Semi-passive RFID and beyond: steps towards automated quality tracing in the food chain

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Abstract: Precise temperature monitoring is the major precondition to supervise quality losses within the transport chain for fresh products. Different types of miniaturised data loggers with electrical and semi-passive RFID interface were compared and applied to record spatial temperature profiles for typical transport situations. The resulting effects of the found temperature variations were evaluated by mathematical shelf-life modelling. Wireless sensor networks with active communication offer permanent access to sensor condition but entail higher system costs. Different approaches for implementation of integrated quality assessment will be discussed using a concept for shelf-life calculation on RFID-level and the intelligent container as demonstrator for an automated transport supervision system.

Keywords: food chain supervision; temperature mapping; RFID logger; shelf life modelling.

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Walter Lang studied physics at Munich University and received his Diploma in 1982 on Raman spectroscopy of crystals with low symmetry. His PhD in Engineering at Munich Technical University was on flame-induced vibrations. In 1995 he became the Head of the Sensors Department at the Institute of Micromachining and Information Technology of the Hahn-Schickard Gesellschaft (HSG-IMIT) in Villingen-Schwenningen, Germany, working on microsensors for flow, angular rate and inclination, sensor test and modelling. He joined the University of Bremen in February 2003. He is Head of the Microsystems Center Bremen (MCB).

1 Introduction

Miniaturised RFID temperature loggers are a useful tool to analyse the transport chain and detect weaknesses. We adapted these devices to analyse the amount of local deviations, to prove the need for spatial temperature monitoring and to estimate the minimum number of sensors that are necessary for reliable detection of local deviations inside a truck or container. To compare the effects of different temperature conditions, it is necessary to develop a scale to assess the resulting effects on product quality. Especially, the question of how alarm conditions should be set is of high interest. The shelf life or keeping quality model that offers a continuous scale to describe quality losses of food was applied to the recorded temperature profiles. Handling variances and unpredicted changes in quality is one of the big challenges in food supply chain management, which can be met by future quality tracking and tracing systems. Passive RFID technology offers no access during transport inside a packed container. To have permanent online access to the freight conditions active communication by wireless sensor networks is necessary. A wireless sensor system, sending a notification as soon as a quality risk is detected, could greatly improve planning processes and outweigh the higher system costs. A further crucial point is the amount of data produced by multiple sensors per container or even per palette. Neither manual evaluation nor transmission over mobile networks with limited bandwidth or expensive rates is feasible. Temperature data have to be preprocessed by intelligent systems, which could be sited at the level of RFID sensors or the means of transport. As application example we introduce a concept for quality assessment on tag level and our demonstrator for quality evaluation at the truck or container level.

2 Miniaturised data loggers for temperature recording

Semi-passive RFID technology offers new ways for the construction of miniaturised low cost data loggers. The passive RFID interface allows wireless access to the device without straining its internal power source. Battery size can be kept very small; they are only needed to record data in the absence of the electro-magnetic reader field. First products have become available since mid 2006. A 3 by 3 mm chip produced by KSW Microtec (www.ksw-microtec.com) contains the RFID air interface, processor, temperature sensor and 7680 bit EEPROM for storage a temperature values and time stamps. In the standard configuration the chip can record up to 700 measurement values. The chip, the antenna and a paper-thin battery are sealed into a credit card sized label. The TurboTag data loggers from Sealed Air (www.turbo-tag.com) uses the same chip as the Variosens Label from KSW, but contain a higher capacity battery (80 J). The TurboTags run through an extended calibration process for the internal clock and temperature sensor.

Currently, temperature tags are only available for the 13.56 MHz HF-Range. Data transmission takes place in accordance with the ISO 15693 RFID air interface protocol. The major drawback of 13.56 MHz RFID technology is the limited reading range of about 10 cm. Sensor tags with an UHF interface are under research by manufactures like KSW; they will enable an extended reading range and allow for automated data transfer to gate readers, but cannot penetrate metals or liquids. Accessing passive tags during transport in a packed container is far beyond technical feasibility.

The two RFID temperature labels were compared in laboratory experiments and field tests with the iButton loggers from Dallas Semiconductor/Maxim (www.ibutton.com) at the size of a button cell and 1-Wire® electrical interface.

The main issue in comparing different logger types is their accuracy. Recommendations for food transports allow deviations of ±0.5°C from the set point. For early detection of temperature shifts and gradients the accuracy should be even better. We estimated the standard temperature deviation for the three logger types by tests in our climatic chamber at −10°C, 0°C, 15°C and 30°C. Considered for a Gaussian distribution, 2/3 of all measurements are inside the standard deviation interval $\pm\delta$. The iButtons showed the best results with a deviation of less than ±0.1°C, followed by the TurboTags with ±0.18°C and the KSW tags with ±0.4°C. The results of the comparison of different logger types are summarised in Table 1.

Table 1 Comparison of different logger types

Type	*KSW*	*TurboTag*	*iButton*
Data points	700	700	4000
Battery lifetime	<1 year	>1 year	1–10 years
Resolution	~0.3°C	~0.2°C	0.0625°C
Tested accuracy $\pm\delta$	±0.4°C	±0.18°C	<±0.1°C
Interface	RFID	RFID	One-wire
Price	5–10$		40$
Handling	+	+	−
Software	±	++	±

The battery lifetime depends on sampling interval and ambient temperature. Temperatures above 50°C lead to an increased self-discharge and reduce the values given in Table 1. Besides the electrical characteristics it is important to consider the effort that is necessary to configure and read out a higher number of devices. The software for the TurboTags allows to programme loggers with an auto incremented serial number just by placing them one-by-one onto a desktop RFID reader. At readout the data are stored in text files named by the serial number. The user interface of the software for the KSW and the iButtons was rather designed for experiments with single loggers. Programming and data storage required several manual interactions with the software per device.

The handling of loggers with a wireless RFID interface turned out to be much more efficient than the mechanical plug-in and out of the iButtons into the adapter for the electrical interface.

3 Spatial temperature profile of trucks and containers

Local temperature deviations are present in almost any transport situation. Reports from the literature indicate deviations of 5°C or more (Moureh and Flick, 2004; Punt and Huysamer, 2005; Rodriguez-Bermejo et al., 2007; Tanner and Amos, 2003, 2004; Wild et al., 2005). There is a broad variance in the speed of temperature changes, depending on the transport conditions. Our own field tests cover two contrasting conditions.

In the first setting the temperature distribution inside a packed and sealed palette was considered. For evaluation of the penetration depth of temperature changes, two test palettes were equipped with 50 or 70 KSW Variosens data loggers. The data were provided by a German producer and distributor of foods.

Figure 1 shows the temperature rise inside the palette at measurement points in different distances to the surface after 60 hr exposure to a non-refrigerated environment 10°C above the initial temperature of 6.5°C.

Apart from an offset between top and bottom layer, the distribution of temperature over space mainly depends on the distance to the surface. The temperature over time functions also shows a regular behaviour. Data analysis showed that the temperature of points close to the surface could be modelled by the first-order time-delay element with the ambient temperature as input function (Figure 2). The delay elements are characterised by their time constant that gives the timespan that is passed until the internal temperature reaches 63.2% of the changed input.

Figure 1 Temperature rise inside a sealed palette after 60 hr without refrigeration

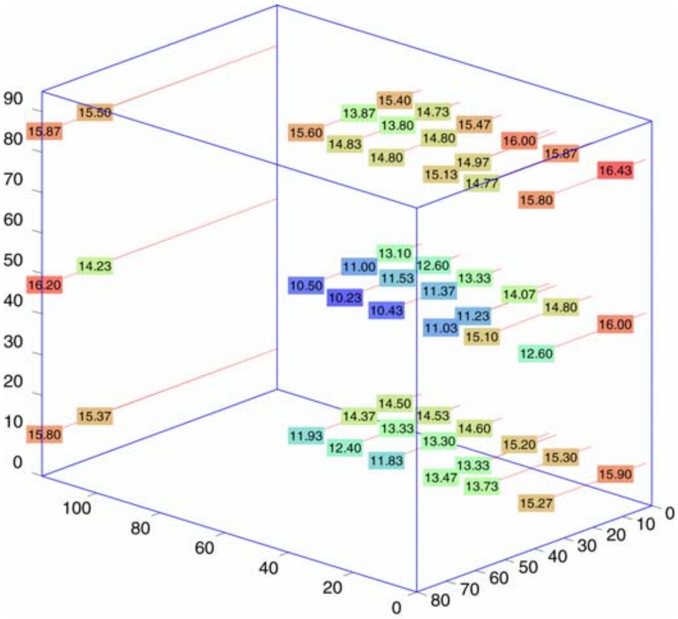
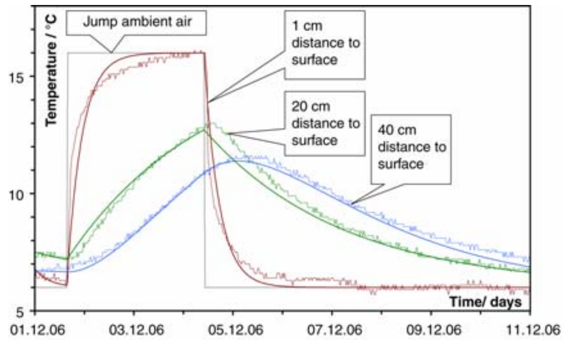


Figure 2 Measured (fine) and modelled (bold) temperature for three selected points inside a packed palette

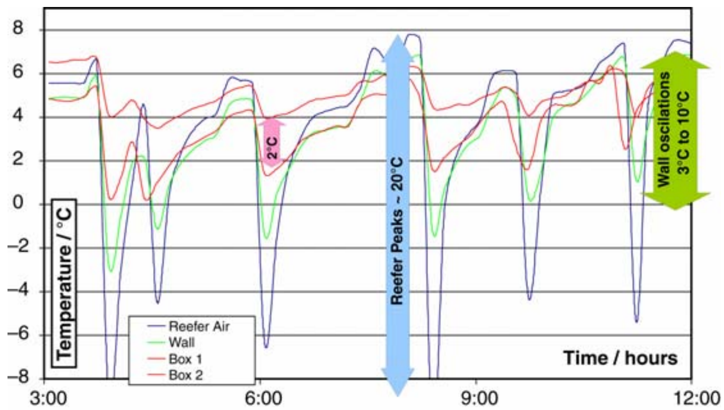


Depending on the distance to surface the time constant varies from 0.3 to 3 days. The core temperature could be better approximated by serial connection of two delays with a time constant of 1.8 days each, describing the transition from ambient over surface to core layer.

In contrast to the first setting with an even distribution of thermal mass over space, we considered in the second setting the spatial temperature distribution inside delivery trucks with partly filled boxes. The experiments were carried out at Rungis Express, Germany, which is a trading company for luxury and exclusive food. Their trucks are separated in three compartments with different temperature zones for deep frozen goods, fish/meat and vegetables equipped with separate ventilation/vaporiser units.

The high amount of free air volume and the permeability of the boxes provide for good ventilation and fast reaction to temperature changes. Figure 3 depicts temperature oscillations caused by on-off cycles of the refrigeration unit. Differences from 2°C to 3°C were found between boxes in the same compartment.

Figure 3 Reefer air (blue), wall (green) and temperature inside freight boxes (red) over time (for colours see online version)



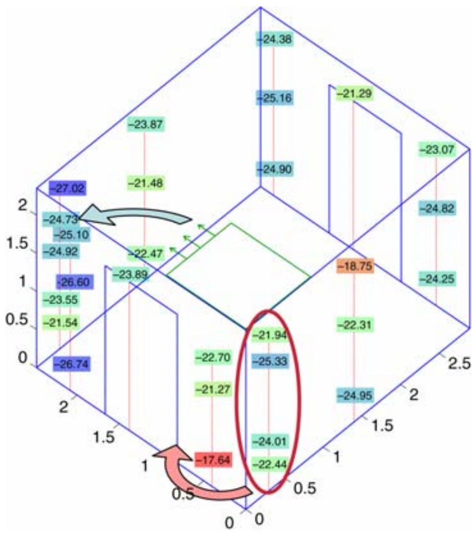
The spatial temperature profile shows a rather chaotic behaviour. Only the position of the ventilation unit could be identified as a predictable influence factor. The average of all loggers on the ventilation unit side was about 2°C colder than the opposite walls.

After switching to deep freezer mode, large spatial temperature differences persist for several hours. In Figure 4 the set point was only reached directly in the below direction of the refrigeration unit (blue arrow). A temperature offset of 10°C was still present after 5 hr in the opposite corner (red arrow).

The temperature could not be approximated by linear interpolation along the axis, especially after changes in set point, loading of freight items with improper precooling and deep freezing. For example the temperature in the middle positions could not be estimated by averaging the values of top and floor position, as in the marked group in Figure 4 (red circle).

The required density of the measurement network depends on the setting. For a setting with an even distribution of thermal mass and airflows, the number of sensors might be reduced to cover the core and each surface side. But in settings like the measurements in delivery trucks, at least one sensor per metre could be necessary for reliable detection of local temperature peaks.

Figure 4 Temperature profile 5 hr after changing to deep freezer mode. Flow of cooling air (blue arrow), return air (red arrow) and position of refrigeration unit (green box) (for colours see online version)

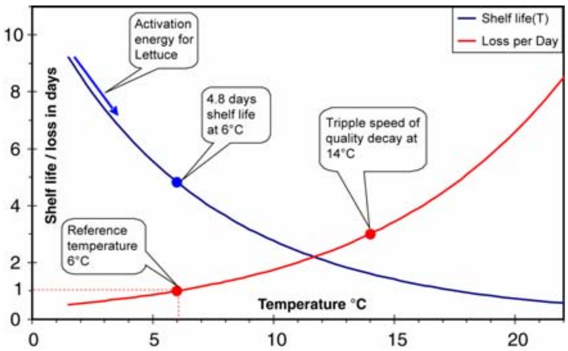


4 Scales to assess to impact of temperature onto quality

Among environmental parameters during transport, the temperature has the most significant influence on the quality of food products. Unfortunately, there is no unique scale to assess the effects of temperature abuse. Most companies restrict their view to compliance with food regulations, which offer only accept/reject decisions based on overstepping of defined temperature thresholds. Quality could be also defined in physical properties like colour, firmness or bacterial growth rate, giving a continuous scale. But finally, quality is what the consumer defines as quality. For optimisation of supply chain processes and increasing consumer acceptance, a more refined assessing scale of quality is necessary. In addition to a printed expiration date a dynamic quality index should be recalculated if temperature conditions change.

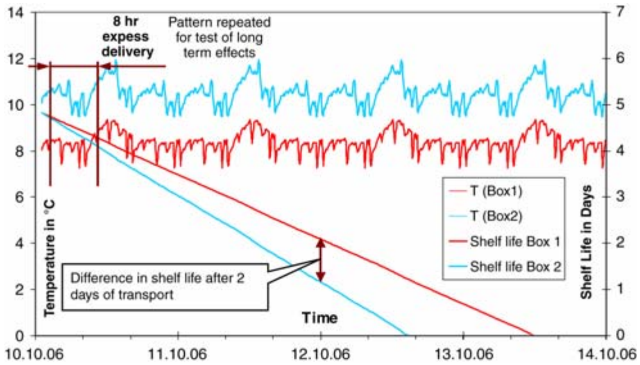
Different physical properties can be subsumed in the concept of keeping quality or remaining shelf life (Jedermann et al., 2006; Tijskens and Polderdijk, 1996). The shelf life gives the number of remaining days until a product specific threshold will be passed. This could be colour loss, bacterial limit or consumer acceptance. A dynamic form of the model allows calculating the 'loss per day' as function of the temperature (Figure 5). To improve model accuracy additional factors like humidity and especially harvest conditions have to be considered.

Figure 5 Shelf life and loss per day in dependency to temperature for lettuce as example



In Figure 6 the shelf life model was applied to data recorded in delivery trucks. After the first 8 hr the calculated shelf lives for two boxes with a temperature difference of 2.1°C average show only a small difference. But after two days the difference increases to 50%. Box 1 will drop below the quality threshold one day earlier than Box 2.

Figure 6 Application of shelf life modelling to recorded temperature data



5 Challenges in food chain management

The supply chain management for fresh foods requires fast decisions; goods are forwarded within hours. The quality of fresh meat, fish or agricultural products might change rapidly. Appropriate planning calls for more information than standard tracking and tracing by RFID could provide. The warehouse operator should not only know where the good is, but also in which state it is. In an advanced solution he should know before the truck arrives, how to handle the incoming freight.

Currently, the major instrument to avoid product losses is fast stock rotation. Most distribution centres make use of cross docking. Large inventories within the chain are generally avoided. But scientific research and inter-company data exchange fall behind the high standards set by just in time logistics in car manufacturing. In food logistics, the risk of out-of-stock has to be balanced not only against costs for inventory buffers, but mainly against the risk for quality loss. Scheer (2006, p.56 f.) gives an estimated average loss over the whole chain from production to retail shelf and consumer's fridge of 35%.

6 Quality oriented tracking and tracing

Future 'Quality oriented tracking and tracing systems' (QTT) (Scheer, 2006) will offer a new approaches to cool chain management. Stock rotation could be based on current quality instead of fixed 'sell by' dates. Warehouse planning will be organised by 'First Expires First Out' (FEFO) instead of 'First In First Out' (FIFO) (Emond and Nicometo, 2006). Cool chain management will not only reduce unnecessary buffers in inventory but also in shelf life. Individual items with high reserves in shelf life will be send exactly were they are needed, for example, international deliveries or retail shops with lower turn over.

An example for this approach is the 'Safety Monitoring and Assurance System' (SMAS) that was developed to reduce risks for the costumer by microbiological contaminated meat (Koutsoumani et al., 2005). A Monte Carlo simulation showed that the number of products with zero shelf life could be reduced from 12% to 4% compared to normal FIFO handling.

'Liking' describes to what extend the consumer is enticed to buy the product because of its optimal ripening state. Nowadays fruits like mangoes is sold in a hard, unripe state with a shelf life buffer of several days. If the risks of product loss are minimised by QTT, retailers could place fruits for display in the optimal 'ready to eat' ripeness state and increase attractiveness to the customer (van Kooten, 2006).

7 Online access by wireless sensor networks

Wireless sensor networks are an emerging technology that offers permanent online access to the freight conditions. A large number of sensor nodes make use of active radio communication to form a network. If a node cannot directly contact the base station, the message is forwarded over multiple hops. By auto configuration, the network could still operate if nodes are moved, added or lost. Demonstration kits and prototypes without housing are offered for prices about $100, like the tmodeSky from Sentilla (www.sentilla.com, former Moteiv Corporation) The Auto-ID Lab subsumes wireless sensor nodes into the EPC class 4 as active tags, which can peer-to-peer communicate with other active tags.

The main difference in passive RFID is the distribution of energy in communication. In active or symmetrical communication both sides emit signals of approximately the same strength (e.g. 1 mW ⇔ 1 mW), whereas passive RFID tags modulate only the reader field with an asymmetrical distribution of energy (e.g. 1 μW ⇔ 1 W).

In summary, WSNs have a much better energy balance than passive RFIDs. Passive communication is primarily confined to applications where the reader side has no energy restrictions, such as a door reader with fixed power supply.

Currently, no logistical WSN solution is available off-the-shelf. Our own hardware development was started by the ITEM, one of our partner institutes at the University Bremen with the aim to prolong service intervals by use of ultra low power hardware components and communication planning based on energy budget monitoring (Behrens et al., 2007).

The drawbacks of active communication are the higher complexity of the electronic circuit and the resulting costs. Currently, RFID loggers are 10 times cheaper than wireless sensor nodes ($10 versus $100). Both prices will drop; the price of sensor nodes will decrease a bit quicker when their mass production starts, but will always be a multiple of the costs of RFID loggers. Sensor notes will therefore be mainly restricted to applications where they return to the owner or are permanently mounted to the means of transport. But the higher costs of wireless sensors are more than outweighed by online or on-the-road access to freight conditions.

Instant notifications on quality problems are of very high value. They could be used to remedy the cause of the problem. But even if a direct access to the means of transport is not possible, online notifications offer new opportunities for improved transport planning: If fixed delivery commitments require the ordering of a replacement, the time of information is very crucial. The more time that is available, the less expensive the replacement purchase gets. If fresh products are sold on a short time basis, a quality tracking system could make sure that only goods are offered to the customers which have sufficient shelf life reserve to arrive in proper quality.

In a more complex scenario, trucks could be redirected on the basis of differences in shelf life predictions. This can be illustrated by the following example: 3 out of 10 trucks with strawberries from Spain have a quality problem. The remaining 7 trucks could be redirected to satisfy each customer at least partly before they arrive in Germany.

8 Automated quality evaluation by local preprocessing

The main interest of the transport operator is to know whether the quality state of the item is ‘ok’ or needs additional examination because of an emerging quality risk. In fact, there is no real necessity to transmit full temperature charts of individual freight items. Automated systems for quality assessment could release the transport operator from the task of manually analysing temperature charts. If the system is implemented on a local embedded platform close to the sensor itself, it could largely reduce the amount of communication data and costs. Only alarm notifications or state flags have to be transferred over mobile networks. Different solutions are mainly discerned by the location of temperature data processing.

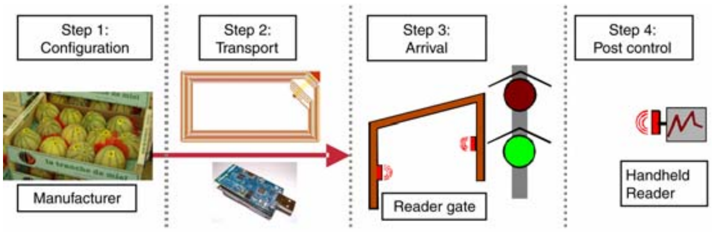
9 Intelligent RFIDs

One approach is to equip RFID data loggers with additional preprocessing facilities. This is motivated by the fact that it is hardly possible to read out recorded temperature profiles from dozens of loggers during the short time span a forklift needs to pass the

RFID reader gate. As proposed by Emond and Nicomento (2006) the tag answers to an inventory request by the door reader with its identification number and a green or red state flag. Only on a special request a full temperature chart will be transmitted. The temperature data preprocessing could be as simple as temperature threshold checking to comply with food laws. But for higher accuracy it should include shelf life prediction and estimation of the time-delayed core temperature by surface measurements.

The entire supervision process is summarised in Figure 7. In the first step the intelligent RFID tag needs to be configured by the manufacturer. Model parameters for different kinds of goods are automatically retrieved from a database. During transport (Step 2) the intelligent RFID measures and stores temperature values without external communication. A warning flag is set if the calculated shelf life falls below a defined threshold. After passing a reader gate at unloading, the quality state is indicated by light signal (Step 3). Problematic freight items are manually checked in post control (Step 4). A full temperature protocol could be read out by a handheld reader. For pilot tests, this concept could be implemented on existing hardware of sensor nodes; passive RFID with user programmable micro controller and UHF interface are currently not available.

Figure 7 Supervision process based on intelligent RFID



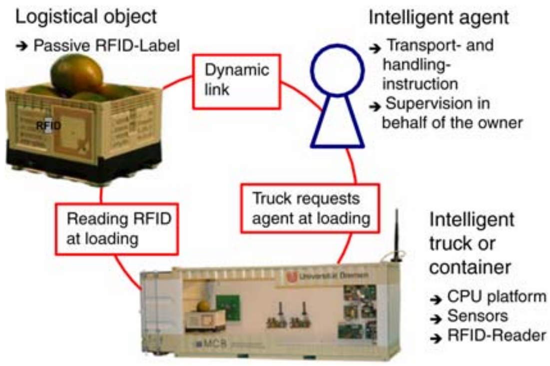
10 Smart containers

Our concept of the intelligent or smart container avoids high system costs for equipping each freight item with an active sensor node by separation of the identification from the measurement task. Each food package needs identification but not necessarily its own sensor equipment. Packages could either share sensor devices or use sensors that are provided by the environment. This concept requires only one low-cost passive identification RFID tag per freight item.

During transport the package is virtually linked to sensors that are mounted inside the means of transport. Mobile software agents are a programming approach to run tasks in a network of computation platforms. In our case we apply software agents to represent the individual supervision requirements of each freight item by an electronic consignment note (Jedermann and Lang, 2006).

When the transfer of the physical object is detected by RFID reader, the new vehicle sends a request to obtain the corresponding agent (Figure 8). The electronic consignment note accompanies the freight item on its way through the supply chain and calculates quality losses by shelf life modelling (Jedermann et al., 2006). The software agent is executed on the processing platform of the current means of transport. The feasibility of this concept was proven by our reduced scale prototype.

Figure 8 Supervision process by mobile software agents



11 Combination of RFID loggers and wireless sensors

By a combination of RFID loggers with wireless sensors, further reductions of total systems costs are possible. In this concept only a limited number of the more expensive wireless sensor notes are permanently mounted to the walls of the means of transport. The measurement of core temperature, which is the crucial factor for quality changes, is performed by RFID data loggers, although these devices could not be accessed during transport.

During transport a raw estimation of shelf life is calculated by online measurements of ambient or wall temperature. This prediction is corrected when the history of the core temperature becomes available on reading the RFID loggers at unloading. During this process the system could also learn to predict the core temperature better on the basis of ambient measurements. This solution combines the ability for 'online' access together with the lower price of data loggers. For automated read out of the data loggers, UHF technology is necessary. RFID loggers with extended reading range are assumed to be market available within the next few years.

12 Summary

Several approaches for improved tracing of temperature conditions during transport were introduced in Table 2. Two obstacles are responsible for the current lack of applications. Firstly, up to now there are no technologies on hand for automated collection of spatial temperature data. Currently, only RFID data loggers are available in high quantities, but they require manual handling because of their low reading range. And secondly, the quality tracing from farm to fork will force a high willingness for cooperation and sharing of sensory data. But if every partner in the supply chain optimises only his own profits and not the system and uses new technology only to blame others for product losses, no one will win in the end (Gregory, 2006). It will take some time until partners of the food chain will acknowledge the advantages of quality orientated tracing and management. The reduction of product losses and new concepts like FEFO will finally lead to increased global profits.

Table 2 Current state and features of tracing technologies

Technology	*Online accessibility*	*Local processing*	*Granularity*	*Current state*
Telemetric systems	✓	–	–	Available
RFID data loggers	–	–	✓	Short range available
Wireless sensors	✓	–	✓	Prototypes, pilot studies
Intelligent RFID	–	✓	✓	Concept
Intelligent sensors	✓	✓	✓	Under development
Intelligent container	✓	✓	✓	Demonstration system

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