Temperature deviations during transport as cause for food losses

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Abstract: Deviating temperature conditions during distribution processes reduce the quality of food and significantly contribute to global food losses. The effect of careless handling and inadequate processing only become visible much later in the cool chain, making it difficult to quantify the contribution of individual processes. Their contribution can be better evaluated by the caused reduction of food quality than by the total food loss. Biological models predict the decrease of shelf-life by the product's temperature history.

Actions should be taken to reduce food losses, first, by identifying problematic processes with temperature logger studies. Remote monitoring enables to immediately detect and mitigate cooling problems. Finally, intelligent stock rotation can compensate variations in shelf-life. The required time for following processes is matched with the calculated remaining shelf-life for each product batch.

The identification and mitigation of cooling problems is illustrated by maritime transportation of bananas in refrigerated containers.

Keywords: Food losses, cool chain, intelligent container, first expires first out, shelf life

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1 Introduction

Food losses and waste (**FLW**) occur at several points in the supply chain from farm to fork. A typical food supply chain often encompasses more than 10 steps (Fig. 1) and multiple independent operators, such as producer, local trucking company, owner of reefer container, shipping and air cargo contractors, import company and retailer. Due to the complexity of the chain, it is difficult to quantify the food losses caused by a specific operator. Furthermore, the effect of incorrect handling of food only becomes visible at subsequent steps.

Fig. 1. Typical supply chain for food, using bananas as an example. Items in parentheses do not apply to bananas.

For example, even if a 1-litre milk carton is transported at the wrong temperature, it may still look perfect from the outside. Any quality problems only appear when the consumer opens the package. Ultimately, the consumer might be blamed for having too-high quality expectations, if she/he discards the product before the printed best-before date, although the actual problem originated much earlier in the supply chain. The same applies to many fruits. An apple or pear can retain a good external appearance, but physiological processes have been accelerated in a way that the fruit will decay long before the expected end of shelf-life.

In this article, we focus on losses and problems arising in the cool chain, and thereby exclude harvest and production steps and customer handling. Most quality problems are related to interruptions of the cool chain or insufficient cooling. Based on our experience and, according to other published studies, temperature deviations are present in any mode of transportation. The cause and magnitude of typical temperature problems vary between ocean, ground, and air transportation.

The share of bulk shipments in the cargo hold of reefer ships is decreasing. Nowadays, **refrigerated containers** are predominant in cooled ocean transportation. Air ducts in the floor deliver an even distribution of cooling air and a defined path for the return air under the ceiling, thus providing good temperature control (Wild, 2005). Compared to other modes, ocean transportation entails the longest journey time of typically two weeks on routes from Central America to Europe and at least double that time on Australian routes. Even small temperature variations over this period can have a harmful effect on food quality. Special container-related problems include blocking air gaps between pallets or boxes by careless stowage and older containers with poor thermal isolation and insufficient ventilation compared to modern units (Jedermann et al., 2014b). The green- or shelf-life of bananas and other fruits can be extended using controlled atmosphere (CA) technologies. Replacing oxygen with nitrogen slows biological processes. In contrast to other transportation modes, CA is available in most reefer vessels and in specially equipped reefer containers.

Refrigerated trucks generally supply cooling air through a set of hoses mounted under the ceiling without providing a defined path for the return air resulting in higher temperature variations (section 3.1). More severely, some trucks have no cooling at all, especially in developing countries. According to Timmermans et al. (2014), *'it is not uncommon to find highly perishable produce being transported in open, unrefrigerated trucks'*. On other occasions, the driver switches off the unit to save fuel and sell it on the black market, although this is seldom detected. Furthermore, the ordered quantities are often insufficient to make up a full truckload. Different items with different temperature requirements are often mixed.

Temperature control during **air transportation** entails only heating to avoid freezing the cargo compartment but mostly with no active cooling. Aviation companies only guarantee fast delivery but not a certain temperature. As a pilot said, *'An airplane is not a refrigerator'*. Competing temperature requirements, e.g. for live animals or pets in combined passenger-cargo planes, prevent optimal temperatures for fresh products. For high-value goods, such as pharmaceuticals, standard aircraft containers, so-called Unit Load Devices (ULD), can be equipped with a cooling system. The Swedish company Envirotainer offers ULD with passive dry ice or active compressor cooling (Baxter et al., 2015). Due to the higher costs and problems with replenishing dry ice and batteries in remote airports, they have only a limited market share.

Transhipment processes are most critical in terms of cool chain ruptures, including links between transport and storage facilities and transitions between different transport modes. Pallets wait at the loading platform or on the airfield without cooling (Timmermans et al., 2014). Peak temperatures can go beyond 40°C, e.g. for highly perishable exotic fruits waiting for flight dispatch in Sub-Saharan countries. Cool chain ruptures happen in developed countries as well. For instance, during interviews conducted by Jevinger et al. (2014), Swedish food chain operators confirmed that products wait too long without cooling on the loading platform during lunch break. Goedhals-Gerber et al. (2017) described a typical problem for the transition between modes. During harbour handling of reefer containers in Cape Town, the electric supply was disconnected for several hours.

Further FLW and quality losses are caused by **mechanical damage** that is mainly related to developing countries since vibrations are caused by 'the poor state of roads, especially in rural areas where most of the production occurs' (Timmermans et al., 2014). The 'naked' fruits are often stuffed without packing on trucks, leading to compression damage. Loading and unloading are done by casual labourers, who handle products roughly (Timmermans et al., 2014).

Other causes for FLW (section 3.2) include inadequate packing, blocking the airflow. Condensed moisture on packing films and poor hygienic conditions increase the growth of microorganisms. Lack of information flow (Huelsmann et al., 2011) leads to maladjusted set points of cooling equipment. Missing documents delay customs clearance and transhipment processes.

1.1 The banana chain as an example

In addition to the above literature reports on FLW and quality problems, we will illustrate this study using examples from our experiments during the trans-ocean transport of bananas.

Bananas were harvested green and unripe in Central America. Due to a lack of technical facilities at the farm, the standard process does not entail pre-cooling. Instead, the packed and palletised bananas were directly stowed at ambient temperature in a reefer container. The container was transported by truck to the harbour, loaded to a vessel, shipped to Antwerp, and then trucked to a ripening facility in Germany. The bananas were first cooled on the vessel, which needs about 2 days until the transport temperature of approximately 15°C is reached. After transport in a 'green' state, the desired 'ripe' stage and yellowness were achieved by ethylene treatment in a ripening chamber.

In one test, the driver of a third-party truck switched off the cooling unit for 6 hours during the transport from Antwerp to Germany, to sleep better at night. At arrival, the driver denied any cooling problems since the current supply and return air temperature were both in the recommended range, but our remote temperature monitoring system could prove otherwise.

1.2 Percentage quality loss instead of total losses

Quantifying the food losses along the cool chain is challenging, data is scarce and comparing different studies leads to contradicting results (section 2), especially if losses should be assigned to specific steps in the cool chain. Another approach is to quantify the percentage of quality loss instead of the percentage of total FLW per step, which leads to the question of how food quality can be quantified. The most generic tactic relies on the concept of shelf-life, providing the remaining number of days that the product can be displayed on the retail shelf until the customer would most likely reject it (Corradini et al., 2018), (Tijskens et al. 1996). For other products that entail health risks not visible externally, the shelf-life is determined as the time remaining before the expected growth of pathogens exceeds a safety threshold.

Reports concerning temperature include not only small offsets over long periods but also peaks of several degrees Celsius lasting for a few hours (section 3). Predictive biological, or so-called, shelf-life models, allow relating different types of temperature abuse to a degree of quality loss. Taking the products temperature history as input, these methods estimate the remaining shelf-life days, and how the shelf-lives are reduced by certain amounts of temperature deviation (section 4).

Applying such models confirms that even if the product is not directly lost, the shelf-life can be significantly reduced. Thus, there is an increased risk that the product does not arrive at the customer in an acceptable quality state.

1.3 Action should be taken to minimise losses

In the face of an increasing world population and the limitation of our planet's resources, any avoidable sources of FLW are not acceptable, and measures should be taken to minimise such phenomena:

- The first and most important action is the identification of critical steps in the cool chain, by temperature data logger studies (section 5). This approach requires only limited additional electronic hardware, namely, a set of data loggers to monitor temperature variations at different locations in the cargo hold, during repeated test trips.
- As a second action, the monitoring of all actual transports is technically more demanding. Monitoring can be fully real-time, with direct access to product temperatures over satellite or mobile networks, or, at the least, the temperature history should be read out after each step in the logistic chain (section 6).
- Based on such a temperature monitoring system and a product-specific shelf-life model, the third action can be applied. Variations in the shelf-life of batches of the same product can be compensated for, by intelligent stock rotation. Products with a low shelf-life are send to nearby shops for immediate sale (section 6). However, not all products are suitable for this action, due to the costs of monitoring temperature at the product batch or pallet level, the effort needed to identify parameters for a specific shelf-life model and the limited freedom in re-assigning deliveries. Nevertheless, studies of various products have shown that between 8% and 14% of food losses can be avoided by such first-expires-first-out (FEFO) warehouse management (Jedermann et al., 2014a).

2 Transport losses as part of the problem

Transport losses by deviating temperatures are a serious issue, but only part of the problem. Overproduction, especially in developed countries, largely contributes to FLW. As a result, 7% of planted fields in the USA are not harvested each year (Gunders, 2012). Parfitt et al. (2010) wrote that food manufacturers would often overproduce, to avoid being “de-listed”, lest additional quantities are required at short notice. High-losses attributable to overproduction also occur in bakery products. Shelves are kept full until shop closure because *‘customers anticipate full shelves’ (Raak et al., 2017)*. The current overproduction also leads to a lack of motivation to improve processes: losses at the end of the chain mean more turn-over for the preceding partners and, *‘the more food consumers waste, the more those in the food industry are able to sell’* (Gunders 2012).

Adverse conditions are often willingly accepted when displaying fruits and vegetables for retail. For instance, Pelletier et al. (2011) states that ‘*It is also a common commercial practice to display strawberries in non-refrigerated displays to stimulate an impulsive purchase, as the intensity of the aroma released by the fruit increases when exposed to ambient temperature’*. The same scenario is also common for asparagus.

Occasionally, the preceding cool chain operators cannot be trusted to have complied with the recommended temperatures, and the wholesaler wants to prevent complaints by subsequent customers, so the best-before date is reduced (Jevinger et al., 2014).

In the light of various problems leading to FLW, and the differences between developed and developing countries, it is hard to quantify the total amount of losses per product. It is even more difficult to deduce the share for the transport process. Since general statistical data are not available for evaluating the contribution of transport processes to total food losses, we suggest starting with a detailed analysis of the causes of transport losses. The deviation from recommended transport conditions should then be converted to a percentage of food quality loss, in the second step.

2.1 The amount of food losses and waste in general

There is a lack of data about the exact amount of FLW. The final report of the European-funded “Food use for social innovation by optimising waste prevention strategies (FUSIONS)” project (2012–2016) identified *‘gaps and lack of sufficient, high-quality data to measure food waste across EU28’* (Vittuari et al., 2016).

A report by High-Level Panel of Experts on Food Security and Nutrition (**HLPE**) established by the United Nations Committee on Food Security (Timmermans et al., 2014) confirmed that *'accurate estimates are not available'*.

An often-quoted estimation is that "*roughly one-third of food produced for human consumption is lost or wasted globally*" (Gustavsson et al. et al., 2011). Most papers on improvements in the food chain start with estimated values for the typical amount of losses. Back-tracking of citations reveals that almost all data were retrieved from **FAOSTAT** data published by the Food and Agriculture Organisation (**FAO**) of the United Nations, as in the following examples:

- Gunders (2012) quotes that 52% of fruits and vegetables are lost in average for USA, Canada, Australia and New Zealand, with the amount of losses related to distribution and retail amounting to 12% for North America.
- Sibomana et al. (2016) cited a similar figure for the South Africa tomato supply chain with 10.2% loss of total production, but a much lower figure for developed countries such as Italy, Spain and Mexico with 4% losses in the supply chain.
- Defraeye et al. (2016) wrote that the losses for fruits and vegetables are between 13% and 38%, depending on the country.
- Mahajan et al. (2017) note significant higher losses during distribution for developing countries with warm and humid climate.

Xue et al. (2017) examined 202 publications reporting FLW data. Over half of these publications was based on secondary sources, mainly data derived from literature. Only 20% was based on first-hand data. Mostly, FLW is evaluated at retailer and consumer level, with only fewer studies on the preliminary steps. Problems such as the predominant focus on industrial countries, the use of outdated data and inconsistent methods hinder a concise evaluation of global FLW.

On behalf of the European Commission, the Bio Intelligence Service (BIOIS) examined the losses at all stages of the food chain for each of the former EU27 member states, but did not differentiate product groups (Monier et al., 2010). By using EUROSTAT data from 2006, various national surveys and extrapolations by BIOIS, it was indicated that the retail and wholesale accounted for 5% of the total FLW or about 4.4 Mt/year (Monier et al., 2010). However, the study method was later criticised by Bräutigam et al. (2014): for example, data gaps for some countries were filled with the average data of neighbouring countries displaying similar economies. Moreover, when the values were recalculated for each country based on FAOSTAT data, differences of three-fold were observed for some countries, which could not be explained by different definitions, e.g., the BIOIS study counts inedible parts of animals, such as bones, among food waste.

A study from Switzerland (Beretta et al., 2013) indicates 48% of total edible calories generated for Swiss consumption is lost across the food chain from production to consumer. However, detailed data on the losses related to transportation are not given, and Switzerland's domestic food supply chain entails rather short transport distances, with only a minor contribution to total losses.

2.2 The lack of data concerning transport losses

For the cool chain between production and the retail outlet, which is the focus of our paper, there are hardly any data. Even if the total or average food losses are known, it is difficult to assign losses to a certain step in the food chain. *'Food losses and waste happening at one stage of the food chain can have their cause at another stage'* (Timmermans et al., 2014), as already illustrated by the examples of milk, apples and pears above. Also, as Nunes et al. (2014) wrote: '*Early decay indicators and advanced shelf-life loss, due to temperature abuse, is generally not visible from the outside*'. In other words, the origin of the defect is not in the same stage as the waste itself (Raak et al., 2017).

The attempt to retrieve data about transport losses by direct queries to cool chain operators also brought only vague figures. Companies do not like to divulge their losses, and thus, confirm quality problems. Even after 6 years of cooperation with a large banana importer, we received only rough figures about losses, which indicated a low single-digit percentage of bananas are lost during the transport from the farm in Central America to the warehouse in Antwerp if all components of the cool chain are under full control of the company itself. However, if third-party vessels and reefer containers are used, the losses increase significantly. The use of third-party logistics is often unavoidable in order to react to fast-changing demands on the European fruit market.

Queries to representatives at a German conference of insurance companies (Gesamtverband der Deutschen Versicherungswirtschaft, 2011) only revealed anecdotic evidence of transport losses, but no average data. The companies fear that published data on food losses would enable their customers to re-calculate their insurance tariffs.

2.3 Causes for transport losses besides temperature

Multiple factors can lead to quality losses during transportation, such as vibrations, infection and growth of microorganisms, as well as wrong temperature and atmosphere conditions (Raak et al., 2017).

Mechanical damage is mainly related to developing countries (Timmermans et al., 2014). Further damage is done by careless packing.

The shelf-life of several fruits can be extended by applying a certain modified or controlled atmosphere. For example, an automated air-flap control increased the carbon dioxide (CO_2) content in ocean containers by self-respiration of bananas to 5% and thereby extended their green-life (Jedermann et al., 2014b). Additionally, the start of an unwanted ripening process can be delayed by controlled atmosphere. The oxygen (O_2) concentration is reduced to 2–5% (Wild, 2005) by replacing ambient air with nitrogen (N_2). The humidity should be above 80% to avoid moisture loss, but below 95% to prevent fungi growth.

Further non-temperature related problems in the supply chain can be found in the already-mentioned HLPE report, with a particular focus on developing countries (Timmermans et al., 2014).

Food losses are often caused by a combination of different factors: the skin of a fruit is damaged by careless packing; microorganisms intrude into the fruit due to poor hygiene conditions; inadequate packing, in combination with temperature fluctuation, lead to water condensation on the fruit, thereby accelerating bacterial and fungal growth (Linke et al., 2013). Temperature deviations also influence respiration of the produces. Consequently O_2- and CO_2-concentration in MA packages changes and may lead to physiological damages, e.g. fermentation reactions as tissue browning and off odours (Tano et al., 2007).

2.4 Cool chain ruptures

In addition to the above-listed causes, most losses are related to temperature abuse. The speed of decay processes, such as bacterial growth, and microbiological and chemical reactions increase exponentially with the temperature (Nunes et al., 2014). Physical reactions such as moisture loss by evaporation, are also enhanced by temperature.

Besides ruptures in the commercial supply chain and during display in the retail outlet, severe cool chain breaks occur at the consumer side during transport home in a hot car and too high temperature in the domestic fridge (Derens-Bertheau 2015).

Cool chain ruptures are a common problem in the food chain. A literature survey by Huelsmann et al. (2011) identified more than 100 reports related to problems during storage (e.g., wrong temperature management) and transport by ship (e.g., a reefer container requires 2 weeks to reach the temperature set-point), air (e.g., high temperature variation during flight operations) and on the ground (e.g., blocking of the airflow by wrong pallet positioning).

Gwanpua et al. (2015) stated that for developing countries, the '*most important cause of postharvest losses is non-optimal temperature control in the cold chain'*. Cooling is often interrupted because of the absence of a reliable electricity source (Mercier et al., 2017).

Cool chain ruptures, especially at transhipment points, happen in developed countries, as well (Jeveinger et al. 2014). Nunes et al. (2014) mentioned insufficient workforce during peak season leading to deviations from recommended processes, e.g., too short pre-cooling because of lacking capacity, prolonged storage without cooling, and generally less care.

3 The omnipresence of temperature deviations

From various experiments in delivery trucks and reefer containers, we found that '*Wherever you measure temperature, you find deviations'*. At least for parts of the food products, the temperature inside the packing was higher than the recommended value. Although this might not be true for every cool chain, this tendency is confirmed by various publications. Ndraha et al. (2018) lists in a review paper 17 studies about temperature abuse in the food chain, in which only one of the studies confirm good temperature management. They conclude that '*Most of the reviewed studies show that temperature abuses occur at all stages in the cold chain, and are not confined to any particular type of food product'.* The general presence of temperature deviations is also not confined to developing countries. The listed studies were all undertaken in Europe and North America.

Another recent review paper by Mercier et al. (2017) mentioned several studies reporting temperature variations with offsets between 2 and 10°C. Further experimental studies can be found, for example, in Defraeye et al. (2016), Goedhals-Gerber et al. (2017) and Jiménez-Ariza et al. (2015).

A direct comparison of the degree of temperature abuse from different studies is hardly feasible. One reason is the different experimental set-up, including variations in the type of transportation, goods, packing and stowage schemes, the age of equipment and the general quality of cool chain operation. Factors like the probe point locations and methods applied to evaluate temperature deviations, hinder a structured analysis of the typical extent of temperature abuse.

3.1 Method of air supply

The transportation modes vary in the way cold air is supplied. The floor of the reefer container usually consists of parallel T-bars with ducts in-between to distribute the cold air. The cooling unit is mounted to the side opposite the door. The return air flows back to the unit through a 10–40 cm horizontal gap above the goods, to an outlet grid under the ceiling (Fig. 2). Typically, 20 pallets can be stowed in a 40-feet container. Gaps between the pallets cannot be avoided because their length and width do not perfectly match the internal dimensions of the container.

Fig. 2. Schematic air flow inside reefer container with palletized bananas. Zones that are still above 18°C at 24 hours after start of cooling are colour marked. The temperatures were calculated according to a two-dimensional air flow simulation. See Jedermann et al. (2017a) for details. Deviations from the actual measured temperatures were caused by the simplified simulation model. Colour legend for temperatures in °C.

In trucks, the cold air is supplied through an outlet below the ceiling. Pipes under the ceiling are often used to improve the distribution of the cold air over the length of the cargo hold. Due to the lack of a structured flow of return air, temperature variations are usually higher in trucks than in containers.

A further type of airflow management is mostly used for pre-cooling of fruits. Instead of vertical airflow, the cool air is horizontally extracted through the pallets by forced air-cooling, making use of vent holes on the side of the boxes.

The temperature distribution also depends on the quantity of loaded goods. A partly-filled truck or container has less structured airflow and higher temperature variations than its fully-loaded counterpart. The worst scenario are trucks with open shelves, to deliver mixed products over the last mile to end-customers. We measured variations of air temperature from -30.4 to -22.4°C, at various locations in the deep freezer compartment (Jedermann et al., 2009).

3.2 Probe locations

It is mandatory for the cooling unit to record the supply and return air temperatures. The records are used to settle legal claims about inadequate cooling. Up-to-date units provide a remote readout of the recorded data (section 6). Albeit only incomplete information can be concluded from the time–temperature curves. A discrepancy between the return and supply temperatures shows that heat is extracted from the goods in the cargo hold. A diminishing difference indicates that the cooling process has completed, but this can also be misleading: an air circulation short-circuit also creates a low difference, although cooling efficiency is largely reduced.

An insufficient flow at the side opposite to the cooling unit can be detected by an additional sensor at the door side. But not all types of deficient air distribution can be detected by such a sensor. A foam block is often used in reefer containers to avoid excessive air passing through the free space behind the door. If the air block is mistakenly not installed, the door sensor indicates good cooling, although insufficient air passes through the cargo.

The effects of temperature abuse can only be evaluated if the product temperature is known. Fig. 3 exemplifies, by data from a trans-ocean banana transport, that there is no direct relation between supply, return and actual product temperature. Optimal sensor locations are, therefore, placed directly in the centre of the product packing.

In daily operation, the opening of packings is not normally allowed, so sensors are often placed on the surface of product boxes or pallets. Surface sensors react quickly to temperature changes. As Fig. 3 illustrates, three power interruptions of between 0.5 and 3.6 hours triggered large peaks in the supply, return and surface sensor data. The product core temperature was still decreasing despite the comparatively higher air temperature. Only the decrease in the temperature slope was markedly slowed.

Some authors recommend calculating the core temperature by mathematical modelling, e.g. Nunes et al. (2014). This method entails larger tolerances, due to variations in thermal conductivity of the packed product, uncertainties of the initial core temperature and varying temperatures at the other sides of the box, which can only be measured by increasing the number of sensors.

Fig. 3. Temperature records from a test transport of bananas in 2012 for the first 5 days. Reefer container with one-year-old Thermo King Magnum Plus® cooling unit (Ingersoll Rand., Belgium). Supply/Return air, warmest and coldest box centre in one layer 1.5 m above the floor, and a sensor located in the box corner adjunct to the coldest position. Dotted lines illustrate the calculation of initial cooling speed, C_T.

3.3 Average temperature offset

The most obvious way to compare the performance of separate cool chains is to calculate the average measured offset relative to either the set-point or recommended temperature. Jiménez-Ariza et al. (2015) monitored temperature deviations in a trans-ocean transport of blueberries in a reefer container with sensors placed in the centre of pallets at different heights. An average offset of +0.54°C was found, indicating a rather good performance of this mode of transportation.

High offsets are generally found if the cooling unit has to compensate not only for thermal energy penetrating the walls but also for the heat created by respiration of fruits or vegetables, triggering differences between the temperature inside the packing and that of the outside cooling air. Bananas produce about 30 W/t heat at 13°C during their green-life. If uncontrolled ripening starts during transportation, the heat production increases up to 300 W/t by the conversion from starch to sugar (Jedermann et al., 2014b). We measured average temperature offsets between 2.5 and 4.9°C above the set-point of 13.9°C for ocean transports over 2 weeks in reefer containers aged between 2 and 12 years. The highest average offset was related to the oldest container. Even after 2 weeks of cooling, the temperature was still 2.2°C too high, for the warmest box.

Respiration activity can even lead to a temperature increase. In pallets of strawberries at an initial temperature of 1.5°C, Pelletier et al. (2011) observed a 4.5°C temperature increase during truck transportation over 5 days. The final temperature of 6°C was far above the set-point of 1.1°C. Wrapping of the pallets with foil to create a modified atmosphere prevented sufficient airflow through the pallets.

3.4 Temperature out of range and power interruptions

Some authors evaluate the cool chain performance by the share of transports, which violate the recommended temperature range. Ndraha et al. (2018) describe several studies, in which 13.6 –58% of the temperatures overstep the recommended value for the cool chain of fish, meat, bagged salad and ready-to-eat food products.

Another indicator for cool chain problems is the duration of power interruptions. Goedhals-Gerber et al. (2017) found the goal to reconnect reefer containers to power supply after arrival at the Cape Town Container Terminal within 40 minutes was hardly reached. The average duration of power interruptions was 1 hour 52 minutes. For 15% of the containers, the outages lasted for more than 3 hours. During the complete harbour operation, 22% of the containers never arrived at the recommended 2°C.

While these studies indicate problems in the cool chain, they are less helpful in evaluating the amount of related quality loss. Without information about magnitude, duration and location of temperature peaks, the shelf-life cannot be calculated, and the effect of temperature abuse might be overestimated:

For four out of eight test transports with cod fish, Göransson et al. (2018) noticed the temperature inside packed pallets was above the maximum storage temperature of 4°C for extended periods. The authors mentioned that the wholesale would probably not have accepted the products if the full temperature history had been disclosed. A calculation of shelf-life showed that the quality loss was less severe than anticipated: the products only lost a maximum of 0.2 days of shelf-life compared to a fictive reference product held at a constant 4°C throughout the transport duration. Nevertheless, the product should be relabelled, to avoid health risks because the initially expected shelf-life is not reached.

Short temperature peaks are often caused by automated de-frosting cycles of the cooling unit, with high values measured under the ceiling. Ventilation is switched off during defrosting. The effect of such peaks hardly penetrates the packed products. Further temperature peaks are caused by door openings, and these effects might also be overestimated if only surface measurements are considered.

3.5 Cool-down time

Fruits are usually harvested at high ambient temperatures above 20°C and need to be cooled down to their recommended temperature between 0 and 14°C. For sensitive fruits, such as strawberries, fast pre-cooling is recommended (Pelletier et al., 2011). Other fruits, such as bananas, are usually packed, palletised and stowed “warm” in a reefer container, partly because of the lack of technical infrastructure at remote farms. This so-called “ambient loading” was also tested for citrus fruits by Defraeye et al. (2016), who used the 7/8ths cooling time, $C_{7/8}$, to evaluate and compare the performance of the cooling process. This method gives the time that is necessary until the difference between the product temperature and set-point is reduced to 1/8th of its initial value. Although this definition allows comparing different cool chains and processes, e.g. pre-cooling versus ambient loading, it creates problems for products with a high respiration activity and persistent temperature offset above the 1/8th threshold.

In this case, we recommend using the initial cooling speed, C_T, to compare different cooling scenarios. C_T is defined as duration after which the product temperature would arrive at the set-point if cooling would continue at its initial speed, measured in °C/hour. If an exponential decline of temperature is assumed, C_T is equal to the time constant of a first-order process, and $C_{7/8}$ can be converted to C_T by a constant factor:

$$C_T = 0.4809 \cdot C_{7/8} \tag{1}$$

The above definition of C_T allows comparing the cooling of different products, even if their cooling curve does not follow a single exponential function. Bananas require at least two exponential functions to include their high respiration activity (Jedermann et al., 2014b). The computed C_T for a typical transport of bananas was between 26 and 104 hours, according to the temperature curves in Fig. 3 for boxes in the sixth of eight layers, counted from the floor. The calculation of C_T also helps to assess the difference between sensors in the box centre and on the inside of the cardboard box. A surface sensor located in the warmest box cooled down about ten-fold faster than the centre, with 9 versus 104 hours.

Defraeye et al. (2016) reported $C_{7/8}$ between 2.5 and 3 days maximum for boxes of oranges in the top layer of pallets stowed in a reefer container according to the standard scheme, equivalent to C_T between 28.9 and 34.6 hours.

The cooling of bananas was up to three-fold slower than for oranges, despite the similar amount of fruits stowed in the container and up-to-date equipment used in both cases. The divergence is most likely caused by the packing of bananas. Bananas are wrapped into a foil liner inside each carton box, to avoid moisture loss.

Pre-cooling by forced air-cooling devices achieves rapid heat removal. Ambaw et al. (2017) measured $C_{7/8}$ values of 2.5 and 3.5 hours, or C_T between 1.2 and 1.7 hours, respectively, for pomegranates in various packing types. If the fruits were wrapped in plastic liners, C_T increased by a factor of about 3, to between 3.8 and 4.6 hours.

3.6 Temperature heterogeneity

In addition to global temperature offsets affecting the whole cargo hold, severe quality problems arise from local temperature variations, only influencing certain pallets or layers of boxes inside. A review by Mercier et al. (2017) revealed several examples of significant temperature heterogeneity inside single pallets. A similar heterogeneity was found by other reports and our measurements.

Such heterogeneity can encompass temperature gradients, for example, in a vertical direction, or a somewhat erratic pattern. The local temperature-over-time function can differ in the cool-down time, or by a persistent offset, or by a mixture of both.

For the **vertical** direction, the temperature heterogeneity in reefer containers showed a rather regular pattern. The lowest temperatures were recorded in the bottom layer, closest to the cooling air, supplied through ducts in the floor. Jiménez-Ariza et al. (2015) evidenced a vertical temperature increase of 1°C inside pallets with blueberries. During a test by Amador et al. (2009) with pineapples, the pulp temperature was close to the set-point of 7.5°C for the bottom layer, whereas the middle and top layers were between 3 and 4°C warmer.

In other cases, differences in the cool-down time are dominant, especially for ambient loading of fruits. Cooling of fruits is about two- or three-fold slower in the top layer than the bottom layer. The figures in Defraeye et al. (2016) show a typical $C_{7/8}$ of 1 day for the bottom layer and 2.8 days for the top layer, in a container with oranges. An earlier test (Defraeye et al., 2015) showed a comparatively less regular pattern, with typically, double $C_{7/8}$ values for the top layers.

We found the slowest cooling in the sixth layer, during our tests with bananas. The eighth or top layer was additionally cooled by the return airflow above the pallets. The average C_T was 24 hours for the bottom layer and 62 hours for the sixth layer, equivalent to 2.6-fold slower cooling.

The temperature distribution in the **horizontal** direction is hardly predictable. Relatively old containers often provide insufficient airflow to reach the last pallet at the door side. During our test in 2012, we modified the packing of the banana boxes, enabling enhanced airflow through the pallets and thereby increased pressure drop over the length of the container. The warmest pallet was found at the door end, as indicated in Fig. 3, although an up-to-date cooling unit was used. In other containers, we observed the contrary. A baffle plate above the air ducts was mounted over the cooling air outlet, to prevent pressure loss through the gap between the cooling unit wall and first pallet, but the effect was so strong that the airflow by-passed the first pallet, leading to a local temperature peak. In other tests, we found the highest temperatures somewhere in the middle of the container. The amount of horizontal variation typically increased with the age of the container, but even with new equipment, we found a horizontal variation of 1.5°C, for the average temperature over 2 weeks of trans-ocean transportation of bananas (Jedermann et al., 2017b). Amador et al. (2009) recorded a 2.1°C warmer rear end than the front end, during a container transport of pineapples.

The cool-down time varied by a factor of 4 in our tests with bananas with C_T between 26 and 104 hours. Defraeye et al. (2015) observed the same variation factor, noting that *'there seems to be no logical pattern'*. During the subsequent test with the improved airflow guidance, the variation was reduced to a factor of approximately 1.5, according to the provided bar graphs (Defraeye et al., 2016).

Besides the general cooling problems mentioned above, the variations arise mainly from the uneven width of air gaps between the pallets. Neither the pallets nor the container possesses a perfect rectangular shape. The cargo hold of our test container was 4 cm wider at the half of its length than at the unit and door end due to deformations by harbour handling and stacking of containers. A typical pallet carries 1 ton of fruits in cardboard boxes, resulting in a bulgy shape with deformations of a few centimetres. Unpredictable gap widths endow an uneven air distribution and cooling of the pallets.

Further irregularities in the local temperature distribution are impacted by variations in the initial loading temperature, respiration activity of the fruits in separate boxes and randomly blocked vent holes.

Whereas a regular vertical gradient can be measured by only a few sensors, it is hardly possible to fully capture an erratic horizontal pattern, without placing a sensor in every pallet or box. At the least, the amount of horizontal variation can be measured by placing sensors in critical positions, e.g., at the door end.

4 Shelf-life prediction

The loss of food quality is a gradual process, often hidden to visual inspection until it is too late. A green banana is just a green banana, without any visual indicator for the remaining time span until uncontrolled ripening commences. Measuring biochemical properties of the food product along the cool chain is hardly feasible in daily operation respectively not possible in a transport container on a vessel. The concept of shelf-life prediction models provides a solution to estimate food quality changes, based on measurements of the environmental conditions, such as temperature.

The end of the shelf-life is defined as the moment when the product's quality falls below an acceptance threshold. Tijskens et al. (1996) defined shelf-life from a retailer's perspective, as the number of days for which a perishable product can still be displayed on a retail shelf until an average consumer would reject to buy it. An alternate definition is based on the idea to replace fixed use-by or best-before dates with a dynamic shelf-life, i.e. the remaining time span during which the consumer is willing to accept the quality and to eat the product at home, or the time span until it is no longer safe to consume the product.

The remaining shelf-life is related to a reference temperature, T_{Ref}, typically defined as the recommended or optimal storage temperature. If the product is stored under non-optimal conditions, the shelf-life must be corrected. The prediction of shelf-life allows comparing diverse cool chain conditions, for example, to decide which pallet is more likely to have a better quality—one that had already spent 3 weeks in the warehouse under ideal temperature conditions, or the one that was only 1 week old, but was transported a few degrees too warm. The answer to this question depends largely on the type of product. Each product or even each fruit variety needs a specific model.

4.1 Limiting attributes

The first step in developing a shelf-life model is to define one or a set of limiting quality attributes:

- On the one hand, the attributes can be based on consumer or retailer perception, either by a simple “like it” or “like it not” decision or by a detailed set of sensory attributes, such as colour, odour, firmness or texture. The model of Mack et al. (2014) for vacuum-packed meat considers the average evaluation of seven sensory attributes by a panel of trained testers.
- On the other hand, the limited quality attributes can be defined according to a physical, chemical or biological analysis of the product, such as chlorophyll, sugar or vitamin C content, skin colour measurement by a spectrometer or pigment analyser, or measurement of firmness by a penetrometer. For meat and fish products, it is common to define the growth of a specific spoilage organism, as the critical attribute.

The limiting quality can vary with the packing. After changing from unpacked to vacuum-packed lamb saddles, Mack et al. (2014) noticed it was no longer possible to relate quality losses to either a specific or total bacteria growth, and instead sensory attributes had to be used.

Quality can also be defined in the context of the processing steps. For instance, the artificial ripening of bananas in specific chambers only produces a good and consistent quality of yellow bananas, if the bananas were completely green at the start of the process. The green-life of bananas is defined as the remaining time span until an uncontrolled ripening commences by physiological processes. The end of green-life is indicated by an increase of respiration intensity (Robinson et al., 2010), accompanied by the first visible colour transitions from green to yellow.

4.2 Biological variance

Food as a natural product is subject to variations. Consequently, shelf-life models are far from providing an exact prediction of the day and hours at which the product will perish. Green bananas, as an example, have a green-life of 48 days on average after harvest and storage at 13°C. In laboratory tests, we measured a variation of ±5 days, yet all fruits came from the same farm, were harvested the same day and taken from the same pallet.

Further variation is caused by nutrition, weather conditions, growing season, leaf disease, age at harvest, adverse harvest conditions, transport conditions, such as exposure to ethylene and vibration, and partly unknown factors (Robinson et al., 2010). Models that are based on the growth of a specific spoilage organism suffer from a lack of knowledge of the initial bacterial load, which, in practice, varies by a factor of 10 and more.

Such uncertainties must be considered in the cool chain and warehouse management. Safety margins must be assigned to best-before and use-by dates. Nonetheless, this biological variance does not hinder shelf-life prediction from being a very useful tool. Subsequent logistic processes can be prioritised, based on the likelihood of an early decay of a product batch (section 6).

4.3 Basic shelf-life model

The development of a concise shelf-life model demands several months of laboratory research. Nunes et al. (2014) recommend modelling multiple quality attributes. The first attribute to drop under the acceptance threshold depends on the temperature history. The complexity of the model increased even more, if other environmental factors, such as humidity and atmosphere, were considered. Such complex models are suitable for high-volume products, like meat or bananas and research purposes, but are too expensive to be investigated for each product type and variety.

For most products, it is suitable to start with a basic shelf-life model and refine the model later, during application. Even a basic model is better than no model. Information about the effects of temperature variations should not be ignored, even if it is only a rough estimation.

The model proposed by Tijskens et al. (1996) for keeping-quality of fresh produce, calculates the loss of shelf-life, $L(T)$, per time unit as a function of temperature under the following assumptions:

- Only the temperature histogram with the length of each temperature deviation is important, not the point in time when they occurred.
- Fluctuating temperatures, T(t), over time, *t,* have no other effect than a constant temperature which is equal to the average of T(t), weighted by the function *L(T)*.

The effect of condensation caused by temperature fluctuations (Nunes et al., 2014) is neglected in simple models but should be considered in advanced studies.

In the simplest form, $f(T)$ is defined by the Q_{10} factor, which describes the extent to which chemical processes are accelerated by a temperature increase of 10°C, with typical values of $2 \le Q_{10} \le 3$, for $L(T_{Ref}) = 1$.

$$L_{Q(T)} = Q_{10}^{\frac{T-T_{Ref}}{10°C}} \tag{2}$$

A comparatively more accurate estimation of the speed of chemical processes is given by the Arrhenius law (Eq. 3), for the reaction rate in comparison to T_{Ref}, where E_A is the activation energy of the chemical reaction in J/mol, R is the universal gas constant (8.314 J/mol·K), and temperatures are in Kelvin.

$$L(T) = e^{\frac{E_A}{R} \cdot \left(\frac{1}{T_{Ref}} - \frac{1}{T}\right)} \tag{3}$$

For a constant temperature, the relation between total shelf-life, $S(T)$, and shelf-life at the reference temperature, S_{Ref}, is given by Eq. (4):

$$S(T) = \frac{S_{Ref}}{L(T)} \tag{4}$$

After defining a reference temperature, S_{Ref} can be evaluated in laboratory experiments. Instead of deriving the missing E_A constant from a model for the complex chemical reactions, it can be estimated by curve fitting to experimental shelf-life data for different temperatures. Table 1 shows the experimental data on the remaining green-life for bananas after arrival in Germany. The following parameters were fitted to the Arrhenius function: T_{Ref} = 13°C; S_{Ref} = 33.5 days; E_A = 95,500 J/mol.

Table 1: Green-life of bananas as a function of storage temperature, following trans-ocean transportation at 14.4°C according to laboratory tests (Jedermann et al., 2014b). For green-life since the point of harvest, 14 days of transport duration have to be added. Available data were insufficient for calculation of the standard deviation for temperatures ≥25°C

Temperature (°C)	Green-life (days)
12	37.5±5.47
15	28.0±5.05

18	15.5±3.90
20	11.0±1.44
25	7.6
30	4.0

The loss per day, *L*(*T*), denotes how much the quality loss is accelerated by increased temperature (Fig. 4) E.g. for bananas, 2 days of green-life are lost per day of storage at 18°C.

Fig. 4: Accelerated green-life loss of bananas as function of temperature.

This model can easily be extended to dynamic temperatures. The *L*(*T*) has to be calculated for short time intervals and subtracted from the initial shelf- or green-life:

$$S(t) = S_{Ref} - \int_0^t L\big(T(\tau)\big)\partial\tau \qquad (5)$$

This model has been applied to numerous food products. Several data loggers rely on such simple models, to provide a shelf-life prediction as an add-on (section 5). Tijskens et al. (1996) listed parameters for 60 species of fruits and vegetables, but their parameters need to be updated, according to new types and varieties.

4.4 Advanced models

The prediction accuracy of such simple models should be verified by cross-validation with additional test series e.g. with temperature peaks at various points in time. If the deviations from the model prediction are larger than what can be expected by biological variance, a more complex model should be considered.

If the quality mainly depends on the growth of a specific spoilage organism, standard growth models are often used to predict shelf-life, especially, for meat and fish products. The logistic model describes bacterial growth by a lag phase, followed by exponential growth and saturation. The lag phase is required by the bacteria to mature and adapt to the nutrients in their environment before growth occurs. Four parameters have to be adjusted to fit the logistic model to experimental data for the specific product. Alternate standard models include the Gompertz equation and Michaelis–Menten kinetics.

If product quality depends mainly on a small set of chemical or enzyme reactions, e.g., the degeneration of vitamin C, chlorophyll or a colour pigment, kinetic modelling can be applied to predict shelf-life. Each reaction has to be translated to a differential equation with certain E_A.

Example models can be found in the supplement to Gwanpua et al. (2015), including a kinetic model for apples and a logistic model for cooked ham. The food refrigeration innovations for safety, consumers' benefit, environmental impact and energy optimisation along the cold chain in Europe (FRISBEE) tool provides an online model for six example food products. This tool also allows calculating the energy use and global warming impact of refrigeration technologies. A further overview of existing models and simulation tools can be found in Ndraha et al. (2018) and Gwanpua et al. (2015).

5 Identify, quantify and mitigate temperature abuse

The first step to reducing losses along the cool chain is to analyse the location, magnitude and the frequency of temperature deviations. Critical steps and logistic service providers have to be identified, and gaps in the cool chain must be closed. The effect of remaining temperature variations can be evaluated by shelf-life models.

5.1 Temperature monitoring hardware

The analysis of temperature variation in the cool chain typically requires packing the product together with sensors for multiple locations in the cargo hold and repeating the tests several times. A large variety of temperature recorders and transmitters are available on the market. The selected device should be suitable for the initial analysis of the chain processes, as well as for temperature monitoring in daily business. The available devices can be categorised by their type of communication interface. In the following bullet points, one exemplary device per category is described. A more concise overview of the available hardware can be found in Jedermann et al. (2017b).

- Data loggers that operate entirely offline, generally provide the smallest and cheapest solutions. The readout is only possible by manual handling (e.g., by electrically connecting the device to a handheld reader). The Maxim iButton® data loggers (Maxim Integrated, USA) can store 4000 temperature values with a resolution of 0.0625°C.
- Semi-passive loggers use radio frequency identification (RFID)-based data transmission. Only a small battery is necessary for the measurement system, but not for communication. The Easy2log© RT0005 ultra-high frequency logger tag (CAEN RFID, Italy) is compatible with 868 and 915 MHz RFID standard protocols. It stores 4000 temperature measurements, and the reading range is up to 10 m. The software of the tag is also able to calculate a shelf-life prediction.
- Wireless temperature loggers with active communication use either standard protocols, such as Bluetooth or ZigBee, in the 2.4 GHz band, or proprietary protocols at 868 or 915 MHz. The communication range of these devices is typically between 10 and 100 m, which is sufficient for integration into an automated system for data readout and upload, e.g. by installing a network of communication gateways at loading platforms in the warehouse, or in trucks. The Verigo™ Pod (USA) records 40,000 temperature measurements, and all data can be obtained instantaneously through wireless communication with any smartphone, which then uploads the data to a cloud server. The advanced version, Verigo™ Pod Quality, provides an integrated shelf-life model with 20 pre-defined parameter sets. Threshold over-stepping is indicated by a light-emitting diode.
- Global system for mobile communications (**GSM**) loggers provide worldwide communication via cellular networks. The MOST® device (MOST Mobile and Sensory Technologies, Sweden) collects data during sea transportation that is then uploaded on arrival at a harbour when a GSM network is in range.

For the wireless devices, radio communication is hindered by the metal walls of containers and the water content of food products. Reading data through several pallets stowed to a container is hardly possible, especially if the radio operates in the 2.4 GHz range. During tests with bananas, the radio signal was attenuated by -60 dB/m (Jedermann et al., 2014c). Frequencies in the sub-GHz range have an attenuation of <10 dB/m and should, therefore, be preferred.

Jevinger et al. (2014) emphasised that if the temperature sensor is to be used for shelf-life prediction, it must provide sufficient accuracy. A deviation of the sensor readings by 0.5°C resulted in an offset of 0.7 days or 8% of the total shelf-life of cod stored at 4°C.

5.2 Action 1: Improve the cool chain and handling

The first and most important action to reduce food losses is to close gaps in the cool chain. Several causes can lead to cool chain ruptures (section 2.4), such as leaving a pallet on the loading platform without cooling for several hours. Such problems should be identified by repeated data logger monitoring in daily operation and mitigated by the better instruction of staff and definition of tolerance levels for transport, trans-shipment and cooling processes.

The result of a data logger study might also indicate that processes have to be modified, for instance, excluding old reefer containers with insufficient cooling or ensuring that pre-cooling has already occurred at the farm. The importance of pre-cooling was highlighted by Pelletier et al. (2011), who confirmed the rule-of-thumb that 1-hour delay in pre-cooling costs 1 day of shelf-life. Strawberries that were directly pre-cooled after harvest to 1.7°C had significantly better quality on arrival at the retail outlet than pallets for which pre-cooling was delayed for 4 hours, or pallets that were directly cooled, but only to 10°C.

Lowering the set-point might seem an obvious solution to compensate for a poor ventilation condition or solve other cooling issues, but it is only feasible on rare occasions. Fruits with origin in warm climate zones are often sensitive to so called chilling injuries, e.g. the storage temperature for bananas should not fall below 13°C; 8 hours at 10°C causes permanent damage to green bananas (Jedermann et al., 2014b). During our tests, we demonstrated that the set-point for ocean transportation of bananas could be lowered from 13.9 to 13.0°C, if up-to-date equipment, with exact control of the reefer supply air, is used. Otherwise, vertical temperature differences cause chilling injuries in the bottom layer of boxes, even if the temperature in the centre of the pallet is in range.

Most vegetables and fresh meat are transported at slightly above 0°C. Even partial freezing damages vegetables or the meat can no longer be sold as “fresh meat”.

5.3 Improving cooling performance

The manner in which the products are packed and pallets are stowed to the container has a large impact on the performance of cooling. We found that the actual heat removed from pallets with banana boxes amounts to only 6% of the theoretical cooling capacity of the reefer unit (Jedermann et al., 2014b), indicating a small share of the cooling air provided by the unit, arrives at the centre of the boxes containing fruits. In consequence, the return air temperature quickly falls below the fruit temperature. Without a significant difference between supply air set-point and return air temperature the unit cannot operate at its full capacity. By combining four independent modifications, we were able to increase the heat removal to 10% of the theoretical cooling capacity. A more even distribution of the width of the gaps between the pallets was achieved by mounting spacers at their corners. The stowage scheme of the pallets was modified so that four pallets each, were arranged around a chimney of 20 × 20 cm, to improve the airflow. The top of the chimney was closed by a foam block. Additional vent holes at the edges of the boxes increased the airflow through the packing. The bananas were packed into two separate foil bags per box, instead of one, to form an additional gap in-between and increase the airflow through the boxes.

The first study of Defraeye et al. (2015) on the feasibility of ambient cooling of citrus fruit confirmed that the limiting factor was not the available capacity of the unit, but the actual heat removed from the boxes, which was much lower than expected, due to airflow hindrance by the packing. Only after improving the packing and modifying the stowage layout to channel more airflow through the pallets ambient cooling became feasible and the actual heat removed came close to the unit’s capacity (Defraeye et al., 2016).

Fresh fruits and vegetables are often packed in plastic films or liners to prevent moisture loss, for which the liners are optimised. This positive effect has to be balanced against the reduced airflow and cooling, e.g. by inserting some holes in the liners (Ambaw et al., 2017).

A simulation study on deviating airflow and cooling conditions (Jedermann et al., 2017a) in banana containers, indicated a 20% reduction in the air supply speed had the highest impact on the average temperature of the boxes, followed by a container with a missing foam block, for preventing short-circuit air circulation at the door end. This latter packing mistake also caused large local peaks. Further large local peaks were associated with the misalignment of the vent holes of neighbouring boxes, thereby blocking airflow in one horizontal layer.

5.4 Relate observed temperature variation to shelf-life

Shelf-life modelling allows predicting the significance of temperature variations on the product quality. The extra days of shelf-life gained by improving the processes and equipment have to be balanced against the necessary investment costs.

Reducing the shelf-life variance is as important as increasing its average value. The time span for the use-by date and related safety margins must be adjusted, according to the predicted shelf-life for worst-case temperatures. A high variance and lack of knowledge of the actual shelf-life of a products batch makes it necessary to increase safety margins.

A cool chain simulation (Fig. 5) was performed on the recorded temperatures of pallets with bananas during ocean transportation, given in Fig. 3, and the simulation was continued for handling after the container arrived in Europe, for constant storage temperatures. The worst-case comprises the warmest pallet in the container combined with subsequent storage at 15°C while the best case is the coldest pallet and storage at 13°C. The reference pallet represents a temperature close to the average of the container, subsequently stored at 14°C. The predicted remaining green-life for each scenario is given as a function of time.

Fig. 5: Simulation of green-life loss along the cool-chain. Temperature recordings from 3 different pallets of a real transport were combined with a simulated subsequent storage at 13°C, 14°C and 15°C, respectively. If an average pallet should have 10 days of remaining green-life as safety margin, ripening has to start until 27.1 days after harvest or 14.3 days after arrival of the ship.

The artificial ripening process must begin before the bananas are expected to undergo uncontrolled ripening. The biological variance of green-life makes it necessary to assign a certain safety margin between the start of ripening and the predicted end of green-life. E.g. for a safety margin of 10 days, further processing of the bananas has to start until day 27 after harvest, leaving 2 weeks for handling within Europe.

At this moment, the worst-case pallet has a remaining green-life of fewer than 2 days. Due to the biological variance of typically 5 days, it might fall below the zero line, turn yellow, and thereby leave the pallet unsuitable for commercial processing. The best pallet is predicted to keep green until day 42.3, permitting almost double the time for handling. A simulated pre-cooling to 14°C within 12 hours would yield 5 days of extra green-life.

Similar cool chain simulations can be found in the literature:

- Jevinger et al. (2014) monitored the temperature of eight test packages with cod along the cool chain from production to household. They observed variations between the packages of 1°C. The resulting shelf-life difference of 1.4 days is equivalent to 16% of the products total shelf-life of 8.6 days at the recommended 4°C.
- A later study by the same authors (Göransson et al., 2018) found shelf-life variances of -0.2 to +0.3 days relative to the fixed use-by date. The negative value means that the printed use-by date has been violated. The shelf-life variation amounts to a maximum of 12% of the time span, for a distribution of 2.5 days.
- Wu et al. (2018) combined a computational fluid dynamics simulation for airflow inside a box containing citrus fruits with a shelf-life model to predict temperature and quality changes over time. Results revealed that even inside one box, the shelf-life varied by 4% after container transportation for 40 days. Several cool chain scenarios, such as pre-cooling versus ambient loading led to variances of 5%, for a first-order shelf-life model, like the Arrhenius model described above.

- The online version of the FRISBEE tool allows combining shelf-life models with recorded cool chain scenarios. However, the actual temperature variation might be higher than in the pre-defined optimal situations.

6 Remote monitoring and FEFO application

While a general study on the performance of a certain cool chain can be done by fully offline data loggers, a further adaption of cool chain processes to the actual quality state of the product is only possible if, at least at some control points, the sensor and temperature information is visible. Typical control points are trans-shipment processes, in which gateways are installed for automated readout of sensor data at loading platforms, or by manually reading temperature data using a handheld reader. Full real-time visibility to access sensor data, even if the product is currently "on the road", is relatively more expensive but enables faster reaction to any problem and provides more time for adjusting warehouse management and delivery planning.

6.1 The "intelligent container"

Our research project called the "intelligent container", which started more than 10 years ago, aims to provide real-time access to core temperature and quality data from pallets with bananas stowed in an ocean container. The first pilot tests were conducted in 2009, on a prototype container.

The project covered the complete information chain. Sensors were packed inside the pallets. The sensor data were processed by a so-called freight supervision unit (**FSU**) mounted beside the container's cooling unit. GSM and satellite communication were used for sending notifications about critical events. Finally, data were stored and displayed by web and database services.

Twenty wireless sensors for temperature and humidity were packed into four test pallets in separate fruit boxes. The sensor notes formed a mesh network, to forward their data to the FSU by using the Institute of Electrical and Electronics Engineers IEEE 802.15.4 protocol, at 2.4 GHz. The processing of the sensor data directly in the container was one of the key concepts of the project. The FSU used shelf-life models to examine the effect of temperature deviations. Expensive satellite communication could be reduced to notifications regarding critical events and one status message per day.

The FSU used the satellite communication system of the vessel for external communication during the first field tests. For later tests, in 2012 and 2013, the FSU was equipped with its own satellite communication module to access the Iridium network (Iridium Satellite Communications, USA). During road transportation and harbour operation, the FSU can also be accessed over the GSM network. Further details of the technical system can be found in Jedermann et al. (Jedermann et al., 2014c).

A list of other public research projects and commercial hardware can be found in Jedermann et al. (2017b). These examples include the aforementioned FRISBEE project to predict shelf-life and greenhouse gas emission based on recorded cool chain scenarios (Gwanpua et al., 2015), and the DynahMat project coordinated by Lund University (Sweden), for dynamic shelf-life labelling (Jevinger 2014).

6.2 Remote container monitoring (RCM)

Besides these research projects and the vast amount of temperature logger types, a new class of real-time commercial transport monitoring systems has found wide industrial applications.

Remote container monitoring (**RCM**) units enable remote readout of reefer status information, such as the supply and return air temperature, set-point, humidity, power connection and engine state. The main focus of RCM solutions is ensuring the cooling unit works correctly at the prescribed set-point and providing improved planning of machinery maintenance.

The RCM unit with the highest industrial impact is provided by Orbcomm™ (Orbcomm Inc., USA). Maersk Line (Maerk, Inc., Denmark) installed their telematics unit in all their 280,000 containers and made the service available to customers since 2017 (Zarkani et al., 2016). The unit uses the GSM standard for communication. The existing ashore network infrastructure can be used, and no specific gateways are required. For offshore communication, Maersk Line installed GSM gateways on more than 400 of their vessels, enabling global uninterrupted real-time access. For transportation on third-party vessels and tracking of high-value goods, Orbcomm™ offers a dual mode telematics unit with additional satellite communication.

6.3 Link to wireless temperature loggers

The idea of connecting temperature loggers inside the loaded goods with RCM systems is straightforward. Nevertheless, it has rarely been applied in commercial solutions. Orbcomm™ only offers a wireless interface for sensors mounted under the ceiling of the cargo hold while sensors to measure the product's core temperature are not provided, though acknowledge the need for such systems in the future (Orbcomm, 2016).

The incompatibility between wireless temperature loggers and RCM systems is primarily attributable to their distinct customer groups. The manufacturers of RCM solutions focus on the expectations of reefer container providers and carriers as their customers, whose main interest is to prove their units are operating correctly, without interruption, and supply cooling air at the requested set-point. The actual content of the container is not of their interest.

The owner of the perishable product is mainly interested in monitoring the product's core temperature and purchases a separate sensor system from an independent company. As a result, wireless temperature loggers and RCM systems have developed independently, without growing together into common communication interfaces and standards. Hardware manufacturers are more interested in selling their own database and cloud solutions instead of supporting open standards and letting others do the lucrative data management business.

Creating a common business case among the multiple participants in a cool chain is one of the key challenges to fostering remote product temperature monitoring. From interviewing cool chain agents, Jevinger et al. (2014) stress the '*importance of sharing costs among the involved actors*'. For example, the producer has to install sensors during packing, and the shipping company has to install RCM and pay for communications costs, without receiving direct revenue from extending the shelf-life in the retail outlet.

6.4 Action 2: Detect actual problems and find remedy

If information on the container status and product temperature are available by remote access, issues can be detected in real-time. The term "live data" is also used to describe the permanent availability of a communication link to the container. Most problems can be avoided or mitigated by access to such live data. Maersk Line state, for instance, that '*more than 59% of reefer claims stem from malfunctioning reefer units, poor supplier handling of off-power periods and wrong temperature set points*' (Orbcomm, 2016).

Even if the problem is caused by the freight or its packing and cannot be mitigated during ocean transportation, the information about actual or expected quality problems is of high commercial value. As an example, if a quality problem is detected only after opening a container with bananas some days after arrival in Europe, two more weekly deliveries from the same farm with most likely the same problem have already been shipped. With access to live data, the farm can be informed to verify their harvest, handling and packing practices, and to check for fungal infections.

After arrival of the vessel, it can take up to 4 days until a banana container is unloaded and the pallets are transferred to the warehouse. Live data helps to prioritise, which container should be processed first.

Banana cartons are often branded for a specific retailer. In case that a container dedicated to a particular customer, is lost due to quality problems, early information is crucial to arranging a suitable replacement. This scenario is even more relevant for products that unlike bananas, are only shipped in low quantities.

6.5 Action 3: Apply intelligent stock rotation to minimise losses

If a direct remedy of cooling problems is impossible, and the actual loss of shelf-life can be predicted by a model, the amount of resulting food losses can be reduced, by intelligent stock rotation. The FEFO concept can be applied on the precondition that the remaining shelf-life of every product batch can be either directly evaluated or predicted, based on the temperature history. Low-quality items are assigned to immediate delivery on the shortest transport routes.

FEFO does not increase the average shelf-life at point-of-delivery but improves the use of existing shelf-life variation. It avoids delivering items of unacceptable quality below the zero shelf-life threshold to some customers and items exhibiting an unnecessarily large shelf-life buffer to other customers. Instead, all customers should obtain about the same amount of remaining shelf-life. In mathematical terms, the FEFO approach optimises delivery planning, by the variance of expected shelf-life at point-of-delivery as a cost function, and on the boundary condition that the shelf-life should always be above zero or a defined threshold.

A survey by Jedermann et al. (2014a) demonstrated the ability of FEFO to reduce food losses by 8–14% of the total transported goods (Fig. 6). Examples included an 8% reduction in losses for cooked ham (Koutsoumani et al., 2005), 14% for strawberries (Emond et al., 2006), 10% for sea bream (Tsironi et al., 2008) and 13% for fresh pork chops (Tromp 2012).

Fig. 6. Comparison of share of product losses for different products with a) random delivery due to lack of quality information and b) shelf-life based stock rotation according to the FEFO approach. Figure adapted from Jedermann et al. (2014) with permission.

Nunes et al. (2014) found 10 days difference between the shortest and longest supply chain, during a study on blackberries. This difference can be used to compensate for shelf-life variations. The authors observed 57% of blackberries had an insufficient shelf-life for the longest supply route. If only berries with a good temperature history and high remaining shelf-life were assigned to these routes, only 1% of the berries would decay before arrival. An average percentage of loss reduction could not be calculated because the exact distribution of delivery times was not provided by the trading company.

These examples show that FEFO can contribute considerably to the reduction of food losses for some products, particularly, high-perishable products, for which a high share of their total shelf-life is consumed by supply chain processes, e.g. by trans-ocean container transport or truck transportation over several days. For shorter chains, such as the delivery of cod in Sweden (Göransson 2018) within a maximum of 2.5 days, the observed shelf-life variance ranging from -0.2 to +0.3 days was too small to gain benefits by FEFO management. Nunes et al. (2014) added that FEFO performs best in peak supply periods. In periods with insufficient supply, the gross retailer has to ship what is at hand.

7 Recent research activities

The remote monitoring of product core temperature has become close to commercialisation. Current research activities are mostly focused on improvements in communication, additional sensor types to measure direct quality indicators and integration of such sensors into intelligent packing, accompanied by prototype tests of wireless sensors for freight monitoring.

7.1 Research prototypes

A couple of new wireless sensor prototypes have been developed in the recent years. Typically, the feasibility of the suggested solution was only demonstrated on a single transport, as in the following examples:

- Xiao et al. (2016) developed a wireless solution for monitoring the supply chain of frozen fish from catch, processing, storage and 15 days of truck transportation, until storage and retail. The focus was on mathematical models to reduce the data volume for transmission over GSM networks by compressed sensing. Shelf-life was predicted using a Gompertz model.
- Thakur et al. (2015) applied RFID data loggers to demonstrate the remote monitoring of chilled lamb products.

- Ruckebusch et al. (2018) tested the communication of wireless sensors through a stack of empty containers at various frequencies. The effect of water-containing products was not considered in this study, so it is less relevant to the food chain compared to the above examples.

Large pilot tests demonstrating cool chain management, based on remote product quality and core temperature measurements, are still scarce. The one known example was conducted on kiwifruits, by Bollen et al. (2015), with tests repeated over 3 years with 20,000 sensors each.

7.2 Communication

The establishment of a widely accepted standard for communication of wireless temperature loggers is the key challenge in communication, with the long-range wide-area-network (LoRaWAN™/LoRa Alliance™, USA) standard as a promising candidate (Silva et al., 2017). LoRaWAN™ is dedicated to the Internet-of-Things applications. Devices have a unique ID, sensor data are transferred by a network of gateways to a cloud server. All transmissions are encrypted. The decrypted data can only be queried from the cloud server by sending a private application key. Separate operators can use the same network of third party or public gateways without losing their privacy. Public LoRaWAN™ access is supported by several research organisations e.g. in Zürich, Bern, Amsterdam and Berlin.

LoRaWAN™ operates at sub-GHz frequencies and is less affected by the water content of food products than other 2.4 GHz wireless devices. During a test in 2017, we showed that LoRaWAN™ could transfer sensor data through a 5 m bulk of apples.

LoRaWAN™ is not designated for data processing on the gateway, according to its encryption concept, which makes it difficult to analyse the temperature data directly in the container, as in our project, and to reduce communication to the detection of critical events. The telematics units from Globe Tracker®, Denmark use only a rudimentary long-range (LoRa) standard, without encryption keys, to provide feedback control of the reefer unit parameters through up to 64 LoRa wireless sensors packed inside the cargo.

Another general problem is the connection of the container's internal network with the outside world. Fort et al. (2018) illustrated a solution to transmit data from the cargo hold by ultrasonic communication to a wireless gateway mounted on the outer surface of the container. The prototype was only tested with non-insulated containers. The effect of the thermal foam isolation on ultrasonic communication remains to be verified in further tests.

7.3 Alternative sensors

Although temperature is the most influential factor for quality, and sensors are cheap, small and easy to integrate, it has to be questioned, if and how quality monitoring systems can be enhanced by additional sensors. Advanced versions of several wireless data loggers already include integrated humidity sensors. However it has to be taken into consideration that many humidity sensors measure inaccurate in the high humidity range over 95% and are sensitive to condensation.

Modified atmosphere storage or packing is often used to prolong the shelf-life by reducing O_2 and increasing CO_2. The effectiveness of such packing can be more accurately quantified if measurements of the actual gas concentrations are available. For climacteric fruits, such as bananas, ethylene gas is an indicator and also a trigger of ripening processes. Mobile ethylene sensors with resolution in the parts-per-billion range, for example, were developed by Janssen et al. (2014).

Besides the increased cost, there are several problems concerning the integration of gas sensors into food quality monitoring systems. Gas concentrations are diluted by an often, unknown air exchange rate. Most sensor elements are affected by ageing. Furthermore, high air humidity of typically more than 90% during transportation of fresh fruits, causes cross-sensitivities.

Sensor systems to measure gas concentration at the packing or pallet level, are still in a prototype state. Wang et al. (2017) presented a wireless multi-gas sensor system to monitor the sulphur dioxide (SO_2) treatment of table grapes. The SO_2 is released from a pad inside the packing. Additional sensors measure O_2 and CO_2 concentrations. Data is transmitted via 433 MHz, to achieve good communication through the fruits.

As a step towards predicting the shelf-life of perishable produce, exemplified using strawberries, Scalia et al. (2015) developed a smart logistic unit that measures the volatile organic components emitted by microorganisms, combined with temperature, humidity and CO_2 sensors. The unit is based on commercial sensors and, additionally, equipped with global positioning system location and GSM communication capabilities.

High resolution anemometers were packed to apple bins by Geyer et al. (2018) to verify and improve the flow of cooling air in warehouses. Similar devices can also be applied to reefer containers.

7.4 Intelligent packing

A lot of research has focused on intelligent packing during the recent years. A marker on the packing indicates by colour change a loss of shelf-life or harmful conditions for the product. Time-temperature integrators have been in use for more than 10 years (Eichen et al., 2008). These devices rely on a chemical reaction with similar E_A as the packed product, leading to decay of a colour pigment with almost the same temperature dependency as the shelf-life loss.

Other indicators react to N_2, ethanol, CO_2 or ethylene concentrations. Papireddy et al. (Papireddy Vinayaka et al., 2017) fabricated a film to indicate fungal infections of bananas. The perishable management through smart tracking of lifetime and quality by RFID (PASTEUR) project intended to integrate temperature, humidity, CO_2 and ethylene measurements into a multi-sensor RFID tag (Hoofman et al., 2013), although the two gas sensors are still currently under development. New biosensors use an antibody reaction to indicate the presence of a specific pathogen, by the colour change of the carrier film. Further details and examples of intelligent packing can be found in an overview by Ghaani et al. (2016).

8 Summary and conclusions

Food losses are present in every step of the cool chain, but their exact amount is hard to quantify. Usually, losses are attributed to either production, processing, distribution, retail or the customer, according to the stage, during which, a severe quality loss deemed the product no longer suitable for human consumption. This common approach entails two problems. First, quality problems caused by inadequate transport and storage conditions only become visible at advanced stages in the cool chain. Second, the degeneration of food quality is a gradual process, often encompassing multiple contributors.

Hence, we recommend using the extent of temperature abuse and quality loss caused in each step, as a scale to identify weak points in the cool chain. Product-specific shelf-life models are the method of choice to evaluate the effects of temperature abuse, which can be converted to the number of lost days of remaining shelf-life, for improved comparison.

In this paper, we suggested a set of three subsequent actions to reduce food losses along the cool chain. Even if not all three actions are suitable for any cool chain, at the least, the first action should be performed. According to our tests in banana and meat chains, the verification of cool chain processes and identification of weak points due to insufficient or interrupted cooling already offers a great potential to reduce food losses. This first action requires only limited sensor hardware, namely, a set of temperature loggers.

Reading recorded product temperature data at some control points, as second action, or even full real-time access in daily operation is expensive but offers the option to react immediately to cooling issues, e.g. a wrongly adjusted set-point, prolonged power disconnection, a defective reefer unit or packing mistakes. The full implementation of live access to the product temperature is currently hindered by the split of the market into incompatible wireless temperature loggers and remote container monitoring (RCM) systems.

When access to the products temperature history is provided, at least at some control points, intelligent stock rotation, according to the FEFO concept, can be implemented as a third action. Literature studies have shown that FEFO can further reduce food losses by between 8 and 14% of the total volume, although FEFO does not fit for every product and cool chain.

At the end of our project on tracing the quality of bananas by the “Intelligent container”, our partner did not implement a remote monitoring system, mainly because we could not provide ready-to-use sensor hardware in large quantities. Although only the first action was finally achieved, the project was highly beneficial to improve knowledge about temperature problems and the influence of packing and to increase the awareness of insufficient ventilation and cooling power of old containers. The positive effect of a new box design was experimentally verified. A combination with improved pallet–stowage schemes increased the efficiency of heat extraction per banana box, by 60%.

Maersk Line (Maersk, Inc.) already showed the future direction, by equipping all their containers with remote monitoring, although the link to the wireless measurement of product core temperature is still missing. Currently, food operators are often not willing to invest in remote monitoring hardware because electronics is not their business and it is still too cheap to throw food away. The discarding of food will eventually change, by the increasing pressure to feed a growing world population with the limited resources of our planet. Increased demand by food operators for concise remote monitoring of cool chain conditions will force technical island solution to merge into common standards, for sensor data exchange and forwarding, although this process will take some years.

Temperature is the key indicator to predict quality losses. The accuracy of shelf-life prediction can be enhanced by the measurement of direct quality indicators, e.g. by low-cost gas sensors. Research that is summarised under the term “intelligent packing” indicates a trend in this direction.

9 References

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Temperature deviations during transport as cause for food losses

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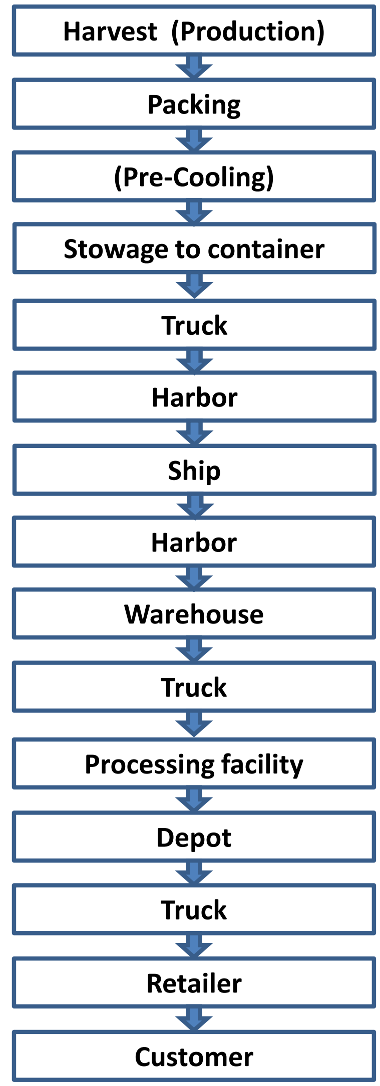
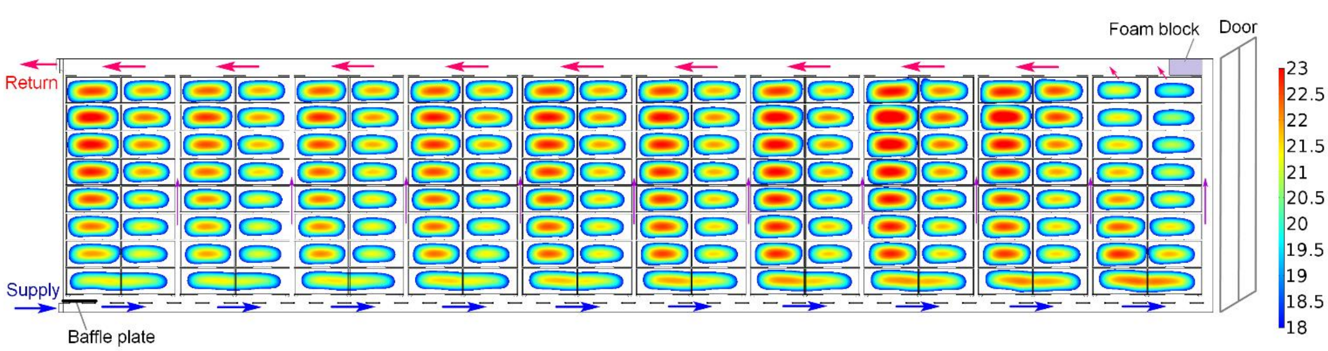


Fig. 1. Typical supply chain for food products, using bananas as an example. Items in parenthesis do not apply to bananas.

Fig. 2. Schematic air flow inside reefer container with palletized bananas. Zones that are still above 18°C at 24 hours after start of cooling are colour marked. The temperatures were calculated according to a two-dimensional air flow simulation. See Jedermann et al. (2017a) for details. Deviations from the actual measured temperatures were caused by the simplified simulation model. Colour legend for temperatures in °C.



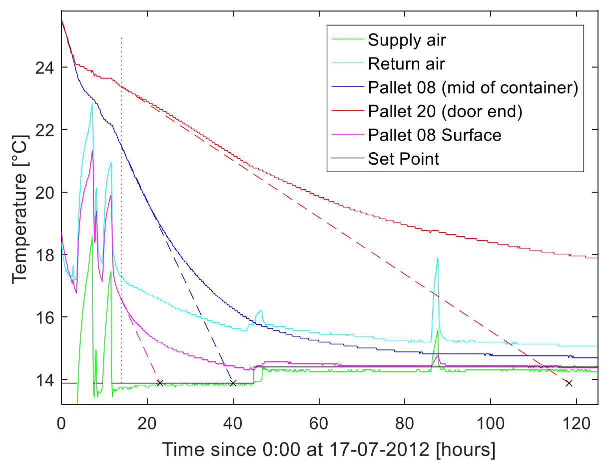


Fig. 3. Temperature records from a test transport of bananas in 2012 for the first 5 days. Reefer container with one-year-old Thermo King Magnum Plus® cooling unit (Ingersoll Rand., Belgium). Supply/Return air, warmest and coldest box centre in one layer 1.5 m above the floor, and a sensor located in the box corner adjunct to the coldest position. Dotted lines illustrate the calculation of initial cooling speed, C_T.

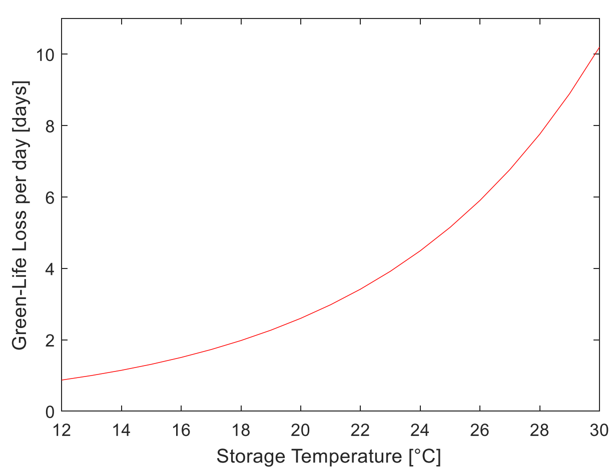


Fig. 4: Accelerated green-life loss of bananas as function of temperature.

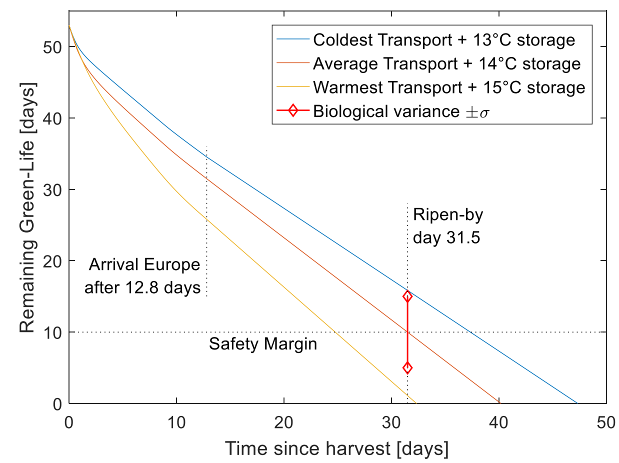


Fig.5: Simulation of green-life loss along the cool-chain. Temperature recordings from 3 different pallets of a real transport were combined with a simulated subsequent storage at 13°C, 14°C and 15°C, respectively. If an average pallet should have 10 days of remaining green-life as safety margin, ripening has to start until 27.1 days after harvest or 14.3 days after arrival of the ship.

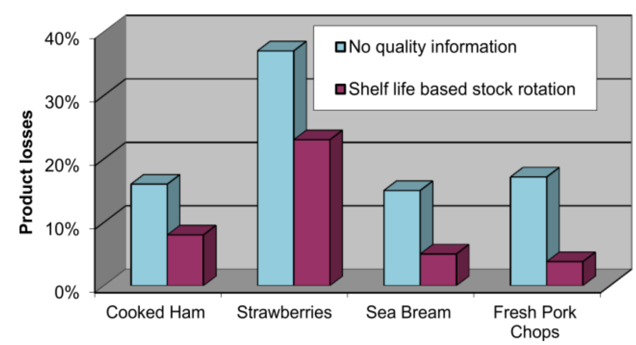


Fig. 6. Comparison of share of product losses for different products with a) random delivery due to lack of quality information and b) shelf-life based stock rotation according to the FEFO approach. Figure adapted from Jedermann et al. (2014) with permission.