Challenges and opportunities in remote monitoring of perishable products

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Abstract: Temperature deviations during transport and storage still cause a significant amount of food loss. A large portion of this loss could be avoided if information regarding deviating transport conditions and resulting changes in remaining shelf life of packed food would be available in real-time. In this study, we detail a prototype of such an intelligent container. The technical system, and results from tests in trans-ocean transportation of bananas are presented. The system is also able to predict hot-spots, which were identified as the most crucial risk for product loss. Although several technical solutions for remote container monitoring (RCM) and wireless temperature data logging are available on the market, a wide application of the concept of real-time shelf life monitoring is still lacking. Most problems result from the splitting of the cold chain into multiple actors, and different manufacturers and target customer groups for RMC and for wireless sensor systems.

Keywords: Shelf life simulation; first expires first out; cold chain management; intelligent container.

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1 Introduction

Approximately one third of all produced food products is lost on the way from farm to fork (Gustavsson, Cederberg, Sonesson, Otterdijk & Meybeck 2011). A significant share of these losses can be attributed to inadequate transport conditions, particularly temperature abuse in the supply chain. In general, the effects of a temperature problem become visible only much later in the chain.

With real-time remote temperature monitoring, it is possible to detect abnormal transport conditions and to take adequate countermeasures. This concept was extended to Quality oriented Tracking and Tracing (QTT) by Scheer (Scheer 2006). The quality of the product can be calculated based on a shelf life model (Tijskens, 2004), with the temperature history of the product as input. The predicted remaining shelf life gives the number of days during which the product can be kept in store before its quality falls below an acceptable threshold, whereupon the consumer is unlikely to purchase it.

For example, a tomato that has been exposed to the wrong temperature during transport may look of good quality for one week in the warehouse, but then suddenly become unsightly in the retailer's outlet long before the expected best-before date, even if the retailer had complied with best practice handling instructions. With shelf life modelling, it is possible to predict such hidden quality degradation based on the product's time-temperature history.

The QTT concept can be linked with a First-Expires-First-Out (FEFO) approach for intelligent stock rotation (Koutsoumani, Taoukis & Nychas, 2005), (Lang & Jedermann 2016). Products with shorter shelf life are immediately sold in nearby stores; products with longer shelf life can be used for export with longer transport duration, or kept for later delivery. Studies have shown that for highly perishable products such as strawberries (Emond & Nicometo, 2006), sea bream (Tsironi, Gogou & Taoukis, 2008) and fresh pork chops (Tromp, Rijgersberg, Pereira da Silva & Bartels, 2012), the total amount of lost products by quality deterioration can be reduced by up to 14% using this concept.

Shelf life modelling requires measurement of the product's core temperature, or at least directly at the product packing. Measurements of return or supply air, or at the pallet surface, give very little information regarding the actual product temperature (Section 2.1).

In recent years, there have been several large research projects undertaken to develop necessary hardware, shelf life models and prototype systems for QTT and FEFO systems (Table 1). The CHILL-ON project focused on development of a bacterial growth model to predict, detect, and ultimately avoid food safety hazards in fish and poultry supply chains. They developed a battery-less Time-Temperature-Indicator (TTI) that can be integrated into intelligent packing. It consists of a chemical substance with kinetics which corresponded to the temperature-dependency of bacterial growth, and an RFID interface providing wireless read-out of the current product quality.

The goal of the PASTEUR project was the development of a multi-sensor RFID tag, containing temperature, humidity and gas sensors for quality prediction. During the 'Intelligent Container' project, a full-scale prototype for remote monitoring was constructed and tested, including wireless core temperature measurement, data processing and shelf life modelling at the container level, and external communication.

The FRISBEE project focused on offline analysis of temperature data and shelf life modelling. A simulation tool predicts the effects of modifications in the cold chain with regard to food loss and CO_2 emissions.

The goal of the DANAHMAT project was to replace static expiration dates with dynamic shelf life labelling by using intelligent logistics and packing systems as well as evaluation of different sensor technologies, shelf-life models and Information and communications technology (ICT) solutions.

Table 1: Large research projects related to remote quality monitoring

Project/ Reference	**Duration/ Sponsor**	**Focus**	**Webpage**
Chill-On (Olafsdottir, et al., 2010)	2006-2010, European Union	Battery-less chemical TTI with RFID interface	http://www.chill-on.com/
PASTEUR (Hoofman, 2013)	2009-2012, European Catrene network	Multi-Sensor RFID Tag	http://www.en.nvc.nl/pasteur-sensor-enabled-rfid/

Intelligent container (Jedermann, Lloyd & Poetsch, 2014)	2010-2013, BMBF, Germany	Prototype container for QTT and FEFO	http://www.intelligentcontainer.com/
FRISBEE (Gwanpua et al., 2015)	2010-2014, European Union	Simulation and database for shelf-life models and temperature mapping	http://frisbeetool.eu/FrisbeeTool/about.html
DANAHMAT (Jevinger, Göransson & Båth, 2014)	2013-2016, Sweden	Concepts for dynamic shelf life labelling	http://dynahmat.com/en/

In this paper, we will first examine one of these projects (sections 2 and 3). The 'Intelligent Container' provides the most concise technical prototype solution. Our field tests confirmed that adequate packing is an essential component to optimize cooling. A combination of modified packing and stowage schemes led to significant improvements (section 3.5).

Despite the research efforts of recent years, these concepts have not generally been put into daily practice in the food supply chain. In the second part of this paper (sections 4 and 5), we aim to answer the following question: What are the obstacles and new changes with respect to the implementation of QTT and FEFO in the cold chain? On one hand, new commercial systems for remote container monitoring (section 4) have come to the market, but they are restricted to GPS tracing of container locations and monitoring of the reefer/cooling machine state, and offer only few options to monitor the temperature and condition of the products inside the cargo hold. On the other hand, several wireless temperature data loggers have been established in the market. From the hardware side, it is easy to integrate shelf life models into these loggers (Jedermann, Edmond & Lang, 2008), as for example the temperature tag from CAEN-RFID does (see Table 3). Options for real-time access are mostly limited to stationary installations, e.g. in agriculture or monitoring of warehouses, or, not provided at all.

The current situation can be summarized as follows: There is sufficient choice of the necessary individual hardware components, but hardly any solutions to link these components in order to provide real-time remote access to freight core temperature and quality conditions.

2 Technical system and field tests with the intelligent container

Wireless sensors for core temperature monitoring can have only a limited communication range, due to cost and size limitations, the requirement for a battery life of several weeks or months, and shielding effects by the metal container walls. Therefore, the communication system for remote food quality monitoring falls into three parts: the internal low-power short-range network which collects core temperature measurements inside the container, external long-range communication by GSM cellular or satellite services, and a gateway to bridge these two systems (Figure 1).

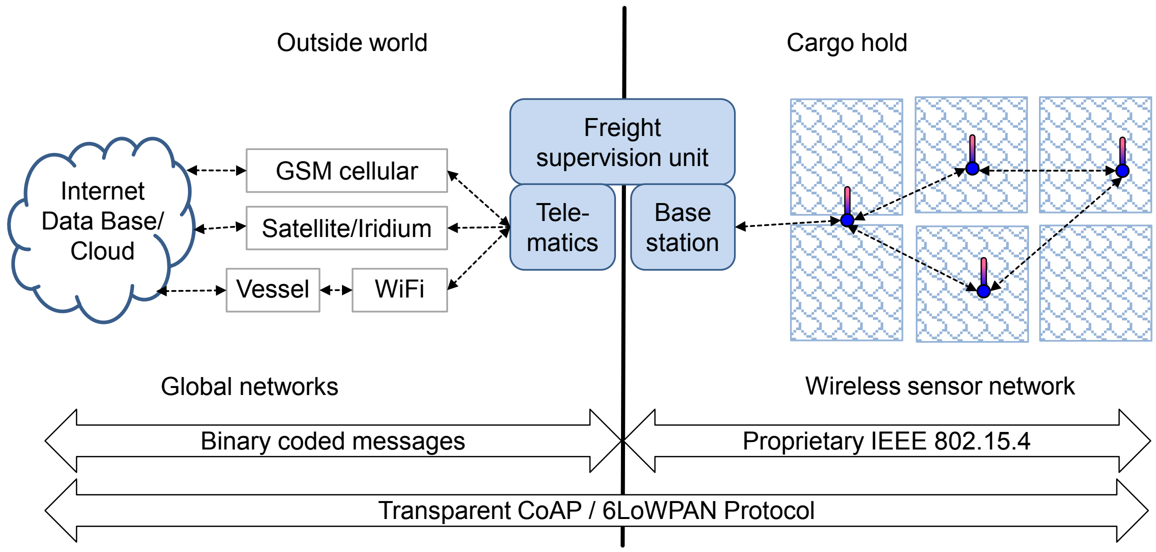

Figure 1: Communication system of the intelligent container

During field tests of the intelligent container, 20 wireless sensors were packed inside boxes containing fruit (Jedermann, Lloyd & Poetsch, 2014). The hardware of the sensors essentially consists of the TelosB 2.4 GHz platform. In order to keep the communication overhead as small as possible, we used the proprietary BananaHop protocol (Jedermann, Becker, Görg & Lang, 2011) based on the IEEE 802.15.4 standard for transmitting temperature and humidity data to the base station. This protocol supports mesh networks with up to 6 hops. It is optimized for small data packets with measurement intervals of 1 minute or longer. The data are collected and processed by the so-called freight supervision unit (FSU), which was implemented on an embedded vehicular PC platform. Power supply was provided by the cooling engine. The FSU forwards the sensor data over different telematics units and global communication networks to a database service. Ashore and close to the coastal strip, GSM cellular networks can be used to provide full access to the sensor data by a web browser. Offshore, only satellite networks are available. The container was placed on deck in the topmost layer. Additional tests ashore showed that satellite communication is still possible if one or two containers are stacked above the container with the FSU. Due to higher communication costs, the FSU sends only short warning messages on shelf life losses, or other unexpected events, in a binary format. In an earlier version of the system, the FSU used Wi-Fi to connect to the communication system of the vessel, which then forwarded messages by an email service over satellite.

The BananaHop protocol has the disadvantage that it is limited to 31 sensors and a fixed format of the sensor data. To overcome this disadvantage and to provide more flexibility to include new sensor types and data formats, an alternate solution was implemented on the same hardware with an 802.15.4 radio. A second set of 20 sensors provided transparent access as IPv6 devices. The message size was reduced by using Constrained Application Protocol (CoAP) (Kuladinithi, Bergmann, Pötsch, Becker & Görg, 2011) instead of the common HTTP protocol to send requests to the sensors. Although the latter solution requires slightly more energy and communication than the BananaHop protocol to maintain routing tables, we recommend this approach for future implementation because it can be easier integrated into existing standards.

The systems were tested during three trans-ocean transports of bananas in 2012 and 2013. Additional data are available from two preliminary test transports in 2009. Bananas were harvested green in Costa Rica. After packing, the wireless sensors were placed in the centre of selected boxes. The palletized boxes were stowed to the intelligent container, with an initial temperature of approximately 25°C. Cooling commenced with a set-point of 14.4°C. Road transportation to the harbour lasted approximately 4 hours, harbour handling 6 hours, and sea transportation to Antwerp 2 weeks. After arrival, the container was sent to a ripening facility in Germany. Following ethylene treatment, and hence ripening, the bananas were sold to a gross retailer.

The quality of bananas in the transport chain can be better described by the concept of green life instead of shelf life. The crucial factor to achieve a consistent quality after ripening, is that all bananas be completely green before starting the ripening process. In this case, any differences in the age of the bananas are evened out during ripening. The green life gives the number of remaining days until the bananas are expected to show the first signs of yellow colour. During our tests, we used an experimental green life model, developed by Praeger (Praeger, Linke, Jedermann, Moehrke & Geyer, 2013), to evaluate quality changes.

3 Summary of results from transoceanic field tests

In the following section, we summarize the main findings of our field tests.

3.1 Temperature and green life variation

Figure 2 shows the recorded curves for the core temperature inside pallets at the door and the reefer end of the container. The time required to cool down the bananas depends very much on the age of the equipment. For a 12-year-old cooling unit, the average temperature was ~2.5°C higher than for a new Thermoking cooling unit. But even with up-to-date equipment, it is not possible to achieve a fully homogenous temperature distribution inside the container. The temperature difference between the warmest and the coldest box was still 1.5°C on average.

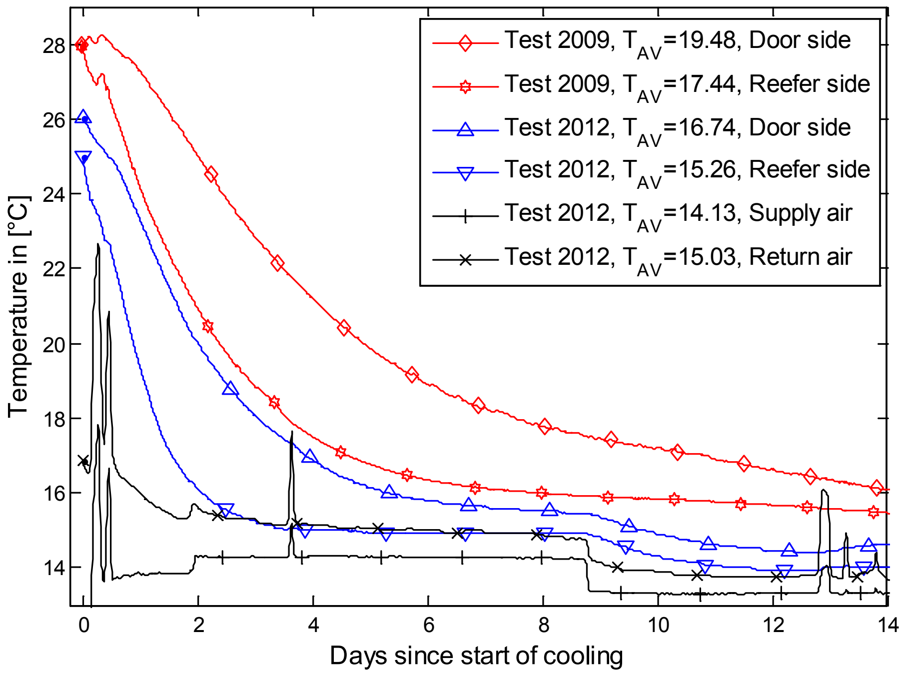

Figure 2: Temperature over time and average T_{AV} for pallets in 2 separate tests. Test in 2009 with a 12-year-old container, and in 2012 with a one-year-old container.

The curves for supply and return air temperature reveal power interruptions during harbour handling, but they do not correlate with the much slower reaction of the product's core temperature. The temperature curves for sensors mounted at the surface of the pallets lay between the supply and return air measurements.

The green life model can be either applied to real-time data to predict their current quality state, or to recorded curves for general analyses of possible transport problems. Figure 3 (top left graph) shows the temperature curves for the coldest and warmest box during our test in 2013. The updated green life is calculated after each measurement interval. The model gives the relative loss *L*, indicating how much green life is lost per day of transport at the current temperature *T*. At the end of the transport, the predicted green life for the two boxes varied by 7.3 days.

Although the green life model is well established under laboratory conditions, it gives only an average prediction. Due to different harvest conditions and biological variance, the model can only be applied to predict which box is most likely to show an unwanted start of the ripening process, and not to predict the exact expiration date for individual boxes.

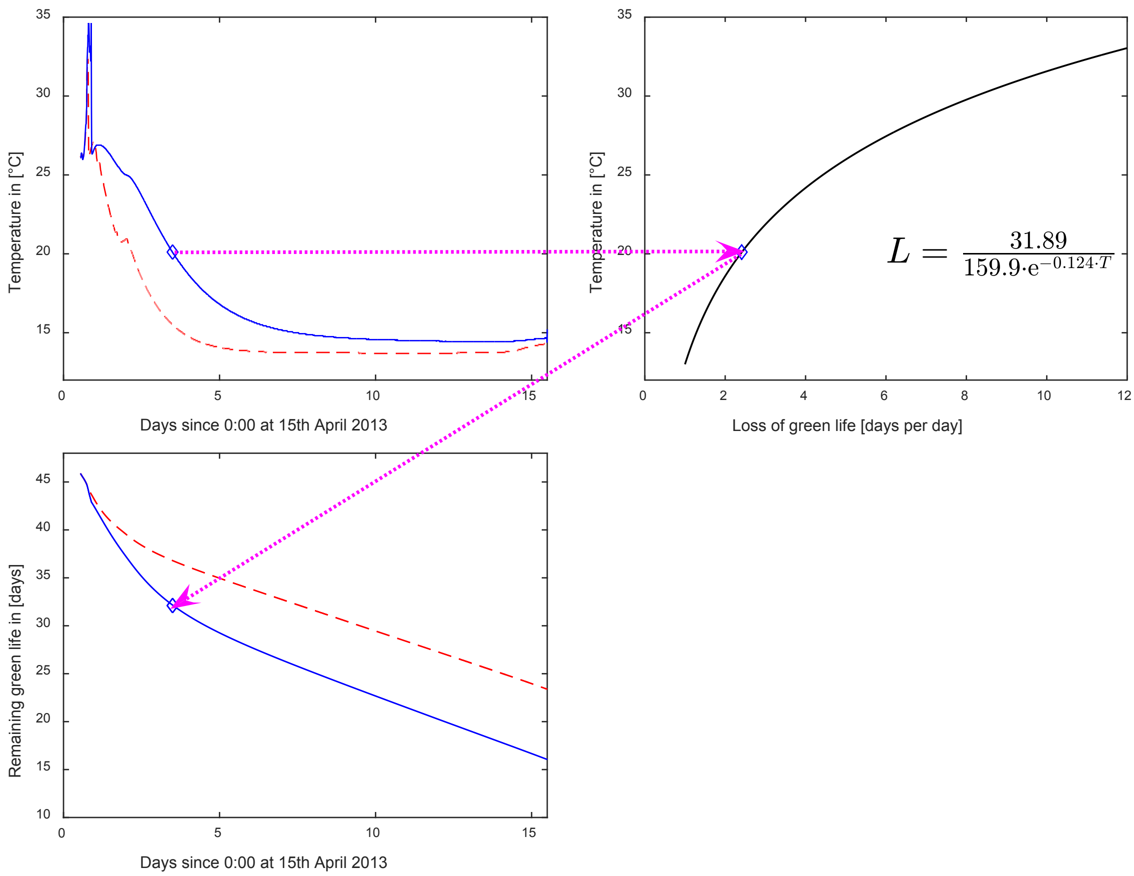

Figure 3: Example for green life calculation. Left top: warmest (solid blue) and coldest box (dashed red) during test in 2013. Right: Green life model according to (Praeger et al., 2013). Bottom: Decrease of green life over time.

3.2 Radio signal attenuation

A further problem that we observed during our tests was radio signal attenuation due to the high water content of the fruit. The 2.4 GHz frequency range used was found to be unsuitable for the monitoring of food products. The communication range dropped below 0.5 meters. At this distance, one third of all communication links completely failed. A theoretical model (Jedermann, Lloyd & Poetsch, 2014) predicted a signal attenuation of -61.6 dB per meter for packed bananas. Therefore, lower frequencies must be used, e.g. 866 MHz with an attenuation of -8.3 dB/m or 433 MHz with -2.2 dB/m.

The model for signal attenuation was verified by additional measurements in 2016. The communication range for the Wizzimode sensors, operating at 433 MHz according to the dash7 (ISO/IEC 18000-7) standard (Weyn, Ergeerts, Wante, Vercauteren & Hellinckx, 2013), was measured to 2 meters in an apple cold-storage warehouse with almost the same water content per volume. The signal attenuation was calculated to -3.3 dB/m. The new LoRa standard (Lora Alliance, 2015) with optimized coding for transmitting small data packets over long distances were found to provide even more stable communication. At a radio frequency of 866 MHz, only 1 out of 500 data packets was lost over a distance of 5 meters.

3.3 Modified atmosphere and CO_2 measurement

The aging process of green bananas is slowed down by reducing O_2 and increasing CO_2 in the atmosphere (Yahia & Singh, 2009). Modern reefer containers provide an automated air flap control to achieve beneficial gas concentration by self-respiration. The air flap is kept closed until an optimal CO_2 concentration of 5% is achieved. The CO_2 concentration was measured during our tests by the built-in sensor of the cooling unit and an additional COZIR W-X (www.gassensing.co.uk) sensor mounted under the ceiling of the cargo hold. During the closure period of the air flap, the increase of CO_2 over time gives valuable information of the biological activity of the bananas. Before opening of the air flap, CO_2 increased by 0.086% per hour, equivalent to a production rate of 4.5 g/(t·h) for a free air volume of 47.4 m^3 and a total load of 17.6 tons. During ripening, the CO_2 production increased by a factor of 10 to 46 g/(t·h).

3.4 Prediction of hot-spots

In interviews with our project partner (Dole), we established that extending the green life is desirable in order to enable longer storage periods in Antwerp before ripening, although critical loss of products is only slightly related to green life variations. Occasional losses of full container loads are related to the development of so-called hot-spots with increased ethylene production. Some fruits can have a higher respiration activity due to mechanical injuries or pathogen infections. The resulting increase of temperature and ethylene concentration in the related box triggers other bananas to increase their biological activity as well. In case of poor cooling conditions, e.g. old equipment or blocked air gaps between pallets, heat production can even go beyond the amount of heat that can be removed by cooling, leading to an uncontrollable temperature rise, increased production of ethylene and finally to uncontrolled ripening of the whole container.

We designed a model to calculate the heat product and heat removal by cooling from the measured temperature curves as separate values (Jedermann, Praeger, Geyer & Lang, 2014). By comparing these two values, it is possible to detect pallets which are at risk of developing a hot-spot.

Fortunately, we did not encounter a hot-spot during our three field tests, but observed a critical condition during an additional test ashore (Figure 4). A pallet that was mistakenly stored close to a ripening room and exposed to ethylene was loaded into the container. After increasing the set-point to 16°C over 24 hours, it was not possible to cool down the pallet again. The calculated heat production increased to 87 W/t at reference temperature of 15°C, whereas the heat production of bananas in proper ‘green’ state is 50 W/t under normal atmosphere, and 30 W/t under modified atmosphere. Due to blocked gaps, the heat removal dropped to 37 W/t.

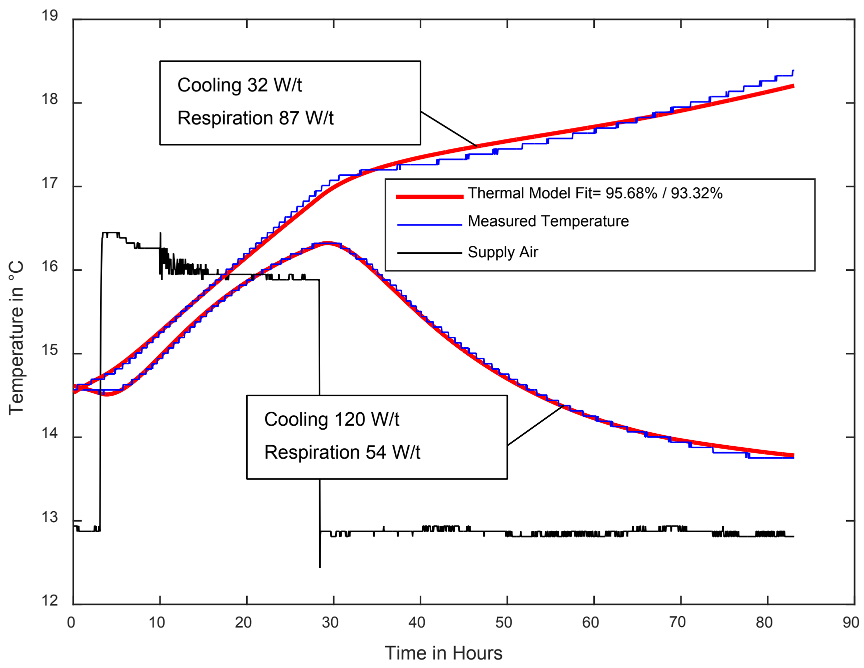

Figure 4: Temperature curve, prediction of the thermal model and calculated values for heat production and removal by cooling.

3.5 Improved packing and stowage

Based on the model calculation of the removed heat, we analysed the effect of different packing and storage schemes. Only approximately 6% of the nominal 16.6 kW cooling capacity of the Thermoking Magnum Plus unit is typically used. The model calculates a total heat removal of 1.03 kW for 17.6 tons of bananas at a reference temperature of 15° and a cooling set-point of 13°C. Different measures, such as additional vent holes in the boxes, spacers to force even gap widths between pallets, and a modified windmill layout for stowing pallets to the container improved the air flow conditions by more than 50% (Jedermann, Praeger, Geyer & Lang, 2014). The heat removal was increased from 58.7 W/t to 92.1 W/t.

This shows that the optimization of packing in regard to cooling and air flow is a crucial design challenge, which if often neglected in practise.

With the improved packing and stowage, we were able to carry out the ripening process directly inside the container during our three field tests. However, it is necessary to measure the temperature in multiple boxes and adjust the set-point accordingly, in order to avoid an uncontrollable increase of heat production.

4 New telematics and wireless temperature sensor systems

The focus of the 'Intelligent Container' project was research. Therefore, we were not able to commercialize the concept after the completion of a public grant in 2013. One major obstacle was the lack of a ready-to-use wireless sensor with a suitable radio frequency.

Since then, several new systems have become available at the market. Remote container monitoring (RCM) has left the niche of research and prototype applications. The most striking development was that Maersk announced that they have equipped all of their 270,000 reefer containers with remote monitoring, and plan to make this service available to their customers in 2017 (Zarkani & Rasmussen, 2016).

Current RCM systems are listed in Table 2, including the ORBCOMM system applied by Maersk. The first three systems focus on monitoring the container's reefer engine, e.g. verifying the set-point, supply and return temperature as well as total machine operation hours and status. In their basic version, they provide only access inside the harbour or shortly before arrival over GSM cellular networks. The idea behind this is that it is not necessary to interfere with the container or modify logistic processes, as long as the container is on the ocean. But all manufacturers provide extended RCM devices for permanent real-time access by satellite communication, or, in the case of Traxens, provide a special gateway, which links container monitoring devices with the satellite communication system of the ship.

Target customers for these systems are owners of reefer containers and providers of transport services with the goal of reducing the risk of erroneous set-point adjustments and for lost or malfunctioning containers. The manufacturers of RCM systems do not sell individual hardware devices. Their business models are based on providing data-as-a-service or on integration of RCM into customers' fleet management systems.

Goods inside the container, which have in general a different owner, are only of secondary interest. According to the presentation on the manufacturers' webpages, wireless sensors for core temperature monitoring are only sold as a secondary business, but not as a key component of the system. E.g. ORBCOMM provides an interface for wireless sensors, but the provided sensors are only suitable for installation under the ceiling of the cargo hold, not inside the goods. For Traxens, information about integration of wireless sensors was supplied only on request.

The fourth system has a different target customer group, mainly owners of high value goods. The device is snapped into a door and not integrated with the cooling unit, in contrast with the other systems. The focus of this device is detection of unauthorized door openings and theft protection, instead of reefer engine monitoring. It is also the only system dedicated for satellite communication. Although this system also includes an interface for wireless sensors, there is no information on applications for monitoring of food products.

Table 2: Commercial systems for remote container monitoring

System	Key features	Satellite communication	Core-Temperature	Homepage
ORB-COMM	Reefer status monitoring, remote start of automated self-test (pre-trip-inspection)	Dual-mode device available	Only wireless sensors under the ceiling	http://www.orbcomm.com/en/hardware/devices

Globe Tracker	Remote monitoring and control of all reefer parameters in real-time	Focused on trucks, but satellite unit available for regions with poor GSM coverage	Interface for up to 64 LoRa wireless sensors	http://www.globetracker.com/cold-chain/
Traxens	Detectors for movement, vibration, door status and temperature. Relaying information to and from the reefer controller	By using the ship's communication system. Own satellite unit planned for the future	Supports local mesh radio network designed for the harsh container environment	https://www.traxens.com/products/container-monitoring-devices.html
Secure System	Theft protection, door opening, electronic seal	All devices equipped with satellite communication	Optional wireless sensors	http://www.securesystem.net/Home

Wireless temperature data loggers have developed independently from the above listed RCM systems for a different group of target customers, such as exporters, wholesalers and distributors of temperature-sensitive products. There is a wide choice of systems available on the market (Table 3); seven systems were found by a survey at the Fruitlogisica trade fair in Berlin, Germany, February 2017 (http://www.fruitlogistica.de/en/). The systems from ZestLabs and CAEN RFID were known from earlier surveys.

The devices mostly use proprietary protocols in the UHF band at 868 MHz or 915 MHz for radio communication. Others apply communication standards such as Bluetooth, NFC (Near Field Communication) and passive UHF RFID (Radio Frequency Identification) EPC class 2. For the BT9 system no information is provided.

A common feature of these loggers is that the customer has to install a certain communication infrastructure to transmit the data. i.e. a set of gateways or repeaters mounted in the warehouse or at the loading platform. Temperature data only become available after arrival of the truck or container. The solution of Verigo reduces infrastructure costs by using standard smart phones or Android tablets to read out their Bluetooth sensors and upload the data to a server. Other solutions offer mobile gateways, e.g. with GSM communication, but are not suitable for being installed beside the cooling unit of an ocean container. E.g. the Mobile Control System from DeltaTrak is only suitable for trucks; it is plugged into the 12 Volt supply in the driver's cabin. It only communicates by GSM cellular networks.

Loggers with build-in GSM communication, which have become available recently, can transmit their data independently from a gateway by using the existing cellular network. This concept is very promising, but has some practical limitations. Without a gateway to bridge between the cargo hold and the outside world, it is difficult for the signal to penetrate the metal container walls. Furthermore, communication is not possible, if a ship leaves the range of land-based cellular networks. GSM loggers are mostly provided as single-use devices with a battery life of up to 30 days. The typical price between 50 and 60 Euros is about the double of other logger types.

Providing data-as-a-service is also very common for temperature loggers. The standard service of Sensitech includes shipping of the loggers to the country where the goods are produced, customs clearance, read-out of returned loggers and providing web-access to the data. The company's TempTaleGeo wireless loggers can also be purchased individually.

The ZestFresh system provides a dedicated solution for shelf life prediction. The tags from CAEN RFID provide the option of calculating a user-configured shelf life model on chip. BT9 describes the FEFO principle in a short article on their webpage. Temperature data measured by BT9 sensors were used to calculate a firmness model in a test with Kiwi fruit (Bollen et al., 2013). DeltaTrak provide another type of modelling. Their software tool emulates changes of the product temperature based only on ambient temperature measurements. However, without knowledge of initial product core temperature and of its thermal properties, the model can provide only limited accuracy.

There is barely any mention of the communication range for sensors packed into the centre of a pallet. For the test with Kiwis, a reading rate of only 76% was achieved, even if the number of gateways was doubled (Bollen et al., 2013). However, because the radio frequency in not given, it is not possible to draw conclusions for other devices.

Table 3: Examples of wireless temperature data loggers

System	Communication	Special features / Remarks	Homepage
Sensitech / TempTaleRF, TempTaleGeo	• UHF, or alternatively • GSM / cellular	Service includes transport to country of product origin and centralized data management	http://www.sensitech.com/products/TempTaleRF
Verigo	• Bluetooth	Read out by smart phone, automated upload to data base	http://www.verigo.io/
MOST	• GSM / cellular	30 days battery life, rechargeable	http://mobsentech.com/
PakSense / Emerson	• GSM / cellular	30 days battery life, single-use	http://www.paksense.com/products/autosense-real-time
ZestLabs / ZestFresh	• UHF	Monitoring of food products including prediction of quality deviations	http://www.zestlabs.com/
Xsense / BT9	no information provided	Gateway/ Communication Unit can be installed in fields, production facilities, storage areas, delivery docks, trucks, or containers	http://www.bt9-tech.com/
Blulog	• UHF, or alternatively • NFC (Near Field Communication)	Hub to connect to the internet by Ethernet or GSM, sends email or SMS alerts	http://blulog.eu/our-products/
CAEN RFID	• UHF RFID	Passive communication for extended battery lifetime. On-chip calculation of user-configurable remaining shelf life model	http://www.caenrfid.it/en/CaenProd.jsp?mypage=3&parent=65&idmod=780
DeltaTrak / Flash Trak	Supports various 3rd party wireless loggers	Telematics Mobile Control System mounted in truck driver cabin	http://www.deltatrak.com/telematics

5 Challenges and changes for QTT

There is a great deal of interest in obtaining real-time temperature data along the cold chain, as Jevinger found in ten interviews with supply chain actors from packing, production, logistics retail and sensor technology (Jevinger, Göransson & Båth, 2014). Their responses show that the actors believe in the concept of shelf life prediction, and that they 'seem positive towards sharing information with other actors'.

From the technical side, a sufficient choice of hardware solutions has become available. However, there are still a number of obstacles and challenges which have to be met, before QTT and FEFO find wide application in the cold chain.

5.1 Business case for multiple actors

The logistic chain for food products is usually split between several actors. A simple chain contains the following actors with different interests and involvement in QTT application:

- The farmer or producer has to install the sensors inside the packing before palletization. However, they receive hardly any advantage, except that their product receives a better reputation, if the end users can keep it in their domestic refrigerators for an extended period of time.
- A logistic service provider (LSP) transports the goods from the origin to the destination country. They own the truck or container and typically must pay for the costs of the RCM system. Their interest is only to verify that the supply air temperature of the cooling unit is in the given range.
- The exporter or distributor gains the most advantage of QTT and FEFO by reducing loss, but they neither own the means of transportation nor are they responsible for installation or retrieval of the sensors.
- The retailer has to collect the sensors before the product leaves their shops. They gain the advantages of a more consistent product quality, and higher consumer satisfaction.

A general problem is that those who must pay for this system are not generally the ones who receive its essential benefits. The costs for RCM have to be paid by the LSP, although they receive no advantages of QTT, only the risk that their customers raise claims, if they detect the smallest temperature deviation. The hardware manufacturer ORBCOMM stated that RCM has its own value beside QTT. They identified several advantages for LSPs (Orbcomm Inc. 2016), such as preventive maintenance based on engine hours, reduced costs for manual daily inspection, theft protection, detection of set-point mismatches and fleet optimization by quick detection of unused or parked semi-trailers and containers. However, ORBCOMM does not mention QTT because it is not in the direct interest of the LSP, which are in the focus of ORBCOMM's marketing activities.

This raises the question of how wireless core temperature sensors can be linked to RCM. The forwarding of temperature data or shelf life messages can be offered as an additional service by the LSPs to distributors. In other fields, the idea of 'including free data transfer in a transportation service' has already been put into practice. Since 2016, free Wi-Fi access is available in German inter-city express trains. Costs are already included in the fare.

For the second hardware component, the wireless sensors or temperature loggers, it is not so apparent who should pay for it: the producer who installs them, or the distributor, who gains the most benefit, but has no physical contact with the sensor. Temperature data loggers have been used for many decades, but mainly for general evaluation of cold chains, and not to the extent of pallet-level monitoring of core temperature as required for QTT. New business models are necessary, detailing how to share the costs of hardware, installation and retrieval of the sensors.

5.2 Communication standards

The second obstacle is the lack of conformance to communication standards. The systems listed in Tables 2 and 3 all provide only an island solution, without capabilities for mutual data exchange. The manufacturers are more interested in selling their own data-as-a-service solutions than in open standards. The problem is not the lack of suitable standards. There has been considerable effort to develop standards for the so-called "internet of things". For example, the IPv6 protocol allows addressing sensor nodes in a global network. The aforementioned CoAP provides transfer of small data packets with less protocol overhead.

Standards from product identification by RFID can also be extended to include temperature and shelf life data, as the device from CAEN RFID demonstrates, which is based on the EPC class 1 gen 2 standard.

The new LoRa standard (Lora Alliance, 2015) is also a promising candidate. According to our tests, it provided the longest reading range inside a cold-store warehouse with apples. The transfer of IPv6 data packets over LoRa is also feasible (Vilajosana-Guillén, 2016), although not fully standardized yet. The RCM system from Globe Tracker already provides an interface to LoRa sensors, but no open data forwarding service.

5.3 Sensor installation and retrieval

Besides the cost sharing, the installation and retrieval of the sensors raises practical questions. Sensors have to be activated, packed into the correct boxes, and sensor positions have to be documented before palletization. Packing is often done in remote farms with only minimal technical equipment available. At the other end of the chain, the sensors have to be collected at a high number of retail outlets, which all have to be instructed how to handle the devices.

Bollen reported several problems from tests on a trans-ocean cold chain for Kiwis with 20,000 Xsense loggers (Bollen et al., 2013). Loggers were packed in the wrong pallet, or data recording was not stopped after arrival, data got lost due to radio communication problems, or data could not be related to information about location and processing of the pallet. After the first test, they were able to compare the model prediction with manual measurement of fruit firmness for only 5% of the pallets. A satisfactory coverage of temperature monitoring was only able to be achieved in the third year.

5.4 Shelf life modelling and biological variance

The last challenge concerns the determination of an appropriate shelf life model. Although several models have been published (Tijskens, 2004), (Gwanpua et al., 2015), it is almost impossible to find a perfect match for a certain product from a certain country of origin. Shelf life parameters vary due to new breeding and different growing and harvest conditions. In general, experimental validation of model parameters cannot be avoided. To obtain better agreement between predicted and actual quality loss, factors other than temperature should be considered for shelf life prediction, such as ethylene production or humidity (Hertog, Jeffery, Gwanpua, Lallu, & East, 2016).

Furthermore, even products from the same farm, packed to the same container and with the same pallet core temperature can show large differences in their quality state. This phenomenon is summarized under the term 'biological variance'. Therefore, determination methods would be desirable for characterization of fruit quality at harvest, which are available only on a limited scale (Burdon, Wohlers, Pidakala, Laurie, Punter & Billing, 2014).

Bananas proved to be particularly problematic. A model prediction was only feasible for the average green life of the container, not for individual boxes. Kiwis, for example, are more suitable for shelf life modelling. A useful predication of fruit firmness with a regression fit r^2=0.69 was achieved during the test described by Bollen (Bollen et al., 2013).

5.5 Ethylene management

Remote monitoring of temperature and of hot-spots is the method of choice to detect risks during the transport of perishable products. For some fresh fruits, especially bananas, the effects of ethylene require additional attention.

On one hand, passive ethylene absorbers based on e.g. potassium permanganate are market-available since several years. They can reduce the effect of an initially higher biological fruit activity or of a hot-spot to other pallets by removing ethylene from the container air. A high absorbance capacity must be provided for the worst case, although only rarely required.

One the other hand, ethylene sensing can give valuable additional information about the current quality state of the product, although suitable sensing technologies have not arrived at the necessary maturity yet for automated ethylene detection in concentration below 1 ppm in the environment of an ocean container with relative humidity above 90% (Janssen et al., 2014). Furthermore, the measurement of ethylene production rate is hindered by using passive absorbers.

New approaches for active ethylene management, which combine ethylene measurement and removal, are still under research. If too high ethylene concentrations are measured, a UV-light source is activated for photocatalytic oxidation of ethylene at a titanium dioxide surface (Pathak et al., 2017).

6 Summary and conclusions

The share of food products that is lost along the cold chain can be reduced by better monitoring of transport conditions. We demonstrated, with a prototype of an 'Intelligent Container', that it is possible to provide real-time monitoring during road and ocean transportation and to detect critical conditions in an early state, which opens the option of adjusting subsequent logistic processes according to the actual quality state of the product.

However, there is no one-solution-fits-all approach. The implementation of QTT requires a detailed analysis of the cold chain including shelf life modelling. The final solution can look different from the initial approach of shelf life modelling, e.g. for bananas, the prediction of hot-spots proved to be the most critical quality issue. The solution might not only include monitoring by electronic devices, but also mechanical measures to improve cooling efficiency, as in our case study for bananas.

There are several solutions on the market to collect information from temperature data loggers over a wireless interface (Table 3), with the drawback that data only become available after arrival of the transport, and thus losing the option to take adequate counter measures in advance. The earlier information arrives, the wider the choice of options for the distributor to compensate for shelf life deviations by adjusting their warehouse and delivery planning according to the FEFO principle.

The missing permanent access to data from the container can be in principle provided by RCM systems (Table 2). However, the most striking obstacle for real-time QTT is the complete split of the market into RCM and wireless data logger systems.

In our first field test, we connected our container through a Wi-Fi link to the vessel's satellite communication system (Figure 1), similar to the solution provided by Traxens. Although such solutions save costs by replacing expensive satellite devices for each container with standard Wi-Fi, they entail a severe disadvantage for application in a real-world supply chain. Beside the providers of wireless sensors and RCM a further party is added to the communication system. If the container leaves the ship, or is loaded to a vessel of another shipping company, communication is lost. Furthermore, the vessels owner might just simply switch the satellite system off to conceal problems in his responsibility, e.g. failure of container power supply.

The greatest challenges are firstly to provide data forwarding services by RCM operators, and to oblige manufacturers of wireless sensors to a common standard for the transfer of temperature and shelf life messages. The second challenge is to find new business models to share the costs of installation, retrieval and hardware of wireless sensors for core temperature measurement. Furthermore, the development of mathematical models for shelf life prediction for new types of products is of high importance. New products require a detailed case study, but the analysis of the cold chain is only a one-time investment. Although the challenges are many, the expected reduction of product losses makes it worth to take the investment.

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