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Challenges and opportunities in remote monitoring of perishable products

Reiner Jedermann[a,*], Ulrike Praeger[b], Walter Lang[a]

[a] Institute for Microsensors, -Actuators and -Systems (IMSAS), University of Bremen, Otto-Hahn-Allee NW1, 28359 Bremen, Germany,
[b] Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB), Department Horticultural Engineering, Max-Eyth-Allee 100, 14469 Potsdam, Germany,

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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.

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

* Corresponding author.
E-mail address: rjedermann@imsas.uni-bremen.de (R. Jedermann).

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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 et al., 2014)	2010–2013, 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/

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.

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 (Fig. 1).

During field tests of the intelligent container, 20 wireless sensors were packed inside boxes containing fruit (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 min 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 h, harbour handling 6 h, 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