles in this Theme Issue, systems for remote online supervision of the cold chain will be ready for the market in the near future.

The introduction and standardization of ERP systems in the 1990s revolutionized supply chain management. The driver at that time was the availability of powerful computer systems, databases and networks. The integration of temperature and quality monitoring per pallet into telematics systems can bring about a second revolution—in this case specializing in food products by integrating their shelf life into the supply chain planning process.

Like any similar initiative that strives to adopt new technology with a process involving dynamics that have not changed in the last five decades, such as the food supply chain, traditional views have to be surpassed. Industry feedback on the wide-scale adoption of FEFO-enabling technologies has always taken a cautious view in regard to the upfront costs of the hardware and software tools, such as monitoring devices like RFID readers and tags as well as the

necessary augmentations to the existing resource planning software. Furthermore, stakeholders, such as farmers, suppliers and distributers, are usually reluctant to enable free data exchange of temperature recordings for a particular shipping lane, out of fear that they could be used against them in filing claims or other types of disputes.

However, it is important to note that quality supervision with better insight may or may not result in dynamic logistics for the cold chain, such as assigning transportation based on the product's predicted shelf life, but it is important either way because it helps to identify the weak links in the chain and can result in structural changes, albeit static, which improve the quality and efficiency significantly. For example, pallets inside a container of strawberries shipped across the continental USA will have up to 5°C temperature differential depending on where they are placed inside the container, causing a notable difference in their quality and shelf life [49]. Hence, a temperature-controlled container's set point is an extremely poor approximation of the actual product temperature. In fact, inconsistency in the quality of fresh produce from the same field can only be explained by temperature variations that it might have encountered during transportation, which can only be measured by a better quality monitoring system using higher resolution than the container level.

Even though the majority of the articles discuss loss reduction, a key advantage of FEFO-enabled cold chains is the provision of consistent quality to all the stakeholders, which also improves the forecasting accuracy and the profits. Different companies might have different priorities, such as offering high-quality/high-cost or low-quality/low-cost perishables depending on their customer base. The logistics parameters of FEFO can be adjusted to accommodate both types of priorities, which is only made possible by accurate prediction of the shelf life of the inventory to be distributed. High-quality perishables can be made available to the customers at a premium cost by choosing the products with relatively long shelf lives to be delivered in shorter periods of time and vice versa.

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