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Criteria for temperature alerts in cod supply chains

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Abstract

Purpose – Wireless sensor network (WSN) technologies are now available to implement real time temperature monitoring systems in food supply chains. The aim of this paper is to examine different types of methods and criteria to establish alerts in decision support systems in perishable food supply chains.

Design/methodology/approach – Logistic and temperature mapping was performed in cod supply chains to obtain data to establish criteria for temperature alerts. Data were collected for both ambient temperature and temperature of products packed in expanded polystyrene boxes.

Findings – Alerts based on single criterion for ambient temperature resulted in false alerts when compared to criteria for product temperature. More complex methods that took into account both temperature abuse and the severity of the abuse resulted in more relevant alerts for the chilled cod supply chain.

Research limitations/implications – The research is based on mapping of cod supply chains with a limited number of iterations.

Practical implications – The scope of the research is the application of WSN in an actual supply chain of chilled cod transported from Iceland to Europe, which has relevance in assisting management decision making in the supply chain to prevent losses of quality and minimize waste.

Originality/value – Failure to maintain a low temperature occurs frequently at handover points where alert systems are usually not in place. The theoretical implication of this paper is the development of a conceptual framework for setting up temperature criteria for real time decision support systems in food supply chains.

Keywords Iceland, Agricultural and fishing industries, Fishing, Supply chain management, Temperature measurement, Temperature criteria, Decision support systems, Food supply chains, Wireless sensor networks, Transportation

Paper type Research paper

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1. Introduction

The main factor influencing the rate of spoilage of chilled seafood is the temperature in the whole supply chain. During transport there are risks that fluctuations in temperature may occur, which can reduce the shelf life of the products. Product losses in food transportation due to temperature mismanagement and quality decay can reach up to 35 percent (Scheer, 2006). Temperature abuse and fluctuations are the main concerns in the fresh food supply chains as they may cause safety and quality problems, and thus also economic losses (Labuza and Fu, 1995; Raab *et al.*, 2008). In the event that products are transported with too high of temperatures, damages may result in losses, costing thousands of dollars (Kevan, 2005). Therefore, the advantage of continuously monitoring temperature throughout the whole supply chain of perishable goods like food products is obvious because of quality and safety concerns and economic reasons (Kuo and Chen, 2010; Kreyenschmidt *et al.*, 2010).

Currently food producers are tracking their environmentally sensitive products using either temperature data loggers placed with the products being shipped, or each location being monitored. In the case of the data loggers, they require manual inspection, which can be costly (Abad *et al.*, 2009). Besides having to read the temperature information, it is necessary to open the container or package. Damaged goods are only discovered at their final destination, when it might be too late for remedial action. Quality problems should be detected as quickly as possible, and alerts should be triggered when temperature is out of bounds. The online temperature monitoring in the cold chain, which provides supply chain actors access to the temperature history, has potential benefits regarding supply chain management, improved transparency and potentially less waste (Olafsdottir *et al.*, 2010).

Within the EC funded project CHILL-ON, technologies have been developed to implement a holistic traceability system with temperature monitoring, shelf life prediction and decision support system (DSS) (FP6-016333-2: developing and integrating novel technologies to improve safety, transparency and quality assurance of the chilled/frozen food supply chain – test case fish and poultry). The studies presented in this paper are part of mapping experiments in the project, where performance criteria were determined to verify the functionality of the developed technologies during implementation in field trials (FT) in fish supply chains.

2. Relevant literature

Wireless sensor networks (WSN) offer opportunities for improved transport planning (Ruiz-Garcia *et al.*, 2009), and give new challenges in monitoring temperature during the entire supply chain from catch to consumer.

2.1 Wireless sensor networks

Radio-frequency identification (RFID) tags are small electronic devices that can identify products from a distance without any physical contact. Implementation of RFID technology has been a challenge especially for small to medium sized enterprises (Ao *et al.*, 2010). Currently barcodes are the predominant method of identifying products in the food supply chain. WSN can combine both the RFID tags and the data logger's technologies and present many advantages for data collection compared with traditional solutions. WSN have been prospected as powerful solutions for many applications, such as surveillance, tracking, locating, etc. (Schwiebert *et al.*, 2001). Their applications are countless with high market potential, but applications of wireless sensors in the food industry are still rare (Wang *et al.*, 2006). These devices can actively monitor the products and verify proper handling conditions of goods, e.g. temperature of food (Evers *et al.*, 2007). It is therefore possible for owners and stakeholders in various parts of the food supply chain to monitor the temperature from catch to consumer and receive instant notifications of potential food quality problems. This would allow corrective action to be taken before the transport arrives at its destination.

WSN are built up with a number of small spatially dispersed sensor nodes, each with limited processing capacity and memory, which transmit data in digital form to a base station (Akyildiz *et al.*, 2002). The sensors are mobile and can record and store data until they come again in range of the base station and transmit the stored data. Furthermore, WSN systems can be equipped with various types of sensors, such as temperature, humidity and volatile compound detection to monitor different environments (Shen *et al.*, 2004). The base station collects data from multiple sensors and sends it via a mobile network such as GSM to a central server. Rapid development of WSN during recent years has resulted in the availability of low cost, low power, multifunctional sensors (Ruiz-Garcia *et al.*, 2009). These new developments in WSN open the possibility of having a battery driven base station, following the products throughout the whole supply chain.

The accuracy of the sensors is critical for early detection of temperature changes, fluctuations and gradients within the cold chain. Standards for food distribution allow deviations of $\pm 0.5°C$ from the set point (EN, 1999). Environmental temperature can vary depending on the location of the logger, packing material, or heat dissipation of the product. This creates the challenge of selecting the right criteria for temperature alerts, which gives the supply chain actors meaningful information on the condition of the products. WSN provide a unique solution to acquire data, analyze it and share it with stakeholders in the supply chain in near real time to support decision making and management of the supply chain.

2.2 Temperature in fish supply chains

The temperature requirements in each unit along the shipping route are set according to the product in question and the target criteria established (e.g. storage life based on the respective average temperature and temperature variance).

Local alerts can be easily deployed based on a long historical data of temperature in the cold room and consistent conditions. In logistics it is very different; even though the temperature criteria is set and the logistics partners agree on the temperature requirements during transport, the actual conditions can be difficult to control. The lack of temperature control caused by frequent interruption of the cold chain during loading and unloading between different transport modes (e.g. land, air) has been reported to be more severe for air freight shipping of fresh fish products, compared to sea shipping (Mai *et al.*, 2010; Martinsdóttir *et al.*, 2010). A study on simulated abusive conditions that could occur during transport (16°C for 8 h) showed a reduced overall shelf life of cod products (Olafsdottir *et al.*, 2006). Logistics providers have already started to implement novel temperature monitoring solutions. However, neither the inter-organizational information exchange of these collected data, nor the combination of temperature data with data on products' safety and quality characteristics, is being applied effectively for food supply chain management (Eden *et al.*, 2010).

Moureh and Flick (2004) found temperature differences inside a truck of up to 12°C that can cause severe deviations in product quality. Studies on the temperature rise within a pallet unit load show large temperature variations even after a short exposure to higher ambient temperature (Jedermann *et al.*, 2006; Moureh *et al.*, 2002; Margeirsson and Arason, 2008). The top layer in a pallet or load is very sensitive to ambient conditions and experiences larger fluctuations, whereas in the center, the temperature remains relatively constant.

Temperature gradient inside the expanded polystyrene (EPS) box has also been reported (Lauzon *et al.*, 2010). Therefore, the placement of sensors inside boxes and on pallets is very critical and clear working guidelines need to be in place when loggers and WSN are implemented for monitoring purposes.

2.3 Alerts

Successful supply chain logistics call for automated and efficient monitoring linked with DSS, to assist in managing the information collected. The DSS should allow for establishing better knowledge detecting weakness, and optimizing the whole process. Alert systems as part of DSS are one of the primary means by which temperature abnormalities are brought to the attention of operators in the supply chain. Alert systems have several factors that have been identified as problematic in fault management; for example, nuisance alerts, ambiguous or underspecified alert messages and alert inflation (Lees, 1984). If alerts occur too frequently and seem too familiar, the observer might miss out when something is truly abnormal (Woods, 1995).

No matter how well the systems or criteria are designed, false alerts occur occasionally, turning on the alert when it should not. This is called a Type I decision error. The possibility that the alert is not triggered when it should be is called a Type II decision error (Box *et al.*, 2003). Both types of errors can reduce the practical usefulness of the alert system. In the temperature alert context a false alert or a Type I error means that an alert is issued when the temperature is within the set range. Alternatively, an undetected valid alert implies a Type II error where the temperature is out of bounds without the operators being appropriately notified.

The design of proper alert criteria for perishable food in logistics is often more difficult than design of temperature alerts in local cold rooms. The phase of transport is much more problematic because of the loading and unloading periods (handovers), but also because trucks are not as well equipped as warehouses (Kacimi *et al.*, 2009). The shift in average temperature and variance when products move from one operator to another makes it difficult to use statistical methods such Shewhart charts, cumulative sum (CUSUM) and moving average. These methods are based on detecting small shifts in average value and variance (Montgomery and Runger, 1999). Additionally, local alert systems may not detect the temperature rise, due to the fact that the products may be located in loading areas that might be in open air outside the facilities. The stakeholder cannot know in advance the real temperature and the temperature variance of the chilled spaces where the products will be temporarily stored during the transport. Furthermore, the local inspection is the responsibility of each partner, since each cold room is not managed centrally, and consequently, other actors in the chain will not have a complete overview of possibly abusive supply chain events.

The aim of this paper is to demonstrate the importance of performing temperature mapping of conditions in supply chains when selecting the proper criteria and methods for temperature alerts. The theoretical implication is the development of a conceptual framework for setting up temperature criteria for real time DSS in the whole supply chain.

3. Methodology

Mapping experiments were performed under dynamic temperature conditions of an actual chilled supply chain of fresh cod loins transported by sea from Iceland to France.

3.1 Experimental design

Three mapping experiments were conducted in real supply chains of fresh cod, where the products were followed through the whole logistics chain. Data loggers were used in the mapping prior to implementing the full scale WSN system in a partly simulated shipping chain during the FT where both data loggers and wireless sensors were applied (Table I).

The three mapping experiments (M1, M2 and M3) were performed in collaboration with a fish producer in Iceland as part of regular shipments of the company. The experimental groups were kept separate from the normal processing, since these were part of ongoing trials, using liquid ice chilling before packaging, with the aim to reach a temperature below 0°C (−1°C to 0°C). The fish was packed in EPS boxes with 5 kg of cod loins in each box and 250 g frozen cooling pads on top.

The details of the experimental set-up and handling of the fish were reported earlier for the FT in November 2009 (Lauzon *et al.*, 2010). Two pallets were tracked during the FT. Pallet 1 (P1) with 90 boxes in ten layers. Nine EPS boxes contained cod loins, which were located in three corners; the rest of the boxes contained salt instead of fish for economical reasons. Pallet 2 (P2) contained 54 boxes in six layers of which six EPS boxes contained cod loins. To simulate actual conditions where products may be subjected to temperature fluctuations and/or abuse during logistics processes a temperature abusive scenario was created in the FT, where the fish boxes were left at high temperature (16°C) for a period of 4 h and then transported in a vehicle without cooling equipment.

3.2 Temperature loggers

Two types of temperature sensors were applied in the experiments, data loggers (iButton DS1922L from Maxim Integrated Products, Inc, Sunnyvale, CA, USA) with an accuracy of ±0.5°C and a resolution of 0.0625°C and a WSN monitoring system made for stationary and mobile monitoring (CMS, Controlant, Reykjavík, Iceland) with an accuracy of ±0.5°C and a resolution of 0.1°C. The WSN sensors were equipped with probes, so the same

Experiments	Date	Temperature logging device	Number of pallets	Number of loggers	Cod supply chain
Mapping 1 (M1)	April 2009	iButton	1	4	Actual transport IS to FR
Mapping 2 (M2)	May 2009	iButton	1	7	Actual transport IS to FR
Mapping 3 (M3)	August 2009	iButton	1	11	Actual transport IS to FR
Field trial (FT)	November 2009	iButton WSN	2	P1: 18 P2: 48	Partly simulated transport (P1: normal, P2: abused)

Table I. Experimental groups, temperature logging devices, pallets and logistic chains sensor was able to record both the ambient and product temperature and they were placed in the same locations as the data loggers.

Different numbers of data loggers were used in each shipment (Table I), with a total of three data loggers placed in each box to monitor product temperature (one in the bottom outer corner, one in the center of the box and one in the bottom inner corner). For ambient monitoring at least one logger was located on the center of each side and on top of each pallet.

3.3 Establishment of temperature criteria

The temperature data collected in the three mappings (M1, M2 and M3) was used to establish the experimental conditions and temperature scenarios for the FT. Temperature criteria for alerts in the FT were determined based on governmental regulations, expert opinion, common practices and requirements from industry participants, as well as the observed temperature scenarios in the mapping trials and optimization of criteria.

Different methods to trigger alerts were explored based on threshold temperature and time periods and also taking into the accumulated temperature effect over a period of time. The optimal parameters for each method were selected by evaluating all temperature scenarios from the mappings, taking into account different threshold temperature (-2°C to 8°C), and time periods (30 min to 5 h). Equal value was given for false alerts and undetected ones. The aim was to minimize the total of false and undetected alerts.

4. Results and discussions

4.1 Mapping experiments

Analysis of actual temperature scenarios showed that the boundaries and timelines were similar in all the mappings (M1, M2 and M3) (Table II) and these conditions provided the basis for the simulated FT.

The initial temperature was dependent on the efficiency of the chilling of the products after processing. The main difference observed in product temperature was the low observed temperature in M1 (Figure 1), where dipping into liquid ice was applied successfully to reach the low temperature (-0.5°C) before packaging. However, it has to be noted that the product temperature turned out to be lower than expected, possibly because the loggers were in contact with the liquid ice. For M2 and M3 the initial chilling was inadequate and the chilling method failed to obtain a satisfactory target temperature. Therefore, the two ice pads inside the EPS boxes and the low ambient temperature during shipping were needed to cool down the products, as has been proven to be an effective way to protect fresh fish fillets against temperature abuse (Margeirsson *et al.*, 2009).

The main fluctuation in temperature occurred at the handover points (Figure 1). For mappings M2 and M3 the temperature was slowly declining after packaging, reaching a temperature around 0.5°C for M2. A further decline in temperature was observed for M3 reaching 0°C on day four. During the transport to the shipping in M3 on day 1, it was clear that the temperature of the truck transporting the products had the temperature set point for temperatures around -18°C which lowered the product's temperature.

Table II. Duration of different steps in the supply chain from the mapping experiment and analysis of data for ambient and product temperature measurements

	Duration (h)			Mapping 1				Mapping 2				Mapping 3			
				Temp.		SD		Temp.		SD		Temp.		SD	
	M1	M2	M3	Amb.	Prod.	Amb.	Prod.	Amb.	Prod.	Amb.	Prod.	Amb.	Prod.	Amb.	Prod.
Catch	14	14	14												
Landing/weighing/market	2	2	2												
Transport to factory	1	1	1												
Storage in factory	15	10	14												
Processing and packaging	2	2	2							0.53	0.49				
Storage before shipment	19	2	23	2.8	−0.4	0.92	0.00	10.0	5.4	0.98	0.97	4.7	1.1	3.46	0.21
Transport to shipper	1	1	1	5.5	−0.4	1.21	0.00	−0.8	0.4	3.76	0.24	−14.5	1.3	4.81	0.16
Storage at shipper	10	4	4	1.8	−0.4	2.27	0.00	6.6	1.4	2.06	0.23	9.5	1.3	2.34	0.23
Shipping to BSM	76	93	83	0.3	−0.4	0.20	0.00	−0.1	0.8	0.49	0.34	−0.2	0.2	0.77	0.34
Storage in Immingham	15	24	13	1.92	−0.4	4.74	0.00	2.0	0.7	0.63	0.12	8.6	0.8	2.66	0.13
Shipping to BSM	16	15	14	0.3	−0.4	1.83	0.00	0.5	0.5	0.20	0.12	1.3	0.8	7.08	0.02
Arrival at BSM	1	1	1												
	172	169	172	0.3	−0.4	2.60	0.02	0.5	0.9	1.95	1.20	1.2	0.5	3.53	0.49

In all the mappings, the dispatch and loading of the products took place in non chilled areas on day 5, where the products were stored for 4-10 h (Table II). For M3 a rapid increase in temperature was observed for the products during the handover on day 5 (about 1°C from the minimum) (Figure 1). This is in accordance with the ambient temperature reaching above 15°C. This high rise in product temperature should result in triggering alerts. The mapping clearly identified the need for alerts at handover points and therefore a similar abusive temperature and time scenario was simulated in the FT.

4.2 Field trials

During the FT two different pallets were traced. Pallet 1 was undergoing an uninterrupted cold chain scenario and Pallet 2 was treated by temperature abuse to simulate the unchilled periods like during handover between shipping and trucking (about 16°C for 4 h), in accordance with the observed scenario in the mappings. The pallet under normal temperature conditions maintained a steady temperature close to 0°C, with small variance in temperature. The initial chilling was successful and the temperature was low from the start. Even with a higher than expected ambient temperature initially, the product's temperature was not affected because of the insulating effect of the EPS boxes. The pallet that received abuses was also observed with steady low product temperature, but the average temperature was slightly higher than that of the first pallet (Figure 2).

The different temperatures between pallets 1 and 2 may perhaps be explained by their location in the container. The maximum difference in ambient temperature in the container was 18°C, which occurred just after loading (overall average difference of 6.9°C). A temperature gradient was also observed for the ambient temperature surrounding the pallet (max. 5.7°C) during the abuse period, with an overall average difference of 0.84°C. During the abuse period the product temperature increased rapidly and reached the maximum at 4°C. For the simulated transport of a truck without temperature control, the temperature first increased during the transport, but then the

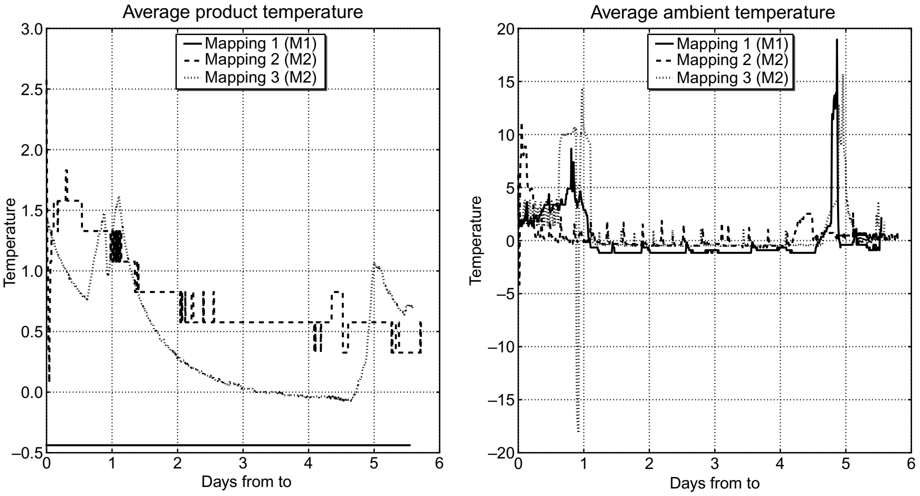


Figure 1.
Average product temperature (°C) (left) and ambient temperature (°C) (right) measured in mappings M1, M2 and M3 from the point of packaging (t0) in Iceland until arrival in France on day six

ambient temperature went below zero during the cold November night in Iceland, resulting in the product temperature declining throughout the journey (Figure 2).

During the FT the largest temperature difference of products in the EPS boxes occurred during the abused period where the temperature difference was 5.2°C and there was an average difference of 0.7°C during the mapping. In general the boxes that were exposed on two sides had a bigger temperature difference than the boxes that had just one side exposed, with a maximum difference of 3.9°C for a box with only one side exposed (Table III). Based on earlier experiments it is well known that temperature gradient will occur inside boxes (Lauzon *et al.*, 2010), within pallets and in containers/cold rooms (Margeirsson *et al.*, 2009). Such temperature differences in the products and in the ambient air underline the importance of defining the location of the sensors to ensure the relevance of alerts being issued. The impact of the higher average temperature for the abused pallet P2: 0.7 ± 1.01°C compared to P1: -0.2 ± 0.15°C (Table IV) resulted in about a one day loss of shelf life as analyzed in a parallel study (Lauzon *et al.*, 2010).

4.3 Temperature alert criteria

The temperature data from M1, M2 and M3 was used to design the experimental set-up for the FT, to simulate an actual supply chain scenario. Based on the mapping data the possible criteria for alerts were explored to ensure that relevant alerts and warnings would be applicable for the respective supply chain.

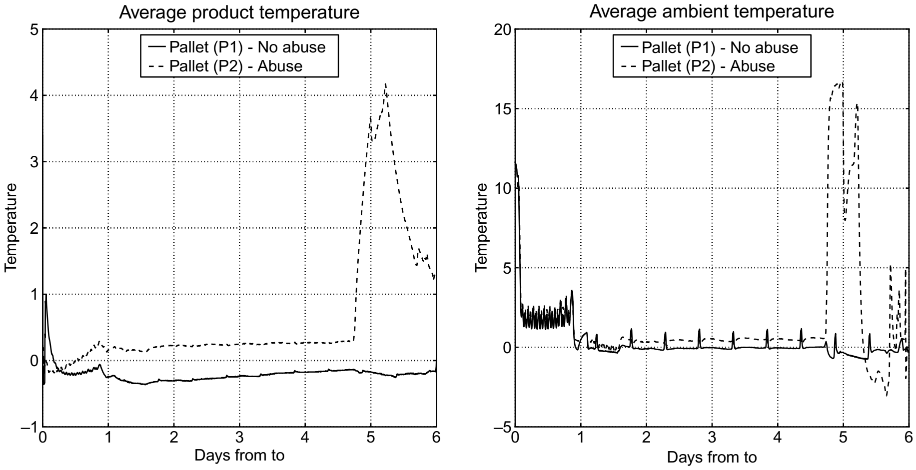


Figure 2. Average product temperature (left) and ambient temperature (right) measured in the field trials from the point of packaging (t0) until the end of the simulated transport for the two pallets, P1 (normal conditions) and P2 (temperature abuse)

Table III. The average minimum and maximum temperature difference within each box

	Box 1	Box 2	Box 3	Box 5	Box 7	Box 9
Average difference	0.71	0.75	0.72	0.44	0.40	0.59
Maximum difference	5.22	4.00	5.15	3.90	3.33	5.28
Minimum difference	0.05	0.19	0.00	0.00	0.00	0.09
Sides exposed	2	2	2	1	1	2

Table IV. Duration of each step in the cod supply chain, average ambient and product temperature and standard deviation (SD) during the FT (November 2009)

	Duration (h)		Pallet (P1) – no abuse				Pallet (P2) – abuse			
			Temp.		SD		Temp.		SD	
	P1	P2	Amb.	Prod.	Amb.	Prod.	Amb.	Prod.	Amb.	Prod.
Catch	11	11								
Landing/weighing/market	13	13								
Transport to factory	1	1								
Storage in factory	4	4								
Processing and packaging	4	4	9.2	0.4	2.89	0.80	10.8	0.2	5.75	0.04
Storage before shipment	20	20	1.8	− 0.1	0.58	0.12	2.0	0.0	0.32	0.02
Transport to shipper	1	1	− 0.1	− 0.2	0.06	0.02	0.4	0.2	0.00	0.00
Storage at shipper	5	5	0.4	− 0.2	0.38	0.02	0.5	0.2	0.08	0.00
Shipping to BSM[a]	86	86	− 0.1	− 0.2	0.09	0.00	0.4	0.2	0.05	0.00
Storage in Immingham[b]	23	7	0.0	− 0.2	0.22	0.06	6.2	2.7	57.72	0.81
Shipping to BSM[b]	5	20	− 0.4	− 0.2	0.30	0.02	1.1	1.5	1.09	0.01
Arrival at BSM[b]	2	3	0.3	− 0.2	1.47	0.00	0.4	1.3	1.95	0.00
Total time (h)	175	175	0.3	− 0.2	1.36	0.15	1.9	0.7	16.37	1.01

Notes: [a]Partly simulated step; [b]fully simulated step

The alert settings suggested also considered information obtained from industry actors, since different requirements are demanded. The logistics company's promise is 4°C in agreement with governmental regulations; however, lower temperature alerting criteria were considered more appropriate, since the industry target temperature was lower than the regulatory requirements, i.e. expert opinion (− 0.5°C), common practices (0°C-1°C) and requirements from the industry participants (below − 0.5°C).

A common method of triggering alerts (single threshold temperature alerts (STTA)) was used to analyze the mapping data from M2 and M3 to select product temperature criteria to trigger an alert (Figure 3). If product temperature was not too high (below product temperature criteria), when the alert was triggered it was considered false and if the alert was not triggered when the product temperature was too high (above the product temperature threshold) it was considered undetected. The data was evaluated by counting the number of false and undetected alerts for different product temperature criteria. The results indicated that when using the low product temperature threshold as suggested by expert opinion and industry partners (− 0.5°C to 0.5°C) the number of false alerts would be very high (above 1,000 for the duration) (Figure 3). Using a more lenient temperature criterion (1°C) would generate fewer and more relevant alerts. Therefore, the product temperature criterion of 1°C was suggested.

4.4 Temperature alert settings

WSN systems offer means to measure both ambient and product temperature and to report alerts if temperature is out of bounds. Most operators use the WSN system to measure the ambient temperature and not the product temperature, for example, because:

- placement of WSN sensors requires opening of packages;
- the environment inside the boxes may limit the transmit range; and
- retrievals of sensors are more difficult.

However, the product temperature gives more information about the condition of the product.

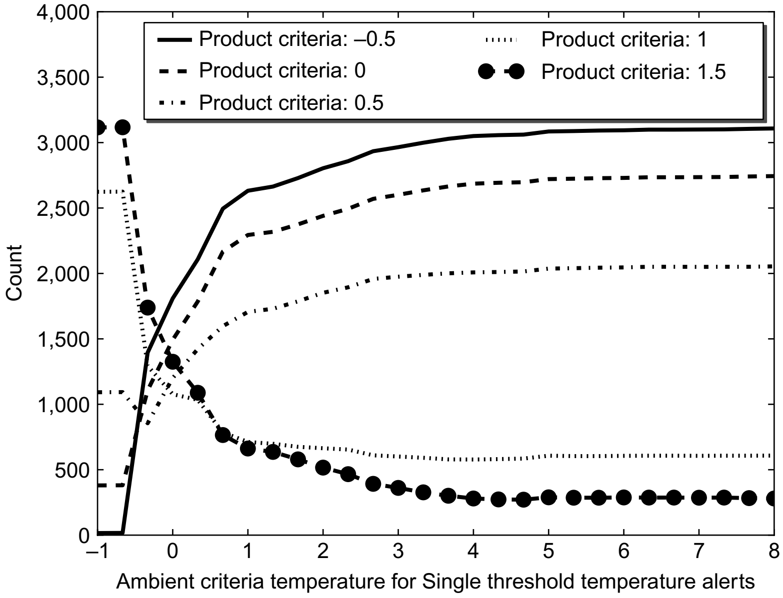


Figure 3.
Sum of false and undetected alerts for different product temperature criteria set and different single threshold alert criteria based on data from mappings M2 and M3

Based on the criteria set for product temperature (Section 4.3) several different methods were explored to analyze the temperature data collected in the FT. The aim was to develop a conceptual framework for setting up knowledge-based temperature criteria useful for real time DSS in food supply chains. The knowledge-based criteria were selected to give the most proper alerts, i.e. having a limited amount of false alerts, and that would not trigger unnecessary alerts because the criteria were too strict. The accuracy of different methods to issue useful alerts was compared against the set criterion for product temperature. Algorithms were applied to define the value for ambient temperature criteria and period to minimize potential non-useful alerts using historical data from the mappings to find out what criteria should be used for each method:

- STTA is the most common method of issuing alerts in WSN systems. Alerts are triggered if the temperature at any point is above the threshold temperature criterion. The method uses one single input, which is the threshold temperature. This value based on optimization using data from mappings was set at 8°C.
- Period based threshold temperature alert (PBTT) implies that the measured temperature needs to be above the set threshold temperature for a predetermined period before an alert is issued. The method takes two inputs, the threshold temperature and the time period. Based on optimization, using data from mappings the criteria were set at 4.5°C and a period of 1.5 h.
- Accumulated threshold temperature alert (ATTA) counts the number of times that the temperature is above the set threshold temperature and subtracts the number of times that the temperature is under the set threshold temperature. The counter has a minimum of zero and a set maximum. The method issues an alert if the counts are equal to the maximum. The method uses two inputs,

the threshold temperature and maximum value. Based on the optimization using data from mappings the criteria were set at 4.5°C and a period of 2 h.

- Accumulated temperature alert (ATA) accumulates the temperature difference between lowest acceptable temperature (T_{min}) and the measured temperature multiplied by the time between samplings. An alert is issued if the accumulated temperature is above the maximum accumulated temperature where the temperature is set at the criteria temperature (T_{max}). T_{min} was defined as -4°C or well below the observed temperature during the mapping. The method takes one input, the threshold temperature, and based on optimization from mappings the criteria were set at 5°C for a period of 4 h.
- Combined methods – a comparison was performed by combining the STTA methods with each of the other three methods. Results from optimization of the parameters based on the mapping data resulted either in considerably longer (3-4 h) or much shorter periods (0.5 h) for the period based methods, and lower ambient temperature criteria (3°C-4°C). The temperature criterion for the STTA was higher than when the method was used alone (10°C-15°C).

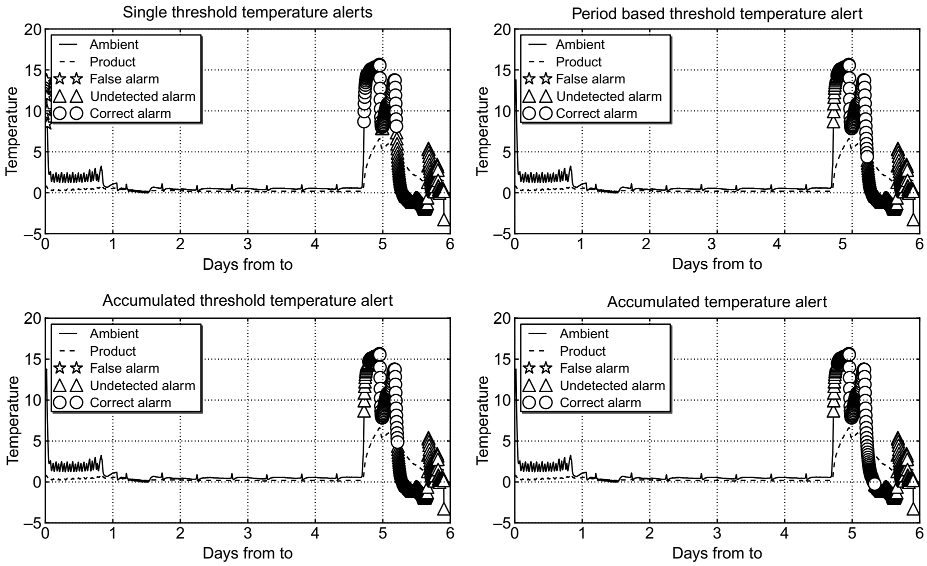
4.5 Temperature alert analysis

The total number of false and undetected alerts varied when applying the different methods (Table V). False alerts were triggered for the abused pallet (P2), only by the STTA method (Figure 4). This occurred in the beginning of the process when the products were in the packaging area and the ambient temperature was too high for a short period of time. Observations were similar for P1, but additionally the method produced false alarms when the abuse started, and the product temperature had not risen above the threshold temperature.

As shown in Figure 4 the methods varied in sensitivity toward temperature abuses. PBTT method did not trigger any alerts for P1, and only triggered alerts for P2 after the temperature abuse had been ongoing for the predetermined period. The method stopped triggering alerts as soon as the ambient temperature decreased below the ambient temperature criterion, although the product temperature was still above the threshold temperature. This resulted in undetected alerts both at the beginning and the end of the abuse period. The ATTA method did not issue alerts for the normal condition but was first to react to the temperature abuse. It stopped triggering alerts as soon as the ambient temperature went below the ambient temperature criteria, resulting in many undetected alarms. The ATA method triggered no alerts during the normal condition and was the second method to react after the temperature

Table V.
Results of alert methods tested both for a pallet with a regular temperature and abused temperature based on the fact that product temperature should not rise above 1°C

	Regular temperature				Abused temperature			
	Cor.	Fal.	Und.	F + U	Cor.	Fal.	Und.	F + U
STTA	0	7	0	7	135	9	207	216
PBTT	0	0	0	0	129	0	213	213
ATTA	0	0	0	0	123	0	219	219
ATA	0	0	0	0	159	0	183	183
Combined STTA + ATA	0	0	0	0	194	6	148	154
Combined STTA + PBTT	0	4	0	4	151	8	191	199
Combined STTA + ATTA	0	5	0	5	151	9	191	200



Notes: Top left: SMB(temperature criterion: 8°C); top right: PBTT (period: 1.5 h, temperature criterion: 4.5°C); bottom left: ACTTA (temperature criterion: 4.5°C, period: 1.5 h); bottom right: ATA (5°C, period: 4 h); the criteria and periods are based on minimization of the number of false and undetected alarms from M2 and M3

Figure 4.
Alerts issued for pallet 2 (abused) from packaging (t0) until end of simulation

abuse started. The method continued to trigger alerts after the ambient temperature decreased, resulting in fewer undetected alerts than the other methods. A combination of STTA with the other three methods resulted in fewer undetected and false alarms. However, false alarms were triggered in all combinations. All the three period based methods gave better results than the STTA method. The ATA method gave the lowest number of undetected alerts, since it not only took into account the period, but also the severity of the abuse.

5. Conclusions

Mapping and exploring the actual temperature conditions in relevant supply chains is a prerequisite activity before defining temperature criteria and alert settings for real time DSS in food supply chains. When products are in shipment they are not always handled by the same organization as the recipient of alerts. Setting the temperature criteria for alerts too low would trigger unnecessary alerts. It could therefore be a considerable unwanted effort to raise alerts for the corresponding freight/handling operator, and this would create unnecessary responses to alerts and work interventions. On the other hand, when setting temperature criteria too far away from the set target temperature of the product, the associated risk caused by this would be that the products might have been damaged before the alert was issued. It is therefore important to provide criteria for knowledge-based alerts with an acceptable temperature criterion. The conceptual framework established for selecting temperature alert criteria and analysis of the mapping data for the chilled cod supply chain demonstrated the importance of having knowledge of actual temperatures in the supply chain, and selecting a proper alerting method and criteria that fits each product and the supply and logistics chain. The selection of a too low criterion for product temperature as suggested by industry experts (−0.5°C to 0.5°C) showed that the number of false alerts would have been very high, while a more lenient temperature criterion (±1°C) generated fewer and more relevant alerts. This reflects a situation where unrealistic demands on maintaining a low chilled temperature was not feasible within the studied supply chain, since the initial chilling of the products was inadequate.

As expected, temperature abuses occurred at handover points between container, truck or storage, where normally no temperature sensors from local systems were monitoring the products. Most operators use the WSN systems to measure the ambient temperature and not the product temperature, although product temperature would give more reliable information on quality. Four different methods using only ambient temperature to trigger alerts were explored and their relevance evaluated by comparing against the respective product temperature. The methods using both period and temperature gave better results than the simpler method only using temperature. The method that took into account both temperature abuse and the severity of the abuse gave the best result for this supply chain.

The results demonstrated that although well defined criteria and methods were applied, using only ambient temperature did not fully trigger alerts in accordance with the product temperature. Ideally, the combined application of online monitoring of product temperature and simple reliable models to predict shelf life of the respective products would give the most relevant information and enhance the sustainable operation of the supply chain. However, when monitoring ambient temperature as demonstrated herein, more complex methods for alerts or a combination of methods can improve the alerting system and give more adequate results for DSS in supply chains.

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