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Quality tracing in meat supply chains

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The aim of this study was the development of a quality tracing model for vacuum-packed lamb that is applicable in different meat supply chains. Based on the development of relevant sensory parameters, the predictive model was developed by combining a linear primary model and the Arrhenius model as the secondary model. Then a process analysis was conducted to define general requirements for the implementation of the temperature-based model into a meat supply chain. The required hardware and software for continuous temperature monitoring were developed in order to use the model under practical conditions. Further on a decision support tool was elaborated in order to use the model as an effective tool in combination with the temperature monitoring equipment for the improvement of quality and storage management within the meat logistics network. Over the long term, this overall procedure will support the reduction of food waste and will improve the resources efficiency of food production.

1. Introduction

Meat is a perishable product with a short shelf life and therefore short selling times. In contrast to fresh fruit and vegetables, packaged meat has to be declared with a use by date [1].[1] Even though shelf life can be extended by various packaging solutions, such as

[1]The update Regulation (EU) No 1169/2011 comes into effect on 13 December 2014 and replaces the former Directive 2000/13/EC.

vacuum or modified atmosphere packaging (MAP) [2–4], freshness is strongly influenced by temperature. Inadequate storage or transport temperatures can lead to a significant reduction in shelf life and early spoilage of meat and meat products [5]. Several weak points exist in cold chains, like the precooling of products before shipping, transferring products from one actor to another, waiting times during consolidation and deconsolidation, or temperature abuse during transport [6–8]. Temperature abuses result in variations of product quality during distribution and at the end of shelf life and may cause spoilage before the use by date is reached [5], leading to food waste and economical losses.

In meat supply chains, mostly environmental temperature on truck level is monitored. However, it is not possible to draw conclusions from environmental temperature to temperature in the pallet or on product level because high variations may occur [9–11]. Also, random measurements at, e.g., incoming inspections do not reveal the temperature history of the product. To determine real shelf life and quality status in each step of the chain, rapid technologies are necessary to identify the real quality of a product in each step of the chain. Nevertheless, until now online measurement technologies to evaluate freshness have not been available. A different approach to estimate the quality status of meat and meat products in each step of the chain is the utilization of shelf life models combined with temperature monitoring devices. Continuous monitoring of product temperature along the entire cold chain and exchange of temperature data are necessary to obtain a complete temperature history for the prediction of remaining shelf life or quality status [5,6]. The availability of temperature data in real time enables quality driven distribution of products.

Nowadays, connection of computer networks with the Internet or a local server facilitates the sharing of temperature data in real time. Huge amounts of data are accumulated and the standards for the availability of gathered data are rising [12]. Data can be gathered, analysed, processed, secured, confirmed and stored automatically and in real time. To achieve these goals, the existing solutions have to be digitalized, extended and harmonized with each other. Existing knowledge has to be formalized, transformed into real-time capable algorithms and measurement methods have to be implemented in software capable for multiple decentralized devices. For an effective practical application, the new solutions should be easy in use, but must be integrable into the existing operations and support the work process as much as possible [13]. Furthermore, the solutions have to be flexible to be adaptable to different kinds of cold chain logistics networks. Two types of logistics networks can be distinguished. In the case of full truck loads (FTLs), goods are transported from the producer to the warehouse or distribution centre directly. If the volume of the goods is less than a truck load (LTL), goods of several suppliers are consolidated in depots or cross-docking facilities and then transported to the warehouse or distribution centre. In this so-called cross-docking logistics network, the goods are only stored for a short time. This allows for staying competitive even for a small volume of transported goods from a small supplier to a big customer and economies in transport costs can be realized [14]. The entire cold chain includes several transport and cross-docking processes, which is a challenge for quality tracing over the whole supply chain. Automated quality tracing in the food chain is possible, for example, with radio frequency identification (RFID) technology and wireless sensor networks [15]. To gather information from RFID tags, a reader connected to the Internet is necessary. This reader can be installed in cross-docking depots and thus temperature logs can be used to calculate the remaining shelf life of the product.

Up to now, there have been various shelf life models and RFID systems available. Nevertheless, the integration of the new models and technologies into an overall software system linked to the required hardware, and the integration into existing operations in a cross-docking logistics network for meat and meat products have not yet been realized.

Therefore, the aim of this study was the development of a temperature-based quality control model for vacuum-packed lamb that can be used for quality tracing along a meat supply chain and as a decision support tool (DST) to improve the overall distribution-, storage- and quality management. In addition, the implementation of this model into software is introduced as well as hardware requirements for continuous temperature monitoring across cold chains. Furthermore, a concept is presented to integrate the quality tracing solution into a cross-docking network using the example of an international cold chain for Irish lamb products. It is shown, how its application impacts logistics processes with the aim to reduce losses along a meat supply chain.

2. Study design

For the development of a predictive quality control model and its implementation as a DST in perishable food supply chains, the study was divided into three different steps.

First, a quality control model for vacuum-packed lamb saddles was established to predict quality status and remaining shelf life of the product as a function of temperature history in each level of the chain. To model quality deterioration, a parameter to characterize the quality decay of the meat product was identified. By combining a linear primary and the Arrhenius model as the secondary model, the quality control model was derived. The developed model is the basis for the DST.

In the second step, a process analysis of the lamb producing chain was carried out to define general requirements for the implementation of the temperature-based model into this supply chain and the DST. This includes the identification of inspection points and reloading processes of the products as well as the availability of temperature data in the whole chain.

As a third step, the algorithm of the model was integrated into software for use as an online tool for quality control at incoming and outgoing inspection points as well as during transportation.

Finally, a concept for the integration of the model into the logistics network of a lamb producing meat supply chain was designed and the practical application of the tool is demonstrated.

3. Development of a quality control model

(a) Product description

In total, 37 vacuum-packed half Irish lamb saddles were obtained from a retailer in Germany. The samples were transported to the laboratory in insulated boxes and cooled with ice packs within 30 min of arrival at the wholesaler. Temperature was monitored during transportation (iButton, Maxim, USA). The lambs were between the age of four and eight months. The lamb saddles had an average weight of 1.5 kg and were covered with subcutaneous fat. Given shelf life was 29 days at 2°C.

(b) Determination of the freshness parameter

Three trials were conducted. In the first trial, a sensory evaluation sheet to describe the freshness loss of vacuum-packed lamb was developed. The characteristic attributes meat colour (filet and cut surface), meat juice colour and volume, gas formation, texture and overall appearance were evaluated in sealed packaging through a descriptive 5-point scale, with 1 representing very good quality (filet and cut surface colour: fresh, dark red to red, glossy; meat juice colour: dark red, clear; meat juice volume: none to very little; gas formation: none; texture: firm, very elastic; overall appearance: very good) and 5 unacceptable quality (cut surface and filet colour: brown, grey, yellowish, smeary; meat juice colour: milky, dull, brownish and/or greenish; meat juice volume: a lot; gas formation: bloating of vacuum package; texture: very soft, not elastic, loss of meat juice when applying pressure; overall appearance: unacceptable, rejection). At each evaluation point, the randomly numbered lamb saddles were removed from the incubators and immediately evaluated by a trained panel in the sensory analysis laboratory at room temperature between 19°C and 22.5°C and controlled lighting to provide standardized evaluation conditions. All sensory attributes except texture were evaluated visually by each panellist, the latter by tactile evaluation. Each panellist judged the overall appearance as a result of the previously evaluated quality attributes. Additionally, the composition of bacterial spoilage flora was assessed to identify a specific spoilage organism (SSO) when evident spoilage was reached. Total viable count and typical spoilage bacteria (*Pseudomonas* spp., *Brochothrix thermosphacta*, *Enterobacteriacae* and lactic acid bacteria) were analysed. In the second trial, storage trials were conducted to investigate the microbial growth behaviour of typical bacteria and to evaluate the sensory quality loss. Twenty-eight lamb saddles were stored under controlled temperature conditions at 2°C in high precision incubators (Sanyo MIR 153, Sanyo Electric Co., Ltd., Japan), and microbial and sensory investigations were conducted at regular time intervals. The microbial investigations revealed high variations in the growth characteristics and the amount of different spoilage organisms between the samples. The microbial flora consisted of various microorganisms contributing to meat spoilage and an SSO could not be identified. Thus, for this product, an SSO-based model is not applicable. Therefore, a sensory-based quality control model was developed including all relevant sensory attributes.

Accordingly, in a third trial, sensory analysis was carried out under different isothermal temperatures to determine the spoilage kinetics. Eight lamb saddles were stored at four different constant temperatures (2°C, 7°C, 15°C and 20°C). Sensory analysis was carried out after 24–150 h, depending on storage temperature and expected spoilage rate.

(c) Statistical analysis

Sensory data and modelling results were fitted with OriginPro 8G (OriginLab Corporation, USA). Statistical tests were run with SPSS (IBM SPSS Statistics v. 21.0, USA). The non-parametric test Kruskal–Wallis one-way analysis of variance by ranks was performed to test for differences in the distribution of the sensory variables. Non-significant results of this test show that there is no difference between samples [16]. Spearman's ρ was used to test the correlation of the ranked sensory variables [17].

(d) Primary and secondary modelling

A primary model was used to describe the development of the quality index and hence quality decay as a function of time by a zero-order kinetics function

$$\mathrm{QI}(t) = b \times t + y_0, \tag{3.1}$$

where QI denotes quality index; t, time (h); b, slope; y_0, starting point of QI (at time $t = 0$).

The influence of temperature on the steepness of the slope b of the quality index was calculated using the following Arrhenius equation in the secondary modelling step

$$\ln(b) = \ln(F) - \left(\frac{E_\mathrm{a}}{R} \times \frac{1}{T}\right), \tag{3.2}$$

where b, slope of quality index (h^{-1}); F, pre-exponential factor (h^{-1}); E_a, activation energy ($\mathrm{J\,mol^{-1}}$); R, gas law constant ($8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$); T, absolute temperature (K).

A combination of equations (3.1) and (3.2) allows calculating the actual quality status resembled by QI as follows:

$$\mathrm{QI}(t_i, T_i) = \sum_i \mathrm{e}^{-E_\mathrm{a}/R \times 1/T_i + \ln F} \times \Delta t_i + y_0, \tag{3.3}$$

where QI, quality index; t, time (h); T, temperature (K); E_a, activation energy ($\mathrm{J\,mol^{-1}}$); R, gas law constant ($8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$); $\ln F$, pre-exponential factor (h^{-1}); y_0, starting point of QI (at time $= 0$).

(e) Results of sensory analysis and quality decay model

The investigated sensory variables cannot be differentiated statistically (Kruskal–Wallis test, $p = 0.454$). All sensory variables show the same changing rate during quality decay. Spearman's

Table 1. Correlation of sensory variables (Spearman ρ-test). $N = 49$.

	colour filet	colour cut surface	colour meat juice	volume meat juice	gas formation[a]	texture	overall appearance
colour filet	1.000	0.956[b]	0.906[b]	0.844[b]	0.888[b]	0.940[b]	0.938[b]
colour cut surface	0.956[b]	1.000	0.912[b]	0.858[b]	0.900[b]	0.914[b]	0.947[b]
colour meat juice	0.906[b]	0.912[b]	1.000	0.901[b]	0.912[b]	0.920[b]	0.923[b]
volume meat juice	0.844[b]	0.858[b]	0.901[b]	1.000	0.941[b]	0.910[b]	0.916[b]
gas formation[a]	0.888[b]	0.900[b]	0.912[b]	0.941[b]	1.000	0.925[b]	0.939[b]
texture	0.940[b]	0.914[b]	0.920[b]	0.910[b]	0.925[b]	1.000	0.944[b]
overall appearance	0.938[b]	0.947[b]	0.923[b]	0.916[b]	0.939[b]	0.944[b]	1.000

[a]$N = 46$.
[b]The correlation is significant at a level of 0.01 (both sides).

ρ shows a very high correlation of all variables (table 1). Owing to the high autocorrelation of variables, multivariate analyses could not be applied. As no differences between variables could be detected, the quality index was composed of the arithmetic mean of the variables without weighting in order to prevent bias in the index

$$\mathrm{QI} = \frac{C_{\mathrm{f}} + C_{\mathrm{S}} + C_{\mathrm{mj}} + V_{\mathrm{mj}} + G + T + \mathrm{OA}}{7}, \tag{3.4}$$

with C_{f}, colour filet; C_{S}, cut surface; C_{mj}, meat juice colour; V_{mj}, meat juice volume; G, gas formation; T, texture; OA, overall appearance.

The quality index increases linearly at all isothermal temperatures. With increasing temperature, a faster increase of the index was observed. R^2 varied between 0.880 (7°C) and 0.928 (15°C).

Linear regression was used to calculate the end of shelf life in terms of sensory acceptance. At the recommended storage temperature of 2°C, the use by date is reached after 696 h. The QI for vacuum-packed meat shows a value of 4.0 at this time and is defined as the limit of acceptance level for this product. Based on this value, the quality reduction of the meat samples stored under higher storage conditions is calculated and follows an exponential course. The QI limit is reached after 397 h at a storage temperature of 7°C, after 171 h at 15°C and after 145 h at 20°C (figure 1*a*).

To model the temperature dependency of the quality index rates, the Arrhenius equation (3.2) was used. The results can be seen in figure 1*b*. From this plot, the parameters for the quality control model (equation (3.3)) could be derived as follows:

$$\mathrm{QI}(t_i, T_i) = \sum_{\mathrm{i}} \mathrm{e}^{-9876.57\times 1/T_i + 30.5} \times \Delta t_i + 1, \tag{3.5}$$

with $\Delta t_i = t_{i+1} - t_i$.

With the new quality control model, the development of the quality index for an exemplary cold chain scenario where product temperature is above the recommended temperature was calculated and is compared to a cold chain scenario with optimal product temperature (table 2). The assumptions for the scenario with inadequate product temperature were based on temperature measurements from various temperature mappings in different meat supply chains. The calculation was made under the following assumptions: (i) no significant variation of the initial quality index after processing, (ii) intact vacuum package and (iii) sufficient precooling before transportation.

The results show that under optimal product temperature, shelf life is reduced by 168 h at the retailer level. Whereas in the distribution scenario with abusive temperature conditions shelf life is reduced by 292 h.

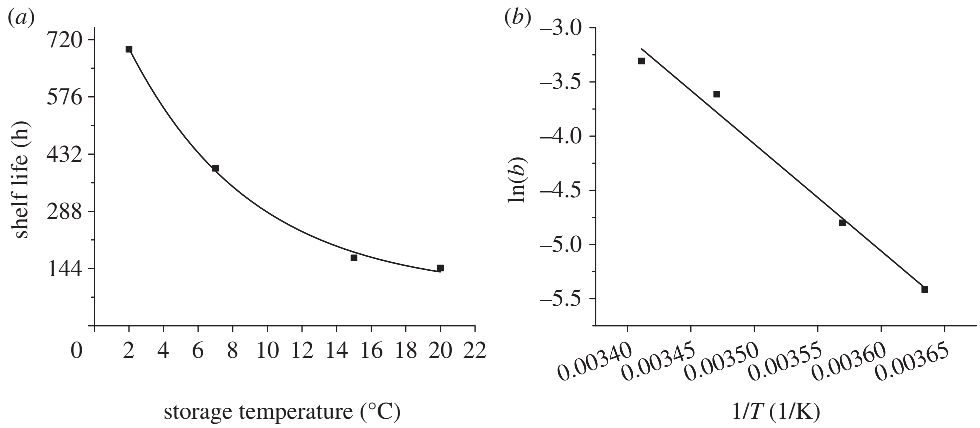

Figure 1. (*a*) Shelf life of vacuum-packed lamb as a function of temperature (filled squares) at 2°C, 7°C, 15°C and 20°C. (*b*) Modelling temperature dependency of slope steepness *b* of quality index with Arrhenius equation (filled squares) ln(*b*) estimated in primary modelling step (solid line) $\ln(b) = 30.50 - 9876.57 \times 1/T$ ($R^2 = 0.978$).

Table 2. Comparison of QI in different steps of a simplified cold chain under optimal and abusive temperature conditions.

		optimal product temperature			inadequate product temperature		
step in cold chain	time (h)	mean temperature (°C)	QI	shelf life reduction (h)	mean temperature (°C)	QI	shelf life reduction (h)
transport	10	2	1.0	10	7	1.1	19
distribution centre	48	2	1.3	58	6	1.4	99
transport	6	2	1.3	64	4	1.5	107
wholesaler	24	2	1.4	88	5	1.7	142
transport	8	2	1.4	96	6	1.7	156
retailer	72	2	1.8	168	7	2.3	292
total	168			168			292

The developed quality control model allows the prediction of the freshness loss under dynamic conditions in the chain. The application of the model in practice requires a simple illustration of the results. Therefore, a common traffic light model was chosen to display the actual quality status. Visualization of the quality status by the colours green, yellow and red enables fast and easy interpretation of the values and thus decision-making. Threshold values for the different signals can be defined by the quality reduction or time-temperatures thresholds. The values can be individually defined by the user.

The implementation of this quality tracing system into an LTL logistics network is shown by a meat supply chain for the investigated lamb products.

4. Process analysis and description of a less than truck load logistics network for Irish lamb products

Interviews with stakeholders and a process analysis were conducted to identify logistical processes and the handling and availability of temperature data and to define general requirements for the implementation into the respective meat supply chain.

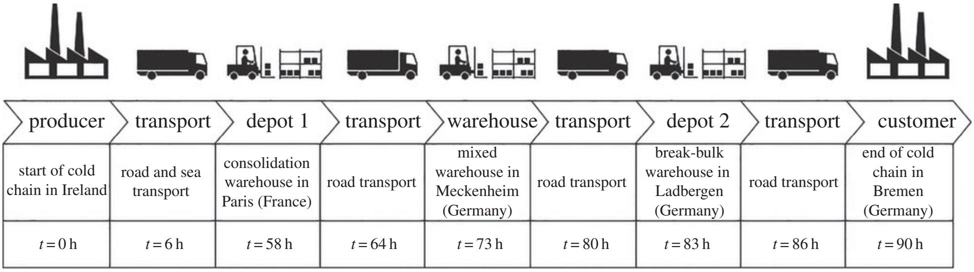

Figure 2. Cold chain of Irish lamb products with cross-docking facilities (depot and warehouse).

Figure 2 shows the cold chain from Ireland to Germany with a short description of the process steps and an approximate timeline in each step. The delivery of lamb products from the producer to the customer takes on average about 90 h, but may vary—depending on traffic, route and season—between 45 and 120 h. Along the entire cold chain, four transport processes and three cross-docking processes take place. In this cross-docking network, the transport of the goods are carried out with four different loading units, i.e. trucks. From Ireland to continental Europe, the goods are loaded onto a trailer which will be shipped by ferry. Including the road transport to the port and to the depot, this step may take more than 50 h. At the cross-docking facilities at depot 1 in Paris, France (consolidation of goods), the warehouse in Meckenheim, Germany (deconsolidation and consolidation of goods) and at depot 2 in Ladbergen, Germany (deconsolidation of goods) de- and consolidation processes are in general carried out in the same areas of the depots. The warehouse represents the centre of the business processes with supply processes (upstream) and distribution processes (downstream). Usually goods are sold and scheduled before arriving at the warehouse. Environmental temperature is monitored in each step of the chain by data loggers. During transportation, environmental temperature is controlled by data loggers, and printed data records are exchanged. Product temperature is controlled at incoming inspections at depots 1 and 2, the warehouse, and the customer with infrared thermometers. However, a complete temperature history for the products is not available.

Based on the process analysis, the technical requirements for continuous temperature monitoring of the products and the implementation of the quality control model into software were defined and are described in the next step.

5. Technical application of quality tracing in meat supply chains

(a) Hardware system to trace quality loss over the chain

In this part of the study, automated wireless sensor nodes (WSNs) were developed (Virtenio, Germany) to monitor product temperature over the whole supply chain. The sensor nodes can log and transmit data and quality information and are attached directly to one product inside the cardboard boxes. The WSNs work in online as well as in offline mode when an Internet connection is not available. Every node is connected in a WPAN (wireless personal area network) using 6LoWPAN and coap-08 protocol for communication. The nodes are initialized using Google Protobuf packages, which contain the model algorithm, time-temperature limits and the measurement interval. Using this information, the sensors start measuring temperature with the included hardware at a specified time interval. The measurement data contain a timestamp (relative to the nodes booting time) and the measured temperature. The WPAN network has a main node which is responsible for package routing inside the network and the communication with a freight supervision unit (FSU) [18] or external software.

In online mode, all measured data are transmitted to an FSU via a serial interface and forwarded to a web server at all times. In this mode, no further data storage, data analysis or data management is implemented on the sensors as the data are available on the server in real time.

In offline mode, temperature is measured and recorded to local storage on each node. A software implementation of the quality control model directly on the sensor hardware predicts the current product status and the remaining shelf life based on the temperature history of the products. In order to achieve fast and easy access to this analysis, a small LED-device is mounted to the sensors, which shows the result of the analysis and therefore the current predicted quality status of the products using green, yellow and red lights, corresponding to the above described traffic light model. As soon as the sensors are deinitialized by the corresponding software (see §5*b*), the measured data are transmitted to the software for further analysis and storage.

(b) Integration of the model into handheld software

The developed software is called *ICLogistics* (OTARIS, Germany) and runs on an ordinary Windows 8 platform and communicates with the sensor network. As it requires WiFi, a camera and the flexibility of mobile use, a Tablet PC was used. When communicating with the sensor network, information is sent as Google Protobuf packages to the networks' root node and vice versa. Fault-tolerant communication is achieved using package indexes. Depending on the communication purpose, the size and the type of the packages can vary.

ICLogistics acts as central data management tool in offline mode or as a simple sensor linkage tool in online mode (figure 3). *ICLogistics* scans the QR codes which contain the freight label information and the sensors network addresses (IPv6). Scanning the freight label provides the relevant information about the quality model to be used, which then is taken from local storage or a web server and sent to the sensors for initialization. In online mode the software hereby communicates with the networks main node via the FSU by WiFi. The FSU then routes the commands and the nodes replies through the network. In offline mode, a mobile WLAN router is used. When receiving the freight, the sensors are deinitialized either with (offline mode) or without (online mode) receiving the recorded data. After every step, an email containing all relevant information (e.g. measurement values and initialization mode) is generated by *ICLogistics* and sent to specified email addresses using any available Internet connection.

For the practical application of the new measurement methods, direct feedback to the user is required. Therefore, the quality control model is implemented in the software as well, the measured data (in offline mode) are analysed and the predicted quality status is displayed by the above-mentioned traffic light model. To generate the overall product status, single records are accumulated. If shelf life reduction oversteps a defined limit, changes in distribution or warehouse management can be planned ahead. On the other hand, if time–temperature thresholds are exceeded, a warning for immediate action is generated. Only if the recorded temperatures are outside the target temperature for a longer time span than given by the model, the overall status switches from green to yellow (warning) or red (error). Thus, when reloading the goods, the temperature might leave the temperature interval for a single record, but without influencing the overall product status. As there are more possibilities in a sophisticated software environment like a Windows 8 program, the visualization is more detailed than on the sensors.

In addition to the real-time analysing, the records are also saved to an XML-file, which is provided after every loading, reloading or unloading step supported by the software. Thus, the measurement data are also available for subsequent analysis. This XML-file is attached to the email mentioned above, so the gathered data are available to all relevant actors as soon as possible.

In the next step, a concept for the application of the developed system into the above described logistics network for vacuumed lamb products is presented. According to this concept, the system was tested in a field trial in the respective supply chain from the producer in Ireland to depot 2 in Germany.

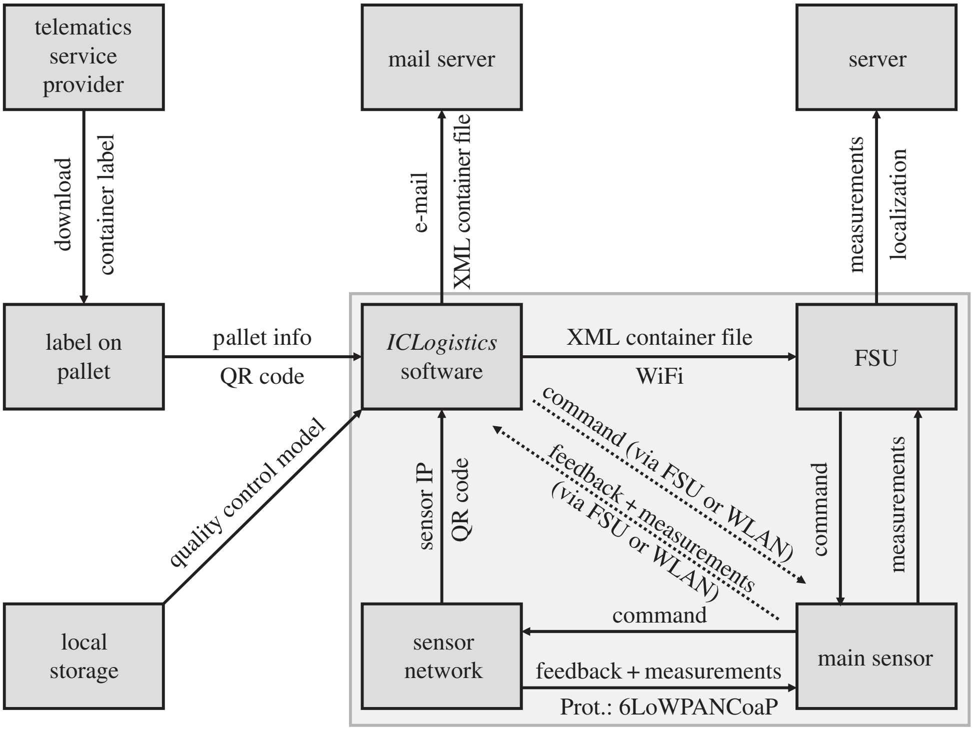

Figure 3. Data management with *ICLogistics*.

6. Integration into a less than truck load logistics network

(a) Concept of quality driven distribution in cross-docking networks with less than a truck load transports and field trial

LTL logistics networks, such as the described lamb supply chain, require a flexible concept and special hardware and software solutions for quality tracing and quality-based decision support. Because of chain characteristics, it is necessary to switch between online and offline mode.

Figure 4 illustrates the application of quality tracing to the respective supply chain. In the first part of the cold chain from the producer in Ireland to depot 1 in Paris, the logging mode is offline. WSNs are initialized via wireless communication and an e-mail is generated after the event with information on the container, pallet, sensors and measuring parameters regarding the quality control model. On arrival at depot 1, a network with Internet connection is available, another email is sent to the warehouse and the actual quality status of the products is transmitted. At this point, the first decision-making is possible, and if time–temperature thresholds are overstepped or product quality is significantly reduced, corrective actions can be taken.

In this case, the information on product status is in time to inform the customer and deliver substitute products. Beginning at depot 1 in Paris, online logging mode is available and quality changes are sent immediately to the warehouse. On the distribution side of this chain, offline logging mode for handling processes in the distribution centre (depot 2) and the last mile transport to the customer is sufficient. Correct cooling and thus the real quality can be documented and, in case of failures, reported to the warehouse. The concept allows early reactions to events that require a change of logistics processes.

The applicability of the system was tested, which included the functionality and readability of the temperature sensors and the transmission of quality information to the warehouse. Owing to logistical reasons, the online mode was not initialized until arrival at the warehouse and

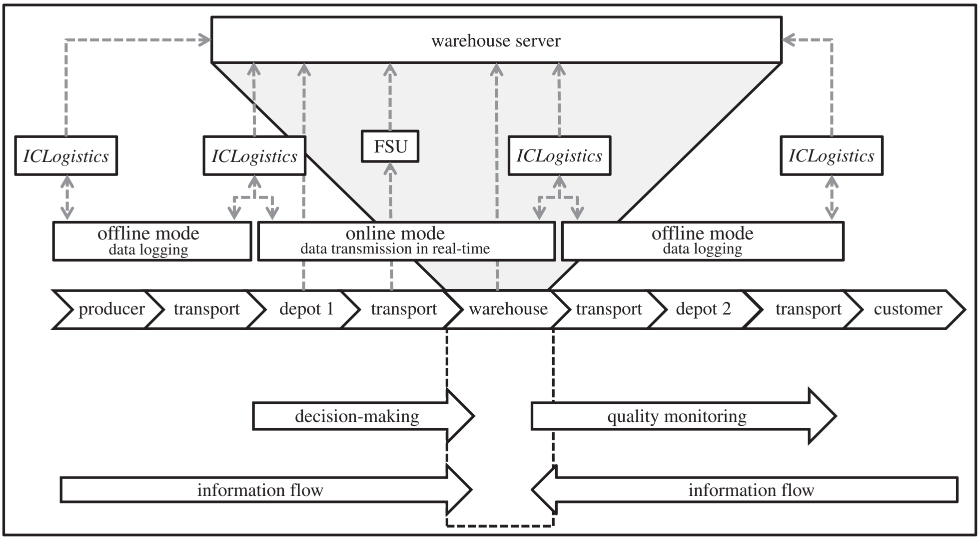

Figure 4. Concept for quality tracing in the lamb supply chain with the warehouse as centre of decision-making.

was tested during the transport step to depot 2. Four temperature sensors were placed at the surface of one product in four different cardboard boxes in the upper level of the pallet. However, in commercial application boxes with the highest risk of temperature deviation should be monitored. The initialization of the sensors shortly before loading for transportation succeeded as planned. On arrival at depot 2, all sensors were read and the complete set of data was transmitted within 2–3 min each. One sensor did not response immediately to the handheld device, which caused a delay in data transmission. This entire process took twice the time planned (20 min) and the prototypes need further optimization for use as commercial applications.

(b) Impact of quality tracing on distribution processes and resource efficient food production

The impact of quality tracing within cold chains is shown in figure 5 for the exemplary lamb chain. Based on the warehouse in this cold chain, all upstream processes are sourcing processes, and downstream processes are distribution processes. The processes coloured grey are performed by using the online mode. Since the QI of the lamb meat increases gradually, the logistics network has to be optimized to deliver products meeting the minimum acceptance level of the customer (QI_D, quality index at the time of delivery). Above QI_E (quality index at the end of shelf life) products will be wasted. At the top of figure 5, the supply chain with optimal product temperature is shown. The quality index will develop as forecasted (target) and should be delivered at time t_D (end of targeted delivery time). Under abusive temperature conditions, a reduction in real quality is predicted (actual). The delivery of lamb products from the producer to the customer takes on average about 90 h, but may vary—depending on traffic, route and season—between 45 and 120 h. Along the entire cold chain, four transport processes and three cross-docking processes take place. The increases of quality loss affect subsequent logistics processes directly. Therefore, the time for distribution is reduced to t_{Dnew} (end of actual delivery time). Consequently, the planned distribution processes have to be changed so that products will be delivered to a customer with shorter transport routes.

The implementation of such a quality driven distribution concept requires flexible logistics processes, which allow temporal adjustments for the distribution. Over the long term, this enables an efficient use of resources and effective process management, resulting in a reduction of losses in each step of the chain and thus more resources efficient food production.

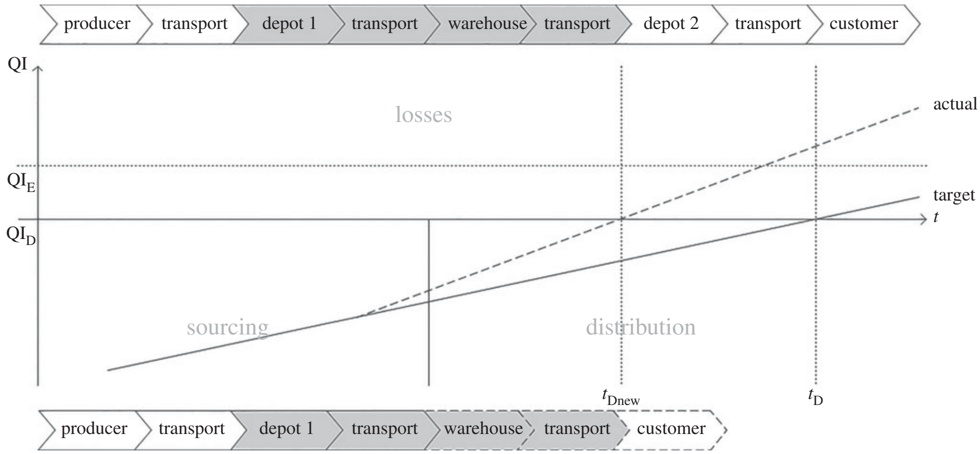

Figure 5. Impacts of quality tracing on logistics processes of cold chains; QI, quality index; QI_D, quality index at the time of delivery; QI_E, quality index at the end of shelf life; t, time; t_D, end of delivery (target); t_{Dnew}, end of delivery (actual).

7. Discussion and conclusion

In this study, a system for quality tracing of meat products was established and tested in a field trial. To predict the actual quality status of vacuum-packed lamb at any time within the supply chain, a quality control model has been developed. Most available shelf life models for perishable products predict the spoilage process based on the growth of an SSO [10,19–21]. Owing to the fact that an SSO could not be identified for vacuum-packed lamb, a sensory-based quality index was used. The model delivers good predictions based on the temperature history of the product. According to Raab *et al.* [6] and Arason *et al.* [11], a continuous monitoring of the product temperature and sharing of temperature data along the chain are a prerequisite for the application of shelf life models, i.e. quality tracing. This however, is not the practice in most of the supply chains, which was also confirmed by the process analysis for the respective chain. Especially sharing of information is often a problem, because of trust issues or missing standardization of data exchange and diversity of technical equipment and measurement procedures [6,11].

The implementation of a quality tracing system is a special challenge in cross-docking networks, owing to deconsolidation and consolidation processes. The developed hardware and software solutions meet these requirements and enable continuous temperature monitoring of product temperature by the application of automated WSNs linked to the product. The quality control model is transferred to the nodes via the described software and predicts the actual quality status in real time. The DST visualizes the actual status of the products, enhancing simple use, also for untrained personnel.

In today's logistics, the use of software like enterprise resource planning (ERP) or warehouse management systems is very common [11]. Using this software, electronic data exchange provides efficient and reliable support along the supply chain. In particular for incoming and outgoing goods scanning of transport units like pallets or boxes, it enables synchronization of material and information flow. Connecting this information from all actors, tracking and tracing of goods is possible. The approach of Arason *et al.* [11] to use ERP systems combined with effective DST is suggested for future work. The development of mobile devices to support logistics processes would also be of advantage.

In summary, tracing the quality of meat products enables the actors in the chain to keep the quality of their products as high as possible. The possibility of direct intervention makes this a very useful tool for intelligent storage and distribution management. Products can be directed according to their quality status, resulting in increased consumer satisfaction and competitiveness. Also, as stated by Lütjen *et al.* [22], quality tracing can lead to higher efficiency in logistics. The system can be easily implemented in different perishable supply chains, but since predictive models are specific for each product, the system is only applicable to a selected part of the shipment in LTL cross-docking networks. In such a case, or when a product specific model is not available, the system can be used for temperature monitoring and corrective interactions as well as for quality management purposes. Over the long term, losses and food waste caused by temperature abuse can be minimized.

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