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aus Waldbröl

Referent:	Prof. Dr. Brigitte Petersen
1. Korreferent:	Prof. Dr. Rainer Stamminger
2. Korreferent:	PD Dr. Judith Kreyenschmidt

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Dedicated to

my family

”If one believes oneself possessed of the absolute truth,

one cannot admit that there are any

other truths in the world.”

Trattato di sociologia generale (1916) - The Mind and Society (1935)

Vilfredo Federico Damaso Pareto (15 July 1848 – 19 August 1923), born Wilfried Fritz Pareto, was an Italian engineer, sociologist, economist and philosopher.

Abstract

Assessment of novel temperature monitoring systems for improving cold chain management in meat supply chains

The objective of this thesis has been to develop a concept to assess temperature monitoring systems. In particular, the ability of such systems to improve cold chain management has been investigated. The improvement potential has been considered taking into account the scoring and ranking of available systems for different meat supply chains.

The concept is based on several empirical and experimental studies which are concerned with four research questions. The detailed examination of a large variety of intra- and inter-organizational temperature monitoring systems, as well as solutions, followed the characterization of key functionalities of these systems. Due to the characterization of implementation challenges, the necessary requirements in customer-supplier relationships in cold supply chains could be established.

Taking these requirements into account, the importance of a three-dimensional (technical, organizational and functional) view of the improvement of cold chain management could be derived, resulting in a three-dimensional generic model. The importance of this three-dimensional view has been investigated in a long-term field trial in a poultry supply chain using Time-Temperature-Indicators (TTIs) as an example. In total, comprehensive data sets from ten “Temperature mappings”, six field trials with Time-Temperature-Indicators (TTIs) and two field trials with RFIDs with a temperature sensor and results from 20 expert discussions were available for the derivation of the assessment concept. 11 companies involved in poultry, fish, pork, beef and cooked ham supply chains on a (German) national, international and global scale have been involved in the study.

Based on the results, a concept for assessing temperature monitoring solutions is been proposed. It is defined as the “Multi-criteria Decision Aid - Cold Chain Management (MCDA-CCM)” - concept. It is a combination of five levels and five columns which contain the respective phases, steps and elements of the process concept. For the process of the assessment, four steps have been defined – Requirement determination (1), Scoring process (2), Calculation (3) and Ranking (4) – divided into the phases “CCM requirement creation” and “Assessment and Decision”. In the first step the ‘‘Three-dimensional generic model” is proposed for determination and categorization of 14 cold chain management relevant technical, organizational and functional criteria. By using a “Scoring model” (step 2), the weighting of the criteria can be conducted. In the final two steps, the Multi-Criteria Decision Aid method PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) permits the calculation of “outranking net flows” (step 3) enabling the ranking of a finite number of temperature monitoring alternatives (step 4). The user-orientated assessment concept facilitates decision making so as to ascertain the best temperature monitoring solution for specific application cases.

Kurzbeschreibung

Ziel der vorliegenden Arbeit war es, ein Konzept zur Bewertung von Temperaturüberwachungssystemen zu entwickeln. Insbesondere galt es, deren unterschiedliche Potenziale zur Verbesserung des Kühlkettenmanagements in Fleisch erzeugenden Ketten darzustellen und zu rangieren.

Die Grundlage der Konzeptentwicklung bildeten mehrere empirische und experimentelle Studien, hinter denen vier Forschungsfragen standen. Die Charakterisierung von Schlüsselfunktionalitäten erfolgte für inner- und überbetriebliche Temperaturüberwachungssysteme. Dabei bestand die Herausforderung, die Anforderungen von Kunden und Lieferanten in Zulieferketten zum Lebensmitteleinzelhandel gleichermaßen zu berücksichtigen.

Dies erfolgte durch die Weiterentwicklung eines generischen Models, indem sowohl technische, organisatorische als auch funktionale Aspekte Berücksichtigung fanden. Im Rahmen einer mehrwöchigen Feldstudie in einer Geflügelfleisch erzeugenden Kette ließen sich exemplarisch die erzielbaren Verbesserungen auf der Grundlage des dreidimensionalen Vorgehensmodells zeigen. Exemplarisch kamen hierbei Zeit-Temperatur-Indikatoren zum Einsatz. Insgesamt standen zur Ableitung des Bewertungskonzeptes umfassende Datensätze von zehn „Temperature mappings“, sechs Feldstudien mit Zeit-Temperatur-Indikatoren und zwei Feldstudien mit RFIDs mit Temperatursensoren sowie Ergebnisse aus 20 Expertendiskussionen zur Verfügung. In die Untersuchungen brachten sich 11 Unternehmen nationaler, internationaler und globaler Wertschöpfungsketten, bezogen auf die Produkte Geflügelfleisch, Fisch, Schweinefleisch, Rindfleisch und Kochschinken, ein.

Aus den Studienergebnissen entstand der strukturelle Aufbau eines Bewertungskonzeptes, das als „Multi-criteria Decision Aid - Cold Chain Management (MCDA-CCM)“ - Konzept bezeichnet wird. Es handelt sich um eine Matrix, bestehend aus fünf Ebenen und fünf Spalten, die die jeweiligen Phasen und Elemente des Vorgehenskonzeptes enthalten. Der Ablauf der Bewertung sieht die zwei Phasen “Bestimmung Kühlkettenmanagement relevanter Anforderungen” sowie “Bewertung und Entscheidung” vor. Jede Phase ist nochmals untergliedert. Im ersten Schritt sieht die Verwendung des „dreidimensionalen generischen Modells“ eine konkrete Festlegung technischer, organisatorischer und funktionaler Kriterien für zu bewertende Innovationen im Kühlkettenmanagement vor. Die im „Scoring model“ festgelegte nummerische Gewichtung 14 unterschiedlicher Kriterien ist die Grundlage für die darauffolgenden Bewertungsschritte. In den weiteren Phasen wird die multikriterielle Entscheidungsmethode „PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation)“ herangezogen. Das zur Verfügung stehende Berechnungstool ermöglicht die Kalkulation von „outranking net flows“ im dritten Schritt. Im vierten Schritt erfolgt schließlich die Bildung einer Rangreihenfolge von präferierten Lösungen für unterschiedliche Anwendungsszenarien zur Verbesserung des jeweiligen Kühlkettenmanagements.

CONTENTS

1 Introduction

1.1 The multidisciplinary field of cold chain management – Introduction to the research problem

Continuing globalization and the steadily increasing scope and volume of the fresh food market have lead to increasing requirements regarding efficient cold chain management (Kuo and Chen, 2010; Orriss and Whitehead, 2000). The actors in cold supply chains have to deal with continuously changing requirements - legal requirements, increasing customer demands and growing expectations of the end consumer as regards the product quality.

Temperature is the most important factor impacting food safety and quality, as it is a major factor affecting microbial growth and the associated risk of illness (Lambert et al., 1991; Zwietering et al., 1991; McDonald and Sun, 1999; Giannakourou et al., 2005; Ólafsdóttir et al., 2006). In cold chains of fresh meat and meat products, refrigeration can be considered as the primary process used for controlling and minimizing pathogenic growth and the growth of spoilage microorganisms. It is required at each stage of the cold chain to so as to guarantee safe meat and meat products (James, 1996). For food businesses, this implies placing great emphasis on ensuring the monitoring of temperature conditions over the entire food supply chain, including distribution, storage and handover points (Taoukis et al., 1999; Smolander et al., 2004; McMeekin et al., 2008).

Several studies have revealed that there is a lack of temperature control within some stages of the supply chain (Kennedy et al., 2005; Koutsoumanis et al., 2010). This reduced level of control leads to information gaps about temperature conditions at various chain stages as well as undetected temperature abuse during distribution and storage (Likar and Jevsnik, 2006). Such unrecognised temperature abuses are also confirmed by Olsson (2004), who investigated food supply chains from the manufacturer to the consumer and who furthermore identified critical points within different stages along the food supply chains. The quality status of meat is considerably affected by unfavorable interruptions of the cold chain (Kreyenschmidt, 2008; Montanari, 2008; Bruckner, 2010). Therefore, temperature abuse leads to economic losses due to waste. Furthermore, such abuse may lead to a negative impact on the brand image of the companies concerned.

Due to legal obligations and due to the fact that temperature is the most important factor affecting the quality and safety of fresh meat and associated products, temperature monitoring can be described as a key factor within overall cold chain management (Kreyenschmidt, 2008; Kreyenschmidt, 2009). The need for integrated methods and novel solutions allowing efficient intra- and inter-organizational temperature monitoring clearly exists. However, to date there has been little understanding and recognition of the added value due the adoption of efficient temperature monitoring in the entire field of cold chain management. McMeekin et al. (2006) and Bruckner (2010) proposed the possibility, that real-time monitoring of temperature (e.g. by using “Radio Frequency Identification (RFID)” technology may allow the combination with extensive microbial databases. The authors state that this will take food safety management on a new level of precision and flexibility; this is also postulated by Kreyenschmidt (2009).

A great challenge for “Cold Chain Management (CCM)” relates to the fact that a range of disciplines need to work efficiently and effectively together (Smith and Sparks, 2004). Bogataj et al. (2005) define global cold chain management as ”the process of planning, implementing and controlling efficient, effective flow and storage of perishable goods, related services and information from one or more points of origin to the points of production, distribution and consumption in order to meet customers’ requirements on a worldwide scale. It is the process of integrating the existing business activities, including special activities for perishable goods conservation along the value chains…”.

In addition, several authors suggest that the opportunity should be grasped to improve quality and safety of fresh meat potentially resulting from chain-wide cooperation and inter-organizational information and risk management (Schulze Althoff et al., 2005; Schulze Althoff, 2006; Petersen et al., 2007). The authors propose that a steady improvement of quality management and supply chain management should occur within meat chains. The approach of Petersen et al. (2007) proposes that systematic inter-organizational data collection; data storage as well as data preparation requires a detailed view of customer-supplier-relationships. It is postulated that efficient quality communication requires effort in an organizational and a functional dimension rather than in a technical dimension (Schulze Althoff, 2006; Mack, 2007; Petersen et al., 2007).

Within this framework it has to be reflected on as to in which manner these dimensions play a role regarding the communication of temperature data. Looking at network research shows that various different approaches are being considered concerning the complexity of the demand for data collection of quality relevant data at important inspection and decision points (Schulze Althoff et al., 2005; van der Vorst et al., 2007). Prescriptive, predictive and comparative quality information provides an important competitive advantage which avoids uncertainty and leads to a very high proportion of safe decisions as to product quality, as well as reducing potential risks (McMeekin et al., 2006).

However, an appropriate enhancement of quality communication will require the application of efficient temperature monitoring systems. So far, the application, and in particular, the integration of temperature monitoring systems has been seen to be, and regarded as, a complex matter. There has been a lack of comprehensive identification and comparisons of pre-existing and novel temperature monitoring solutions in operation. Furthermore, there have been few, or no concepts proposed, providing information how to assess and rank temperature monitoring solutions according to their potential to improve cold chain management.

1.2 Research objective and outline of the thesis

The overall objective of this thesis is to propose an assessment concept for temperature monitoring systems. The aim is to improve the interdisciplinary field of cold chain management in meat supply chains using the most efficient temperature monitoring system.

This leads to the following research questions:

- What are the key system functionalities and key challenges of temperature monitoring systems for improving cold chain management in meat supply chains?
- How can temperature monitoring solutions support the improvement of cold chain management?
- Which possible further advances in improvement processes in real meat supply chains have to be taken into consideration within the context of the assessment of the technologies?
- How can different temperature monitoring systems be assessed taking into account the multi-criterial nature of technology selection and heterogeneous user perspectives in cold supply chains?

The thesis proceeds as follows: in chapter 2, key challenges regarding the implementation of novel temperature monitoring solutions are examined and discussed. Key characteristics, physical principles and application areas of traditional and novel temperature monitoring solutions are summarized. On the basis of expert interviews and focus group meetings, a three-dimensional view of the integration of novel temperature monitoring systems is proposed.

Chapter 3 focuses on the use of a generic model. The advanced generic model should take into account the three-dimensional view regarding relevant aspects for improving cold chain management. In this chapter, key success factors for the optimization are determined and investigated in detail. As a result, chapter 3.2 includes a quantitative analysis of the technical, organizational and functional circumstances inherent in cold chain management in meat supply chains. In parallel, temperature conditions in meat supply chains are investigated using a developed temperature mapping method (chapter 3.3.2). Furthermore, the influence of temperature on the quality and the remaining shelf life is analyzed (chapter 3.3.3). Chapter 3.5 illustrates the developed three-dimensional generic model for the optimization of cold chain management.

Chapter 4 focuses on the derivation of assessment criteria resulting from the validation and usage of the three-dimensional generic model in a real-world meat supply chain using a novel temperature monitoring solution as an example. Taking into account a technical dimension, the development and validation of a mathematical model characterizing the kinetic behavior of the deployed Time-Temperature Indicator (TTI) under non-isothermal temperature conditions was undertaken. For a functional background, the response of the TTI was compared with other quality parameters of meat. The organizational issues as well as inspection and decision points within the respective supply chains were also determined using the inter-organizational inspection model.

In the last chapter, chapter 5, a concept for assessing and evaluating temperature monitoring solutions is presented. Different phases, steps and elements are discussed on the basis of the categorization of temperature monitoring alternatives (chapter 2) and knowledge gained through different case studies (chapter 4). Moreover, different model approaches are considered for the assessment and ranking of temperature monitoring solutions: the three-dimensional generic model (chapter 3) as well as two theoretical approaches of decision theory.

A summary concludes the thesis.

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2 Temperature monitoring in meat supply chains[1]

[1] This chapter is published in the British Food Journal with authorization of the supervisor of this thesis according to the Promotionsordnung of the 28th of August 1985 and following statutes of changes of the Agricultural Faculty of Bonn University – see list of publications (Raab et al., 2011b)

Abstract

Purpose – An efficient temperature monitoring is a prerequisite for cold chain management and thus for the production and supply of high quality and safe products as well as for the reduction of waste and economic losses. The aim of the research is to identify and compare already existing temperature monitoring solutions in operation and novel temperature monitoring solutions with a view to their use for efficient temperature monitoring in meat supply chains. A special focus is made on the identification and specification of challenges by the implementation of temperature monitoring solutions as well as whole systems which allow an optimal monitoring of the temperature conditions in meat supply chains, as required by the new European food law.

Design/methodology/approach – The paper is a literature review of existing and novel temperature monitoring solutions and systems and it face challenges by the practical implementation which allows continuous monitoring of the temperature conditions in meat supply chains. Firstly, the relevant literature relating to these aspects was examined and secondly, expert knowledge was carried out with system developers of temperature monitoring and information management systems, participants in the meat supply chains and researchers.

Findings – In the article different intra- as well as inter-organizational challenges relating to the practical implementation of temperature monitoring solutions have been identified and described. Further on, it has been identified that technical, organizational and functional challenges should be taken into concern regarding optimal cold chain management.

Originality/value – The paper provides a holistic perspective of temperature monitoring solutions in meat supply chains. The proposed solutions to the specified challenges make an important contribution to determining criteria for the assessment of temperature monitoring solutions and systems in meat supply chains, resulting in improvement of cold chain management. Thus, may result in increased food quality and safety.

2.1 Introduction

In the USA, the economic damage due to quality loss in beef is estimated as US$ one billion per year (Koutsoumanis, 2009). Scheer (2006) points out that the product degradation takes place at all stages within the meat supply chain. To reduce these huge economic losses is a particular challenge for the whole meat industry.

Fresh meat is a highly perishable product and is thus characterized by a short shelf life. It is well known that temperature is the most important influencing factor on meat quality and safety (Lambert et al., 1991; McDonald and Sun, 1999; Möller, 2000; Kreyenschmidt, 2003; Koutsoumanis and Taoukis, 2005; Gospavic et al., 2008; Nychas et al., 2008). Incorrect handling, improper storage and transport conditions with respect to temperature leads to a reduction in shelf life (Gill, 1986; Fu and Labuza, 1992; James, 1996; Smith and Sparks, 2004; Bogataj et al., 2005; Montanari, 2008). In addition, temperature abuses increase the growth and survival rates of pathogenic bacteria and enhance the potential for subsequent toxin production (Lambert et al., 1991; Lee et al., 1996; Jol et al., 2006).

Fresh meat and meat products have to be processed, stored and transported in cold conditions within a temperature range of +2°C to +7°C depending on the type of meat. Each degree above the defined temperature range leads to a reduction in shelf life (Almonacid-Merino and Torres, 1993; Moje, 1998) and thus leads to the before mentioned substantial economic losses (Taoukis et al., 1991; Fu and Labuza, 1992). Up to now, major problems regarding incorrect temperature conditions have been found at the transfer points of products from one actor to another (Kreyenschmidt et al., 2003; Olsson, 2004; Nychas et al., 2008; Ovca and Jevšnik, 2009). Other critical temperature points within meat supply chains are the product cooling prior to palletizing or loading at the producer, waiting times at dispatch and loading points, temperature abuse during transport caused by excessive door opening times and inappropriate handling and storage of the goods at the retailers (Taoukis et al., 1991; James, 1996; Olsson, 2004; Bogataj et al., 2005; Montanari, 2008; Raab et al., 2008; Ovca and Jevšnik, 2009).

Identification and control of these weaknesses and the improvement of continuous temperature monitoring in the cold chain is regulated in the European “Regulation on specific hygiene rules for food of animal origin (Regulation (EC) No 852/2004)”. Consequently only short term aberrations are allowed due to practical issues, such as un- and reloading phases during distribution.

To meet legal requirements and to eliminate or minimise weaknesses in the cold chain, efficient temperature monitoring is of great relevance to all involved in the supply chain, from primary producers, to processors, distributors, retailers and finally to the consumer (Wells and Singh, 1989; Almonacid-Merino and Torres, 1993; McMeekin et al., 1993; Moureh and Derens, 2000; Commère, 2003; Jansen and Harms, 2004; Taoukis, 2006; Nychas et al., 2008). An efficient temperature monitoring system focuses on the control of the product temperature during the entire supply chain, it integrates information management of the relevant temperature data together with its effective use and thus it supports the minimisation of waste and costs (Kreyenschmidt et al., 2005; Raab et al., 2008). Successful implementation and use of temperature monitoring systems is therefore directly correlated with the approach to cold chain management as defined by Bogataj et al. (2005). This approach to cold chain management involves additional information about the characteristics of a perishable product whereas traditional supply chain management focus on information exchange and the transaction and location of products.

A multitude of different temperature measurement solutions are already used in the meat industry, especially in the last years, several new solutions and holistic systems have been developed which should provide for comprehensive temperature monitoring during the whole supply chain, as required by the new food law (Kreyenschmidt et al., 2005). But full implementations providing temperature control over the entire supply chain are mostly absent and the participants in the meat supply chains are often not aware of the characteristics of the different systems which are available on the market and which solution fits their company's requirements best. Nevertheless, there is a certain amount of literature regarding temperature monitoring equipment (Childs et al., 2000; Wolfe, 2000; Dada and Thiesse, 2008) but most of those papers focus on very special technological research questions. A comparison of the different solution or system characteristics, possible application areas and especially the challenges posed in implementing of these solutions and/or systems are still missing (Jansen and Harms, 2004).

2.2 Methodology

The central objective of this literature review was to identify and compare existing and novel temperature monitoring solutions and to examine their functionalities, advantages and disadvantages as well as application areas in the meat industry. Special attention was paid to the identification of existing challenges for the successful implementation of temperature monitoring systems in meat supply chains.

The research process consisted of a number of sequential stages. First, a large group of studies from refereed journals were investigated, resulting in a total of 407 publications (journals, book chapters and books), which were reviewed. The publications were identified through computer aided searches of databases of published works and conference proceedings. The articles were searched for using the title as a key, based on the following two following criteria: (1) it must contain explanations on temperature monitoring solutions or (2) it must describe difficulties to be overcome regarding of temperature monitoring in meat supply chains. From the review of the second criterion six challenges have emerged as important to the implementation of temperature monitoring solutions.

Secondly, the relevance of the challenges which were faced by the literature review was verified by individual discussions with more than 100 experts from the meat industry, system developers of soft- and hardware regarding temperature monitoring systems and researchers involved with the workshops “Cold Chain-Management” at the University of Bonn (Kreyenschmidt and Petersen, 2006; Kreyenschmidt, 2008). A focus group meeting with 18 experts from an international meat company was conducted to consider the challenges regarding practical implementation involving participants within meat supply chains. As the implementation of temperature monitoring technologies involves company managers, quality manager, logistic managers and other staff members it is of interest to reveal the multiplicity of views held, within a group context, by using the approach of focus group meeting. The experts were asked to agree or disagree on the individual opinions elicited within the workshops on implementation challenges within a group discussion.

The review is structured in three parts: In the first part, a number of already existing and novel temperature monitoring solutions for the meat sector are illustrated and compared. Secondly, inefficiencies regarding temperature monitoring in meat supply chains are exemplified. Further, the challenges to be met regarding the implementation of novel temperature monitoring solutions which permit continuous control of the temperature conditions in meat supply chains are determined and specified. Finally, the conclusion points out the main important challenges and suggests areas for future development and the arriving at new approaches for dealing with these challenges.

2.3 Temperature monitoring systems and their application in meat supply chains

During the recent years substantial technological progress has been achieved by the development and use in practice of wireless sensor networks combined with temperature sensors. Also, conventional thermometry devices and electronic data loggers have been refined recently. Besides that, the use of time-temperature indicators (TTIs) to control temperature conditions in meat supply chains from production to consumption has been discussed extensively in recent years but implementation in the meat industry has only begun recently (Taoukis and Labuza, 1989; Kreyenschmidt et al., 2005; Taoukis, 2008).

Table 2.1 gives an overview about different existing and novel temperature monitoring systems, their functionalities, advantages and disadvantages as well as possible application areas. Requirements as to the technical components of the measuring devices in relation to the respective application areas are defined in the European standards DIN EN 12830, DIN EN 13485 and DIN EN 13486.

Table 2.1: Principle, advantages and disadvantages of different already existing and novel temperature monitoring systems

System Categories	Principle/Components	Advantages	Disadvantages	Possible applications	Sources
Contact thermo-meter	• Mechanical: • Volume dilatation of liquids, bimetal or gas in dependency of temperature changes • Electrical: • Changes of ohmic resistances in dependency of temperature	• Simple, rugged, inexpensive • Measurement of core and product temperature	• Random sampling, no temperature history • Damage the product • Hygiene critical • Pre-cooling of the sensor is necessary • Agglomeration of the food around the sensor leads to inaccuracy and slow time response • Needs opening of packages	• General application: • Entrance control, process control, outgoing inspection	McFarlane (1995), Leigh (1991), Wolfe (2000), Michalski (2001), Brunnhuber (2002), Salas-Bringas (2007), Estrada-Flores (2008)
Infrared thermo-meters (Non-contact thermo-meter)	• Pyrometer: Measurement of thermal radiations • Measurement device including an optical system, a detector, and a control and analysis system (see also of contact thermometers)	• Surface temperature can be measured without contact • Very short response time • Nondestructive • Non-reactive	• Accuracy depends on the material and the surface integrity • No temperature history • Visual contact needed • Needs opening of the packaged products	• Temperature control during different stages in the process such as entrance control, process control, outgoing inspection	Childs *et al.* (2000), Brunnhuber (2002), James and James (2002), Heldman (2003), Littek (2005)
Graphic recorders	• Bimetal coils as a as sensing and writing elements	• Environmental temperature can be controlled continuously	• No digital information • Only measuring of environmental temperatures	• Fixed system application in cold stores and vehicles • Monitoring air temperatures (containers, airplane holds, railcars and vehicles	Wolfe (2000), Littek (2005), Estrada-Flores (2008)
Data loggers	• Microprocessors or controllers that collect and store digital information of temperature measurements on data storage units • (see also physical principles of contact thermometers)	• Environmental temperature can be controlled continuously • Automatic analysis with appropriate software • Alert function • Integration of shelf life algorithms possible	• Needs mostly a physical connection for data transfer • Too bulky and cost-effective in many application settings • Mostly only control of the environmental temperature • Long reaction time to temperature changes	• Monitoring air temperatures during all stages (production, cooling rooms, within vehicles) • Suitable for quality assurance analyzes	Wolfe (2000), Rogers (1997), Behrendt and Klün (2002), Kreyenschmidt *et al.* (2005), Littek (2005), McMeekin *et al.* (2006b), Dada and Thiesse (2008)

System Categories	Principle/Components	Advantages	Disadvantages	Possible applications	Sources
Wireless technologies with integrated temperature sensor	• Wireless data transfer on the basis of different kinds of standardized wireless technologies (see also physical principles of contact thermometers)	• Wireless data communication • Parallel reading of several data records • Timesaving • Real-time information via networking (online control via GPS) • Environmental temperature can be controlled continuously • Automatic analysis in dependency of the software • Fast acquisition of the goods and optimisation of the product flow • Integration of shelf life algorithms	• Missing standardisation for some frequencies like RFID • RFID technology: Interference of the readability through metal and fluid or highly viscous products	• Monitoring air temperatures during all steps (e.g. production, cooling rooms, within vehicles) • Suitable for quality assurance analyses • Support in storage management, quality assurance systems and traceability systems	Behrendt (2004), Kreyenschmidt et al. (2005), Oertel et al. (2005), Dittmann (2006), Kerry et al. (2006), McMeekin et al. (2006a), McMeekin et al. (2006b), Ogasawara and Yamasaki (2006), Scheer (2006), Wang et al. (2006), Bovenschulte et al. (2007), Jedermann and Lang, (2007), Regattieri et al. (2007), Dada and Thiesse (2008), Estrada-Flores (2008), Estrada-Flores and Tanner (2008), Finkenzeller (2008), Fu et al. (2008), McMeekin et al. (2008), Abad et al. (2009), Jedermann et al. (2009)
Smart Active Labels	• RFID inlet or inlay connected with power source embedded into a label • Wireless data transfer on basis of different kinds of standardized radio technologies	• Low cost RFID inlet • Flexible self-adhesive tags • Usable for smaller items • Integration of shelf life algorithms (see also wireless technologies)	• Data acquisition and storage is limited (see also wireless technologies)	• Item level, transport units, or container units • Reading of the data at the incoming inspection • Efficient stock-keeping • Integration in quality assurance systems • (see also wireless technologies)	Behrendt (2004), Kreyenschmidt et al. (2005), Furness (2006)
Time-temperature indicators (TTIs)	• Chemical-, photochemical-, microbiological- or enzymatic reactions that strongly depend on time and temperature	• Usable for single units • Low price • Indirect freshness control	• Know how about the food kinetic is necessary where the label is attached to • No digital temperature data • Only a colour signal	• During the whole supply chain from production to consumption (incoming inspection, process control, outgoing inspection) • Support in storage management and quality assurance systems	Byrne (1976), Rose (1977), Taoukis and Labuza (1989), Taoukis et al. (1991); Wolfe (2000), Taoukis (2001), Brunnhuber (2002), Kreyenschmidt et al. (2002), Kreyenschmidt et al. (2003), Taoukis and Labuza (2003), Kreyenschmidt et al. (2005), Kerry et al. (2006), Ellouze et al. (2008)

Within meat supply chains the application of temperature monitoring systems varies according to the parameters which are to be measured, such as the control of the environmental, surface or core temperature of the products (Brunnhuber, 2002; Littek, 2005). The applications also vary as some systems supports the temperature control on company level (entrance control, process control, final inspection) (Prändl, 1988) and other solutions especially the novel technologies focus on control of the temperature during the whole supply chain from production to the retailer or end consumer. The applications also vary according to the parameters which are to be measured, like the control of the environmental, surface or core temperature of the products (Brunnhuber, 2002; Littek, 2005). This has led to the implementation of a variety of different systems which are used by the different participants in the supply chains and in intra-organizational terms of view (Table 2.2).

Table 2.2: Estimate of the level of use of different temperature monitoring systems at different inspection points within meat supply chains on a 5-point-scale

Measuring Methods / Measuring points	Contact thermo-meters	Infrared thermo-meters	Graphic records	Data loggers	Wireless technical with tem-perature sensor	Smart Active Labels	TTIs
Slaughterhouses	+++	+++	++	+++	-	-	-
Processing companies	+++	+++	++	+++	-	-	+
Logistic providers	+++	++	+	+++	+++	++	+
Wholesalers	++	+	+	++	++	+	+
Retailers	++	+	+	++	++	++	+
Butcher’ shop	++	-	++	+	-	-	-

-- not available, - mostly not available, + partially available, ++ mostly available, +++ available

Conventional thermometry using the likes of contact thermometers is often used at the entrance control point, in processing companies, at the wholesalers or retailers to control product’s core temperature (via contact thermometers) or product’s surface temperature (via infrared sensors) (Brunnhuber, 2002). In comparison to technologies like data loggers it delivers no information about the temperature history of a product. During slaughtering, processing, storage and transport, temperature is controlled mostly by the use of electronic data loggers which measure the environmental temperature (Brunnhuber, 2002; Koutsoumanis and Taoukis, 2005) whereas product temperature is checked only randomly during these stages within the supply chains. An advantage of electronic data loggers is the possibility of making a detailed analysis of the digital data. On the other hand there may be problems with regard to data recovery, manual examination for “progress reports” and also the retrospective analysis of information when using electronic data loggers during storage and transport (McMeekin et al., 2008).

A relative new set of technologies which are already implemented by some logistics providers are wireless communications systems like wireless wide area networks (WWAN), wireless local area networks (WLAN), and wireless sensor networks (WSN) systems (Guo and Zhang, 2002; Qingshan et al. 2004; Wang et al., 2006; Ruiz-Garcia et al., 2007). Different wireless communication technologies can be considered, for instance ZigBee or Bluetooth and Radio frequency identification technology (RFID) (Mackensen et al., 2004; Mackensen and Kuntz, 2005, Ruiz-Garcia et al., 2007; Ruiz-Garcia et al., 2008). During recent years applications on the basis of Radio frequency identification systems (RFIDs) in food supply chains have emerged due to their capability to identify, categorize, and manage the product and information flow throughout the supply chain (Kärkkäinen, 2003; Behrendt, 2004; Michael and McCathie, 2005; Dittmann, 2006; Jedermann, 2006). Ruiz-Garcia et al. (2009) describe possible synergies of the integration of WSN and RFID. Smart semi-active or active RFID tags combined with temperature sensors can monitor temperature conditions within the supply chain (Michael and McCathie, 2005; Amador et al., 2009; Amador and Emond, 2010). This permits the collection of real-time information on the quality status of the product (Michael and McCathie, 2005) and provides the possibility of an acceleration of the product flow which is of high relevance regarding the handling of perishable products (Kärkkäinnen, 2005). An improved management of meat products leads also to a better control of the stock balance and optimization of storage management (Lettmann, 2007). It has the advantage that status information about the transport temperature of the products can be determined in the areas where products are shipped and stored (Mousavi et al., 2002, Kreyenschmidt et al., 2005, Kerry et al., 2006; Kumar and Budin, 2006; Bovenschulte et al., 2007). Thus, such systems can be highly advantageous for cold supply chains (Asif and Mandviwalla, 2005; Pope et al., 2005; Kumar and Budin, 2006; McMeekin et al., 2006a; Ogasawara and Yamasaki, 2006; Bovenschulte et al., 2007; Jedermann and Lang, 2007; Abad et al., 2009). Several authors predict an increasing relevance of systems based on wireless technology in the forthcoming years (Kreyenschmidt et al., 2005; McMeekin et al., 2006a). Other authors point out that there are still limitations to temperature monitoring on the basis of RFID systems in meat supply chains due to e.g. insufficient reliability, a lack of global uniform standards and an adverse impact on efficient operation in the presence of moisture and the reflectivity of metals (Narsing, 2005; Labuza, 2006; Estrada-Flores and Tanner, 2008).

A system which has not been implemented on a large scale in the meat supply chains so far are time-temperature indicators (TTIs). Even though Petersen and Kreyenschmidt (2004) and Kerry et al. (2006) declare that the use of TTIs offers great potential regarding cold chain monitoring for fresh products. In comparison to other technologies TTIs are devices that can be attached as labels on single items and can indicate the temperature conditions from production to the point of consumption by a change in color of the label (Taoukis and Labuza, 1989; Fu and Labuza, 1992; Giannakourou et al., 2003; Estrada-Flores and Tanner, 2005; Taoukis, 2006). The principles of these indicators are based on time and temperature dependent enzymatic, chemical, mechanical, electrochemical or microbiological reactions causing a color change (Wells and Singh, 1988; Taoukis et al., 1991; Fu and Labuza, 1992; Labuza and Fu, 1995; Taoukis and Labuza 1997; Tsoka et al., 1998; Labuza, 2000; Wolfe, 2000; Brody, 2001; Kreyenschmidt, 2003; Vaikousi et al., 2008; Ellouze et al., 2008).

2.4 Challenges of temperature monitoring in meat supply chains

Significant technological progress has been made in the field of temperature monitoring systems - on the one side several novel systems have been developed and on the other side, existing solutions have been radically improved. The implementation of such novel technologies as wireless technologies can deliver a significant contribution to support the continuous monitoring and control of the temperature throughout the entire supply chain (Litwak, 1999; Kreyenschmidt, 2008). But it still has to be taken into account, that even if sophisticated technological solutions are in existence, the successful implementation of them is still a great challenge from the intra- as well as inter-organizational point of view. A variety of aspects have to be taken into account which will affect all cold chain participants - the developers of temperature monitoring equipment, the participants in the meat supply chains as well as the research sector.

2.4.1 Intra-organizational challenges

Linking the product characteristics with temperature data

Within meat supply chains, numerous different kinds of meat products are handled. Due to different factors like a_w-value and gas composition inside the package, the products show different sensitivity to temperature (Kreyenschmidt, 2003). Up to now the provision for the temperature sensitivity of a product is often insufficient and the collected temperature data are not correlated and interpreted with regard to the specific product. If different products are stored or transported together under fluctuating temperature conditions, products with higher temperature sensitivity e.g. poultry fillets will be more affected by higher temperatures than products with a lower sensitivity (e.g. beef fillets). This means temperature data have to be analyzed and interpreted with regard to the specific sensitivity of each product (Raab et al., 2008). But until now, participants within the meat supply chain are not aware of the specific effect of non-isothermal temperature conditions on different products and the linkage between temperature data and product characteristics. This can lead to an under- or overestimation of remaining shelf life of the products, thus resulting in health risks on the one hand and wastage and economic losses on the other hand. Even if several predictive food models have been developed in the recent years (e.g. Scott, 1937; McMeekin et al., 1993; Zwietering et al., 1993; Ross, 1996; McMeekin et al., 1997; Neumeyer et al., 1997; McDonald and Sun, 1999; Ross, 1999; McKellar and Lu, 2004; Mataragas et al., 2006; Brul et al., 2007; Li et al., 2007; Gospaciv et al., 2008; McMeekin et al., 2008, Kreyenschmidt et al., 2010) the implementation of these models are still missing in meat supply chains. Thus, knowing and considering the characteristics of a product is a key challenge to be met when considering a most efficient temperature monitoring system (Kreyenschmidt et al., 2010).

Measurement procedure and interpretation of temperature data

Measured temperature data and analysis are often insufficient and may lead to incorrect decisions for further handling of the products. One aspect is that during storage and transport the environmental temperature is controlled which often differs from the product temperature (Gill et al., 1996; Moureh and Derens, 2000; Artès, 2004). Temperature mappings by Raab et al. (2008) within a poultry supply chain have shown fluctuations in environmental temperature between -5°C and +15°C at different locations in a truck within the unloading periods (between 110 min and 480 min of transportation commencement) whereas the product temperature was nearly constant. Thus, controlling the environmental temperature is not always meaningful since it delivers no information about the history of the product temperature. This means that the measurement procedure, especially the placement of the temperature devices, has to be taken into account. The combination of temperature monitoring solutions with heat transfer models could be one possible solution to this problem (James et al., 2006) whereby the development of heat transfer models and simulation models of heat diffusion become more and more important (Liehr et al., 2009).

Another aspect is that the software of several monitoring systems only shows the average temperature, which can lead to ignorance of short term temperature abuses during handling and to a misinterpretation of the data. Production of waste due to wrong decisions can be the consequence.

These aspects point out that next to the monitoring of temperature data, an efficient data management and statistical analysis system is of great importance. This leads to a challenge regarding the optimization of software for the analysis and interpretation of temperature data for routine operations at inspection points.

Availability and handling of temperature data

Come to a decision on the basis of temperature data must be possible within minutes as fast handling is an important aim in cold chain management regarding cost-efficiency and continuity of the cold chain (Kärkkäinen, 2003; Jedermann et al., 2009). Efficient data management and statistical analysis needs continuous data collection in digital format but currently data are mostly stored in paper format. This makes the availability, handling and long-term interpretation of data difficult and besides that the process is very time-consuming. Novel technologies already allow the collection of digital data for further data analysis and full documentation of temperature data with a digital format and in real-time. The problem is that due to the different temperature systems in each stage of the supply chain the data are often not comparable since lots of different data formats are used. The implementation of temperature monitoring equipment is always connected with considerations regarding integration of these data in the existing information management system. Thus, it has to be taken into account that simultaneously adjustment to a digital information system is needed when a new system is implemented. Even if the new technologies offer great possibilities to monitor temperature conditions continuously, it has to be mentioned that due to these systems, huge amounts of data will be produced (Jedermann et al., 2009). In this context the providers of temperature monitoring system have to think about a reduction of the huge amount of data into a summarised form that will enable fast management decisions in meat supply chains. Efficient and fast data management is needed in case of perishable products, which will be a great challenge in the future (Kärkkäinen, 2003; Jedermann et al., 2009).

Choice of the best fitting system

In temperature controlled supply chains the maintenance of quality should have greater importance than economic factors (Olsson, 2004) but cost is a principle factor in the implementation of new technologies (Kerry et al., 2006). The problem is that for the optimization of temperature monitoring systems, detailed cost benefit analyzes often do not exist, which makes the decision regarding the implementation of a new system even more difficult.

Besides the cost aspects several other factors have to be taken into account if new systems are to be implemented: Considerations of the logistic unit which will be controlled and also technical functionalities like the accuracy of the system and stability as to environmental and other factors (Jansen and Harms, 2004). Further on, the adaptation to existing system architectures interfaces and usability factors are a prerequisite (Raab et al., 2008).

Up to now extensive guidance to support the decision making process of the selection of the appropriate system is missing. Therefore researchers as well as the sales and development companies involved in temperature monitoring systems should confront these challenges together with the meat industry.

Training and education of employees

Another important aspect is the usability of the temperature monitoring equipment by the available human resources (Estrada-Flores, 2008). The training of employees concerning the handling of the systems, the correct documentation of the data, the correction of adverse events and the integration within standard operating procedures is a key issue which should not be underestimated (Bishara, 2006). Therefore training courses should not only address the measurement equipment itself, they should also include the provision of knowledge about the food characteristics. These aspects are even more important if a system will be implemented in a global cold chain management system. Also Olsson (2004) points out that the knowledge of temperature monitoring systems has to be increased within all stages of the supply chain to solve the temperature related problems.

Besides the training activities also developing companies should make it a prerequisite that systems have to be set up in such a way that they are easy to use in the day-to-day business routine and also easy to understand.

2.4.2 Inter-organizational challenges

An inter-organizational cold chain management system is becoming more and more important. On the one hand tracking and tracing of single items is required by law (Billiard, 2003; Montanari, 2008). On the other hand the documentation of additional product attributes is mandated (e.g. the quality of products in the case of perishables) (Kärkkäinen, 2005). Consequently the monitoring and documentation of temperature is of importance at the company level but also at the chain level.

Up to now temperature monitoring is primarily concentrating on internal processes within each company. A “supply chain thinking” and collaboration among the participants within the supply chain is often missing (Olsson, 2004; Nychas et al., 2008). Temperature data are mostly not exchanged within the supply chain and therefore continuous control of the product temperature is missing (Dada and Thiesse, 2008). Tracking of temperature data throughout the supply chain is a complicated issue due to the fact that meat supply chains are often heterogeneous and complex (Raab et al., 2008). The meat industry is characterized by a very heterogeneous structure in terms of market participants, size of the companies, the methods used and the length of distribution routes as well as the number of distribution channels (Eggers, 1998; Hartmann and Schorndorf, 2005; Spiller et al., 2005; Raab et al., 2008). Such heterogeneous structures lead to a challenge regarding tracking and tracing of temperature data within the complex logistic flows (Wilson, 1996; Raab and Kreyenschmidt, 2008, Kuo and Chen, 2010). Moreover there are complex market interactions with regard to upstream and downstream processing and retail stages, especially in the form of their customer-supplier relationships and as regards legally binding contracts (Schulze Althoff et al., 2005). These circumstances play an important role regarding the exchange of data throughout the supply chain as the actors must be willing to exchange temperature data.

The availability of a full temperature history along the supply chain and a collection of the temperature data within a data warehouse can be pointed out as important factors for a successful managing of meat supply chains (Schulze Althoff, 2004). A further challenge is that each participant within the meat supply chains has different needs concerning to information and communication systems as well as consultant services (Evangelista, 2005; Schütz, 2009; Schütz and Petersen, 2009).

Improvements in information and communication systems and therefore the availability of a full temperature history along the supply chain will encourage the identification of weak points within the supply chain, the prediction of remaining shelf life in different stages of the supply chain and therefore the improvement of storage and distribution management (Raab et al., 2008). The efficient implementation of such technologies in meat supply chains is a challenge in which the before mentioned factors have to be considered in order to derive maximum benefit.

2.5 Conclusion

Efficient temperature monitoring and the effective information management of temperature data is an important prerequisite for providing high quality and safe products and to avoid economic losses. The review has shown that in recent years, huge progress has been made in the improvement of existing temperature measurement devices and in the development of new temperature monitoring equipment, especially in the field of wireless monitoring systems. But up to now such novel solutions are not widely used in the meat industry and in the whole food industry as well as (Eden et al., 2011). Indeed, a huge number of different temperature monitoring systems are used in meat supply chains but continuous control of the temperature of the products within the whole supply chain is often time-consuming and in many cases not practical.

Further on, the review showed that up to now companies are only focusing on temperature control until the “point of sale”. But the consumer, who is often one of the weakest points in the cold chain (Schmidt et al., 2010), is often not integrated in the concept of the continuous improvement of food quality and safety and is not concerned by any regulations (Geppert et al., 2010). Thus, concepts should be developed and efforts made to integrate the consumer into the cold chain management concepts as well.

The review points out different intra- and inter-organizational challenges regarding an improvement of temperature monitoring in meat supply chains. From an intra-organizational point of view, the implementation of temperature monitoring systems supports quality management at different intra-organizational inspection points. In this context we conclude that, taking all these factors into account, the product sensitivity, particularly the linkage of the temperature data and the product characteristics, is a particular and important challenge to improve food quality and safety. The research progress of the last years has shown that predictive food models can be possible solutions to link product quality with the temperature history of the product (Koutsoumanis, 2001; Dalgaard, 2002; Cayré et al., 2003; Gospavic et al., 2008). Predictive food models allow the prediction of the food quality and remaining shelf life based on microbiological growth as it depends on temperature conditions in the supply chain. The rapid calculation of the remaining shelf life and risk assessment based on the temperature history allows the optimization of storage management from the FIFO concept (First In - First Out) to the LSFO concept (Least Shelf - Life First Out) (Taoukis et al., 1998, Giannakourou et al., 2001; Koutsoumanis et al., 2005) - - thus reducing food waste. But a key element of the integration of such models is the continuous control of the product temperature during the different stages of the supply chain. Novel solutions on basis of RFID can enhance continuous control systems but at the moment these solutions are too costly for use with consumer packaging (Delen et al., 2011). Costs per unit are particularly important in the meat sector, as meat products have a low price per unit which gives difficulties regarding cost/benefit.

The review has also shown the upcoming importance of inter-organizational temperature monitoring, which is complex due to the heterogeneous structure of meat supply chains in terms of cold chain management. In this context, ensuring collaboration between the participants is one of the most important challenges to be overcome (Ólafsdóttir et al., 2010; Eden et al, 2011). This also includes sharing of real-time data with regard to product characteristics. One main lesson which can be concluded is that the view on technical, organizational and functional aspects of intra- and inter-organizational temperature monitoring and information management of the gathered temperature data may deliver an important contribution to the improvement of cold chain management.

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3 Three-dimensional generic model for the optimization of cold chain management in pork and poultry supply chains[2]

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3.1 Introduction

Intra- and inter-organizational control of the temperature at important inspection and decision points are important parameters in recording the temperature history of the entire supply chain. In particular, inter-organizational monitoring requires specific temperature monitoring equipment and management of the data. Implementation of innovative systems and technologies for communicating and exchanging information in food supply chains is one key aspect in optimizing data collection, storage and exchange (Smith and Sparks, 2004; van der Vorst et al., 2007). Furthermore, technological capabilities for efficient transportation, handling and storing are necessary to maintain temperature monitoring along the cold supply chain as described in chapter 2 (Smith and Sparks, 2004).

Next to technological requirements, the optimization of cold chain management has to take into account key issues regarding quality control and temperature monitoring. Further on, practical conditions in pork and poultry supply chains, theoretical issues dealing with supply chain management as well as the framework of the process model and the closed loop system have to be taken into concern. Supply chain management aims at the improvement of various functions and processes within one company and between companies (Lee, 2004; Lietke et al., 2006; Hanf and Dautzenberg, 2006). Optimization of logistics, decision making and increase of information exchange are of concern for supply chain management aspects of perishable products (Hanf and Dautzenberg, 2006, Lettmann, 2007). The developments of optimization models for cold chain management have to take into account the intra- as well as inter-organizational complexity of pork and poultry supply chains. The theoretical framework of the process model in combination with the closed loop system includes such aspects as regarding interdependencies between organizations and inspection as well as decision points within the process of each involved company (e.g. Petersen, 1985; Schulze Althoff et al., 2005; Schulze Althoff, 2006). According to the definition of a food supply chain, not only producers, their suppliers and customers have to be taken into account but also transport companies, warehouses and retailers (van der Vorst et al., 2007). This makes cold chain management relevant research questions, with the focus on inter-organizational structures in terms of infrastructure regarding logistic aspects, especially distribution types and methods, particularly complex. As the exchange of quality and temperature data is one important aspect in the optimization of cold chain management in entire pork and poultry supply chains, detailed knowledge about horizontal as well as vertical collaborations and coordination is also needed.

Additionally, the linkage of temperature data with product characteristics will deliver an important contribution to the process of cold chain management (chapter 2.4.1). For example, if a full temperature history has been collected, the remaining shelf life of products can be calculated using predictive shelf life models (Labuza, 1993; Bruckner, 2010). The development of predictive microbiological growth models to describe spoilage of food requires a detailed knowledge of freshness loss and the behaviour of the microorganisms mainly responsible for the spoilage in the context of different influencing factors (e.g. Whiting and Buchanan, 1993; Meszaros et al., 1994; McMeekin et al., 1997; Stanbridge and Davies, 1998; Kleer and Hildebrandt, 2001). For fresh aerobe packaged pork and poultry the growth of *Pseudomonas* sp. is mostly responsible for the reduction of shelf life through the production of ethyl- and methylester as well as sulfurous compounds, which lead to sensory changes in the meat (Pooni and Mead, 1984; Labuza and Fu, 1995; Kröckel and Hechelmann, 1998).

At the moment the remaining shelf life of products in every stage of the supply chain can often only be estimated using time-consuming methods like traditional microbiological analyzes (Petersen and Kreyenschmidt, 2004). Indeed, determination of remaining shelf life allows companies to optimise their storage management and minimise economic losses (Lettmann, 2007). This will be an important added value in the optimization of cold chain management as it will permit the drawing of conclusions as to the quality status of the products at every stage of the supply chain. Therefore, more and more food producers and retailers are searching for cost effective and intelligent systems which are able to predict the shelf life of a product after processing and which also allow a calculation of the remaining shelf life at each stage along the the cold chain. This can be done using predictive microbiological growth models combined with innovative tools to measure temperature conditions (e.g. Smart Active Labels, time-temperature integrators) (Kreyenschmidt, 2007). Besides the characterization of the growth of the specific spoilage organism, successful implementation of predictive modelling demands detailed knowledge about practical conditions in supply chains, including quality control aspects, temperature and storage monitoring, packaging aspects and technical details of cooling efforts (Kreyenschmidt et al., 2007).

The objective of this study is to develop a “Three-dimensional generic model for optimization of cold chain management” taking into concern the key issues of temperature monitoring (technological factors) and information management of temperature and quality data in different cold chains (organizational factors). Further on, the linkage of temperature data with product characteristics (functional factors) is integrated into the three-dimensional generic model, generating added value for the actors in the supply chains. To reach this aim, the study integrates existing design factors and methods as well as results of the generic model for the prediction of remaining shelf life (already published by Raab et al. 2008 and Kreyenschmidt, 2010).

Thus, to develop a three-dimensional generic model for the optimization of cold chain management in fresh meat supply chains, the theoretical framework of the three-dimensional approach is combined with three approaches: Empirical supply chain assessment, a temperature mapping approach and microbiological analysis. In a first step, questionnaires were developed to gather information on different supply chains regarding organizational structures, specific inspection schemes and technical circumstances (Inspection model). In a second step, temperature mapping in a German poultry supply chain was conducted to estimate the realistic temperature conditions in meat chains (Temperature monitoring model). In a last step, shelf life tests at different temperatures were conducted in the lab on pork and poultry products to generate a microbiological growth model for shelf life prediction (Kinetic model).

3.2 Theoretical framework

The theoretical framework of this study focuses on the three-dimensional approach:

Three-dimensional approach

Several authors state that efficient intra- and in particular, inter-organizational information management in food supply chains has to take into concern different dimensions (Trienekens, 1999; Beulens, 2003; Schulze Althoff, 2004; Schulze Althoff et al., 2005).

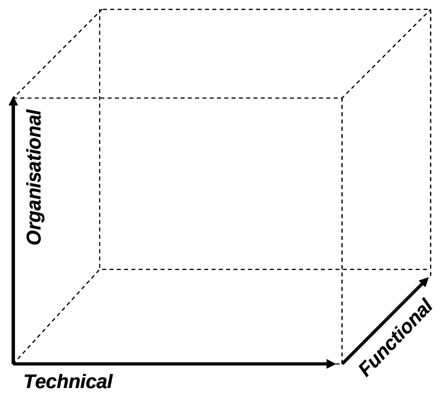

Figure 3.1: Three-dimensional scheme of requirement dimensions (Schulze Althoff, 2006)

The technical dimension implies aspects of data distribution and storage, the possibilities of data exchange and in general the technology it incorporates. Lambert et al. (1998) describes the technical dimension as group which includes mainly visible, tangible, measurable and easy-to-change components. These can be planning and control methods, the work flow structure, communication and information flow facility structure, and product flow facility structure. Organizational structure indicates the performance of different tasks as well as activities, for example in cross-functional teams. Van der Vorst (2000) understands under this aspect management methods, power and leadership structure, risk and reward structure and culture and attitude of the involved organizations. Luning et al. (2006) describe in their techno-managerial approach a technical and an organizational or managerial perspective, respectively. As well as these perspectives, Schulze Althoff et al. (2005) define a third dimension (Figure 3.1). Under the third dimension “functional requirements” Schulze Althoff et al. (2005) determine the information management in a quality and health management context. In relation to cold chain management, mainly the proposed linkage of quality related data to other data sets at inspection and decision points may be categorized in this dimension (chapter 2.5).

3.3 Research design

In order to use the three-dimensional approach for the optimization of cold chain management, it is necessary to investigate which aspects of cold chain management have to be taken into account within which dimension. It is necessary to start with an empirical supply chain analysis of organizational structure, inspection schemes and technical circumstances. Also temperature conditions and variations in meat chains have to be investigated. To generate one linkage of product characteristics with temperature data, a shelf life model is suggested, which made storage tests and the respective microbiological investigations necessary. The evaluated parameters should deliver an important input for the overall model. The studies will focus on poultry and pork chains in Germany.

3.3.1 Design of the empirical supply chain analysis

Two separate questionnaires were developed for pork and poultry supply chains in Germany.

The questionnaires were divided into three parts.

1. Analysis of organizational structures of supply chains.
2. Analysis of inspection scheme of quality data and of cold chain management.
3. System architecture and technical circumstances of information management and cold chain management.

In the first part “Analysis of organizational structures of supply chains” the product flows with regard to distribution ways and length were characterized. Additionally, the sojourn time at the different distribution stages of the supply chains was determined and the respective structures of cold chain management. Furthermore, key actors in the supply chains and interdependencies among actors were identified. In the second part “Analysis of inspection scheme of quality data and of cold chain management” quality and temperature controls at the entrance control point as well as during processing were evaluated. Questions regarding cooling methods, such as cooling technologies in the transport vehicles and in the cooling area of the companies, were also integrated in this part.

The third part “System architecture and technical circumstances of information management and cold chain management” characterized the collection, storage and availability of quality and temperature data as well as information exchange between supply chain actors. Information flow and information demand in order to make management decisions aimed at improving quality and cold chain management were determined. This led to a characterization of intra-and inter-organizational information management and system architecture. The questionnaire was addressed to slaughterhouses, processing and transport companies, wholesalers and retailers in Germany and was sent by post, email and online-newsletter of the respective associations to the companies (see example of the questionnaire for poultry in Figure A-0.32). The sample included 28 companies in the pork sector and 23 companies in the poultry supply chain.

3.3.2 Description of the temperature mapping approach

Temperature conditions from slaughterhouse to wholesaler in a poultry supply chain were investigated experimentally in intra- and inter-organizational stages. The temperature mapping included investigation of conditions in the various cooling and processing rooms and during transport from a poultry producer to the wholesaler in June and August 2007 (Table A-16, Study no. 1 and 2). Figure 3.2 gives an overview about the structure of the supply chain as well as investigation and measuring areas of temperature conditions.

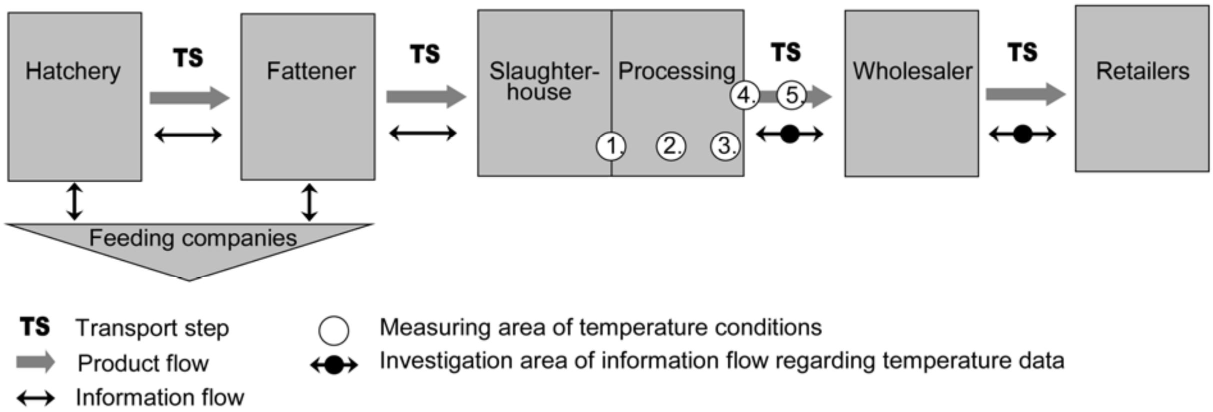

Figure 3.2: **Investigation and measuring areas for determination of temperature conditions and information exchange in the exemplified poultry supply chain (1. air chilling of the chicken, 2. processing and filleting, 3. cooling rooms, 4. packaging area as well as rooms of consignment sale, 5. transport vehicle)**

Temperature mapping from production to packaging

The experiment was conducted to determine the temperature conditions within cooling rooms, processing rooms, packaging areas and rooms of consignment sale at a poultry slaughterhouse. Every three minutes the temperature was recorded by data loggers (ESCORT JUNIOR Internal and External Temperature Data Logger; Escort, New Zealand). The experiment ran for 37.5 hours in each of the rooms and started at 00:00 for investigation of one production cycle.

Temperature mapping during transport from a poultry producer to a wholesaler

To analyze variations in temperature conditions during transport and differences between environmental and surface temperature of the meat the following temperature measurements were conducted at different places within and also outside the transport vehicle:

- Measurements in the transport vehicle during transport from a poultry producer to a wholesaler.
- Measurements at single packages in a single pallet during transportation.
- Measurements inside a single package (surface and core temperature of the meat in a single package).

To measure temperature variations within the truck four data loggers were placed at different places in the transportation vehicle (one placed close to the door, one in the middle of the truck, one at the back of the truck and one close to the cooling device). Figure 3.3 shows the size of the truck and the placement of the investigated pallet inside the truck.

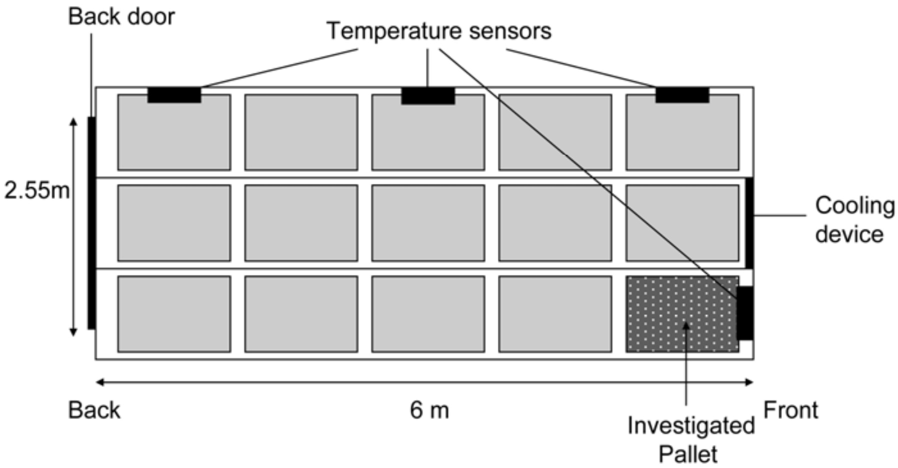

Figure 3.3: Storage pattern of pallets in vehicle viewed from above and location of data loggers within the truck (modified after Moureh et al. (2002))

Figure 3.4 gives an overview of the composition of the pallet where the temperature conditions were measured. The pallet was loaded with 2 x 2 x 11 cardboard cartons. Each cardboard carton contained 10 kg of chicken breast, wrapped in plastic film.

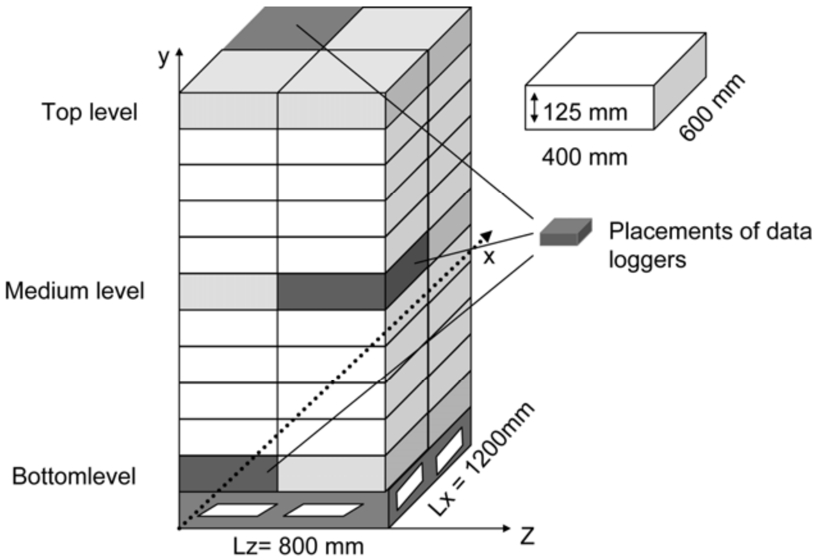

Figure 3.4: Pallet composition and positions of data loggers (modified after Moureh et al. (2002))

Temperature conditions within one pallet were investigated at three cardboard boxes: at the top, the middle and the bottom in order to determine whether the temperature is affected by the location on the pallet and/or by the position of the pallet in the truck.

To investigate the environmental temperature of each cardboard box as well as the surface and the core temperature of the meat, the temperature loggers were placed outside and inside the package. Temperatures were recorded every three minutes. The locations of the temperature sensors in the single cardboard box are shown in Figure 3.5.

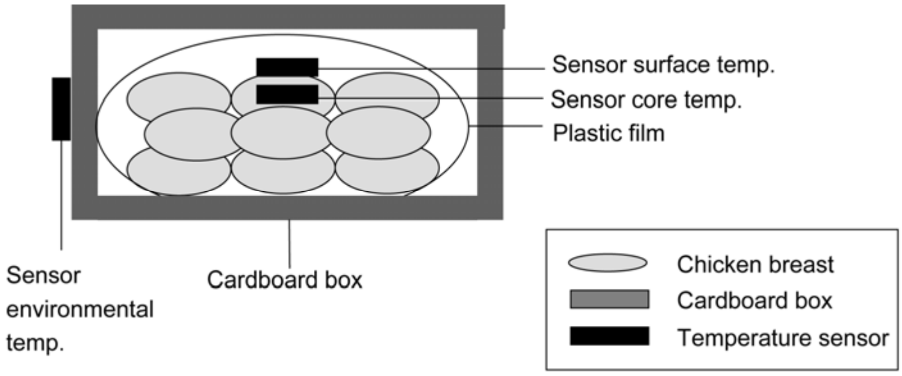

Figure 3.5: Cardboard box composition and location of temperature sensors at the package (side view) (modified after Moureh et al. (2002))

3.3.3 Experimental design of the shelf life tests

Pork loins were purchased 24 h after slaughtering from a butcher and transported to the laboratory in a cooling box within 15 min. In the laboratory the loins were parted under sterile conditions into pieces of 200 g. Poultry fillets, of 125 g each, were purchased from a wholesaler 24 h after slaughtering and also transported to the laboratory within 20 min in a cooling box. The pork and poultry samples were put in individual pouches and wrapped with low density polyethylene films. The samples were stored under controlled temperature conditions in high precision low temperature incubators. The poultry samples were stored at 5 different isothermal temperatures (2, 4, 7, 10 and 15°C) and the pork samples at 4 different isothermal temperatures (4, 7, 10 and 15°C). Additionally, one dynamic temperature scenario was investigated with both poultry and pork samples, following a cycle of 4 h at 12°C, 8 h at 8°C, and 12 h at 4°C (T_{eff} = 6.7°C).

The shelf life tests were conducted in 2007. Temperature conditions were continuously controlled by data loggers. After appropriate time intervals microbiological and sensory measurements were made from individual packaged poultry and pork samples. For microbiological analysis a representative product sample of 25 g was transferred to a Stomacher-bag. 225 g chilled saline peptone diluents (0.85°% NaCl with 0.1°% peptone) were added and homogenised for 60 s in a Stomacher 400. Appropriate 10-fold dilution of the homogenate was made with saline peptone diluents. Total viable count was determined with Plate Count Agar (Merck, Darmstadt, Germany). Plates were aerobically incubated at 37 +/- 1°C for 72 h. For determination of *Pseudomonas* sp. surface spreading on Pseudomonas Agar Base (Oxoid Basingstoke, United Kingdom) plus CFC supplement (Oxoid, Basingstoke, United Kingdom) was used. Petri dishes were aerobically incubated at 25 +/- 1°C for 48 h. All measurements were performed in duplicates.

Sensory analysis was conducted by a trained sensory panel. Odor, texture and color were evaluated using a simple 3 point scoring system (1 - 3), where 3 was equal to good quality and 1 was equal to not acceptable quality. A sensory index was calculated by the following Equation:

$$SI = \frac{2 \cdot C + 2 \cdot O + T}{5}$$

SI: sensory index, C: color, O: odor, T: texture

(2.1)

Using linear regression a sensory response function of time was calculated. As soon as the sensory index is SI = 1.8 or lower the product is defined as spoiled from a sensory point of view (Kreyenschmidt, 2003). Modelling the growth of *Pseudomonas* sp. as a function of time and temperature was done using the Gompertz Equation (Equation 2.2) (Gibson et al., 1987).

$$N(t) = a \cdot e^{-e^{-k \cdot (t - xc)}} + N_0$$

N(t): microbial count at time t, t: time, a: difference between initial and maximal microbial count, k: growth rate constant, x_c: time at which maximum growth rate is obtained, N_0: microbial count at time t=0

(2.2)

From the fitted parameters the maximum growth rate and lag phase were determined using Equations 2.3 and 2.4.

$$\mu_{max} = \frac{a \cdot k}{e}$$

(2.3)

$$t_{lag} = xc - \frac{a}{k}$$

(2.4)

μ_{max}: maximum growth rate and t_{lag}: lag phase

Based on the sensory investigations the end of the microbiological shelf life was calculated. The end of shelf life is assumed for poultry when the bacterial count of *Pseudomonas* sp. is higher than $10^{7.3}$ cfu/g. For pork the end of shelf life is assumed when the bacterial count of *Pseudomonas* sp. is higher than 10^{7} cfu/g (as published by Raab et al., 2008, further investigated, determined and modified by Bruckner et al., 2009; Bruckner, 2010). To determine the temperature dependency of the growth rate the Arrhenius Equation (Equation 2.5) was used as a secondary model.

$$ln(\mu_{max}) \quad = \quad ln(k_{\mu}) - \frac{E_a}{R} \cdot \frac{1}{T}$$

k: reaction rate constant, E_a: activation energy, R: gas constant (8.314 kJ/mol/K), T: temperature (K)

(2.5)

Finally, a scenario for practical application of the model will be proposed for a simplified cold chain.

Statistical analysis

All calculations and Figures were performed with Origin software 7.5 (OriginLab Cooperation, USA) and Microsoft Excel 2002.

3.4 Results

3.4.1 Characterization of structures of cold food supply chains

The results from the organizational part of the questionnaire show that 34% of the German pork products are distributed over an area less than 50 km from the slaughterhouse or processing factory to the wholesalers, 33% are distributed 50 to 250 km, 19% are distributed between 250 km and 500 km, and 14% of the products are distributed over a distance of 500 km plus. The results from the empirical analysis of German poultry products show that only 18% of the poultry products are transported less than 50 km and above 500 km. Most of the products are transported within a distance of 50 to 250 km (36%), 27% of the products are transported within 250 to 500 km from slaughterhouses or processing factories to their customers.

Regarding the sojourn time in the different stages of the pork and poultry chains, the survey showed that there are huge variations. In the local German poultry supply chain used as our example, products are delivered within 1 - 12 h from the time of production to the wholesalers. If products are intermediately stored during transport total sojourn time within this stage is approximately 18 - 20 h. To get more detailed knowledge about quality inspection at the entrance control and during process control; companies were asked in the second part of the questionnaire about applied methods for quality inspection. The frequency of occurrence of different quality inspection methods at the entrance control and during process control is displayed in Figure 3.6.

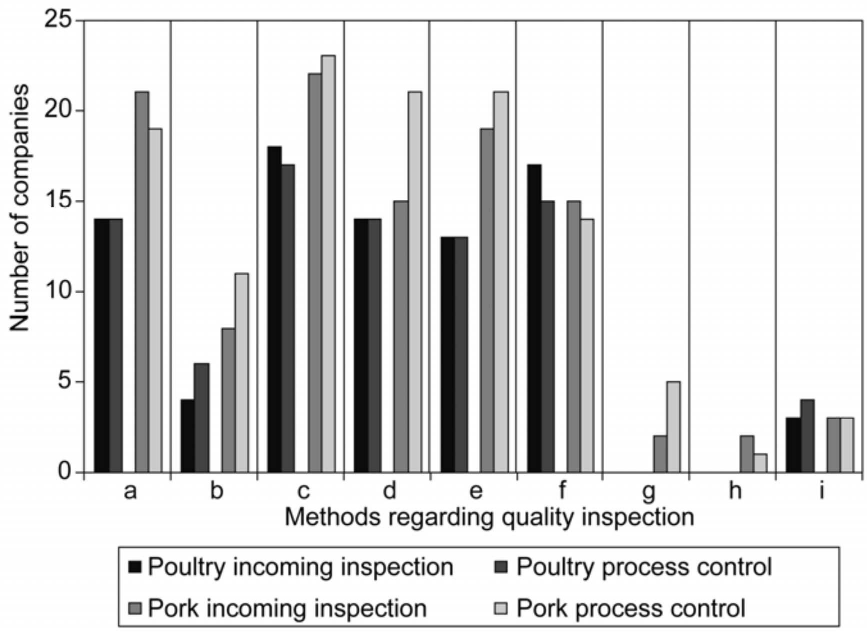

Figure 3.6: Frequency of occurrence of different methods regarding quality control at the entrance control and during process control (poultry: n=23, pork: n=28) (a: sensory control, b: pH-value, c: product temperature, d: ambient temperature, e: microbiological investigations, f: control of "best before"-date, g: rapid methods, h: others, i: not specified)

The most frequently mentioned methods for the entrance control of fresh pork meat are control of the product temperature (22 times), sensory investigations (21 times) and microbiological investigations (19 times). These data comply with the mentioned methods at the entrance control of fresh poultry meat but here the control of ambient temperature was mentioned with a higher frequency compared to the random sample (14 times). In general few differences were found between the methods used at the entrance control and at the process control. Only few companies investigate pH-values and use rapid methods. The most frequently named microbiological inspections were total bacterial count and investigations of *Enterobacteriaceae*, *Salmonella* and *Staphylococcus aureus*, *Pseudomonas* sp. is only investigated by 4 of 28 companies in the pork sector and 7 of 23 companies in the poultry sector.

Figure 3.7 shows the points at which environmental, core and surface temperatures are monitored at the entrance control and during process control in companies in pork and poultry supply chains. The core temperature of fresh pork is measured at the entrance control and at the goods issue by 14 companies. Eight of these companies also measure the core temperature of the pork in the production area. The surface temperature of the pork meat at the mentioned inspection points is measured by 9 companies.

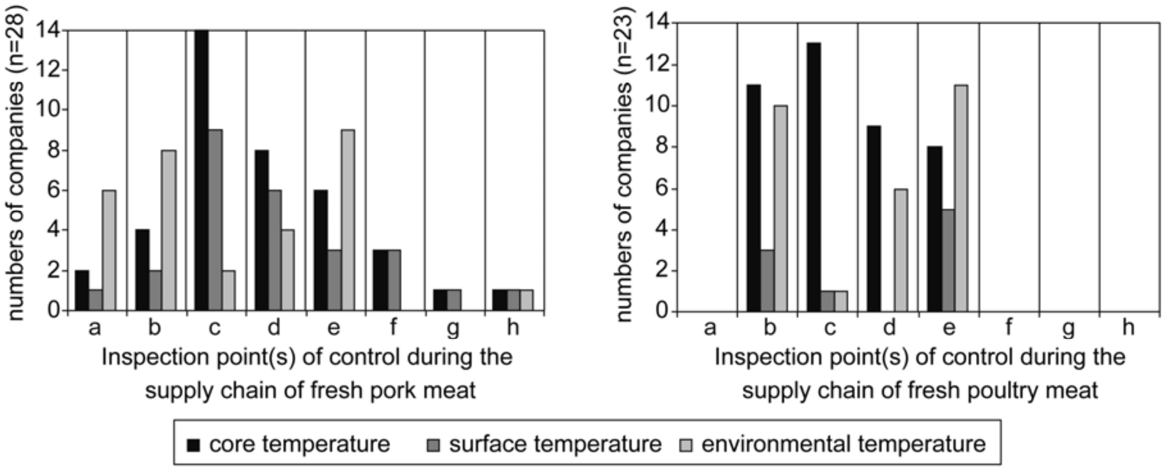

Figure 3.7: Frequency of occurrence for the determination of core, surface and environmental temperature at different places in the respective supply chain (poultry: n=23, pork: n=28) (a: whole company, b: consignment area/transport vehicles, c: entrance control and goods issue, d: production area, e: storage and cooling rooms, f: control of the goods, g: packaging, h: not specified)

Temperature control during transportation of pork products is most frequently done by data loggers (mentioned 18 times), followed by resistance temperature sensors (13 times), mechanical temperature recorders (5 times) and thermocouples (3 times). The third part of the survey aimed at the system architecture and technical circumstances of information management. The storage and availability of temperature data and quality data were evaluated with regard to data availability for decision making. Less than 50% of companies in pork and poultry supply chains exchange quality and temperature data with upstream or downstream partners.

Quality inspection and temperature control data at the inspection points is most frequently stored in paper form (mentioned 25 times) in pork supply chains. Additionally, PCs with special software are used for optimization of the information management. Paper forms are also used most frequently in fresh poultry supply chains for the storage of quality and temperature data at the entrance control (17 times) as well as during process control (15 times) and at the goods issue (15 times).

Figure 3.8 shows an overview of the methods of data collection and storage of various types of quality and temperature data in poultry supply chains.

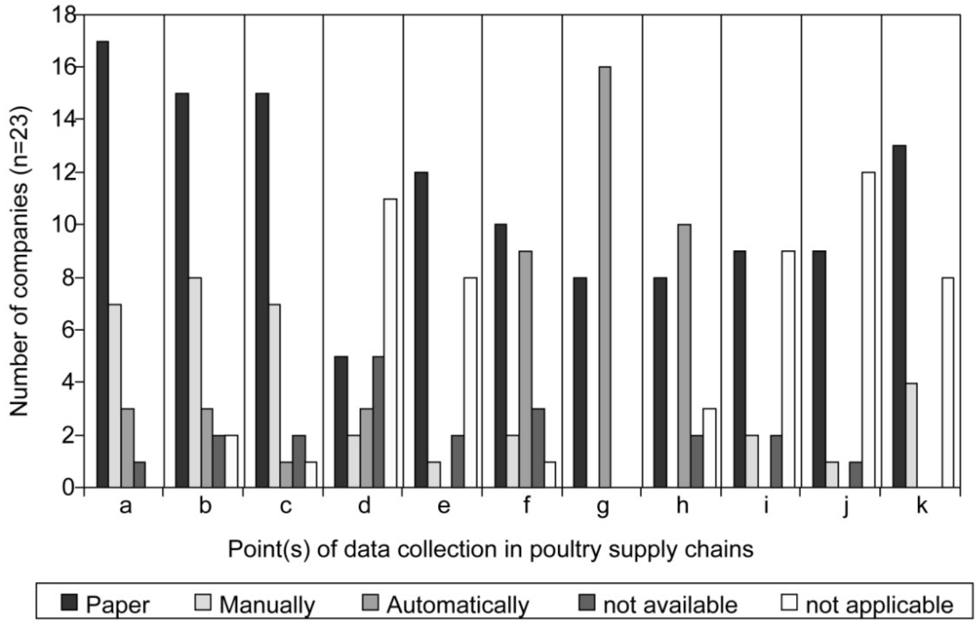

Figure 3.8: Data collection and storage of quality and temperature date at various stages in the process of actors of different stages in poultry supply chains (n=23) (a: data collection at the entrance control, b: data collection during process, c: data collection at the goods issue, d: external data, e: statement of health inspection, f: temperature data of transport vehicles, g: temperature data of the storage rooms, h: temperature data of process rooms, i: previous food business ID, j: primary production method, k: area/country of origin)

3.4.2 Analysis of temperature conditions in cold supply chains

Figure 3.9 and Figure 3.10 show the results of the temperature mapping at the measuring areas of the exemplified poultry supply chain. The measuring areas (1 - 5) are numbered according to the description in the methods section (Figure 3.2). The description of the results in the different measuring areas is focused on the time interval during which production runs in the respective rooms. Figure 3.10 shows the temperature measurements in the rooms of air chilling of the chicken, processing rooms, storage and cooling rooms as well as the rooms of consignment sale (measuring areas 1 - 4).

Temperature conditions in the air chilling rooms vary between -1.2 °C and +2.0°C (measuring area 1). In processing rooms (measuring area 2) the temperature fluctuates from 7.1 °C to 10.5°C. Continuous cooling in storage and cooling rooms (measuring area 3) is interrupted by frequent defrosting cycles. The temperature fluctuates between 0.8°C and 6.8°C in the storage and cooling room of chicken breast fillet and between 0.5°C and 2.8°C in the second storage and cooling room. Sojourn time in these rooms differs between 4 h and max. 24 h. Further experiments were conducted in the room of consignment sale and the docking stations of the trucks (measuring area 4) to investigate areas where temperature fluctuations take place through environmental factors. As shown in Figure 3.9 the temperature fluctuates between 3.4 °C and 6.5°C in the docking stations, where the sojourn time of the products is around 2 - 4 hours.

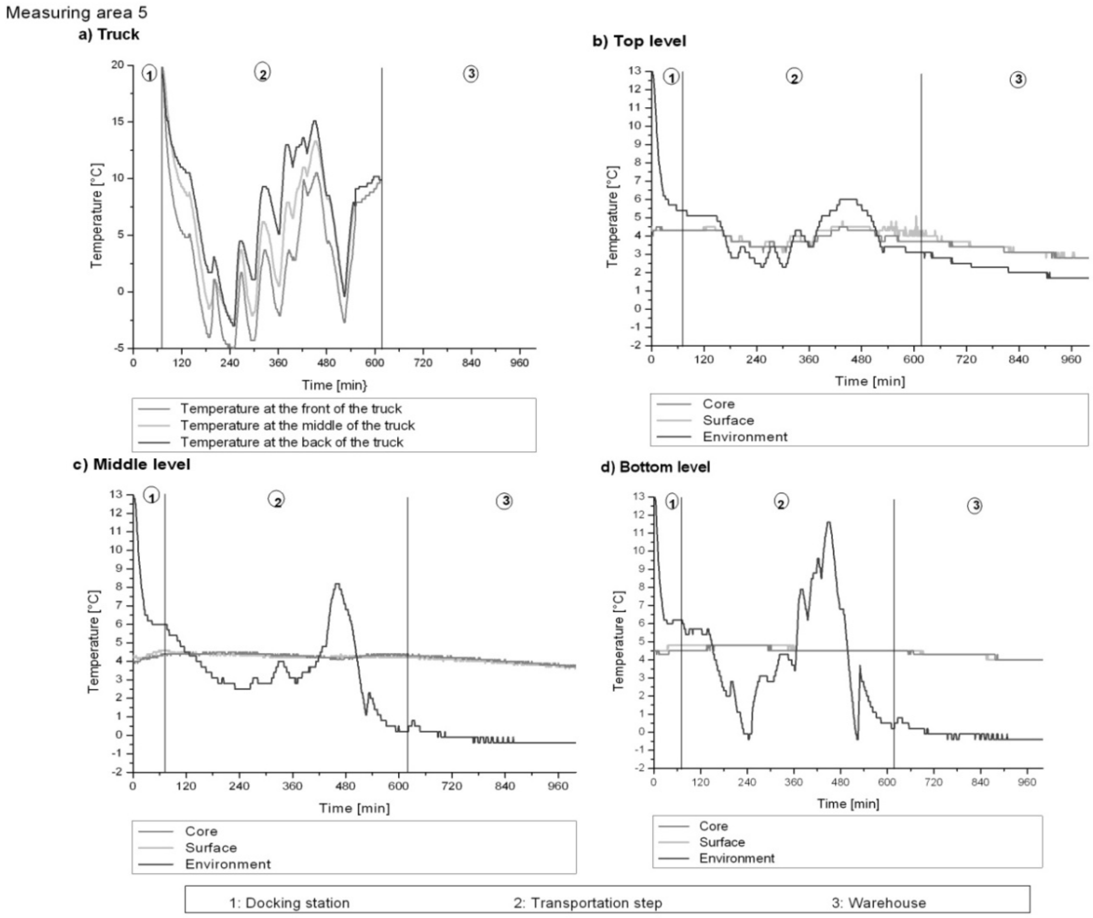

Figure 3.9: Temperature conditions at different places in the transport vehicle and temperature conditions of three cardboard boxes at different locations at the tested pallet (top, middle and bottom of the pallet)

After the distribution and consignment stage, products are loaded onto the truck and transported to the department of the wholesaler (after a period of 11 hours). The transportation stage starts at 2:00 p.m. at the processing company. The mean ambient temperature was about 17 °C on the day these measurements were taken.

Figure 3.9 shows the results of temperature mapping during transportation at different locations in the truck and at one single pallet at the front of the truck. The temperature investigation at different locations within the truck during transportation shows fluctuations between -5°C and +15°C within the unloading periods of the truck (between 110 min and 480 min of transportation). Furthermore, results show temperature differences of up to 10.3°C between different locations in the truck.

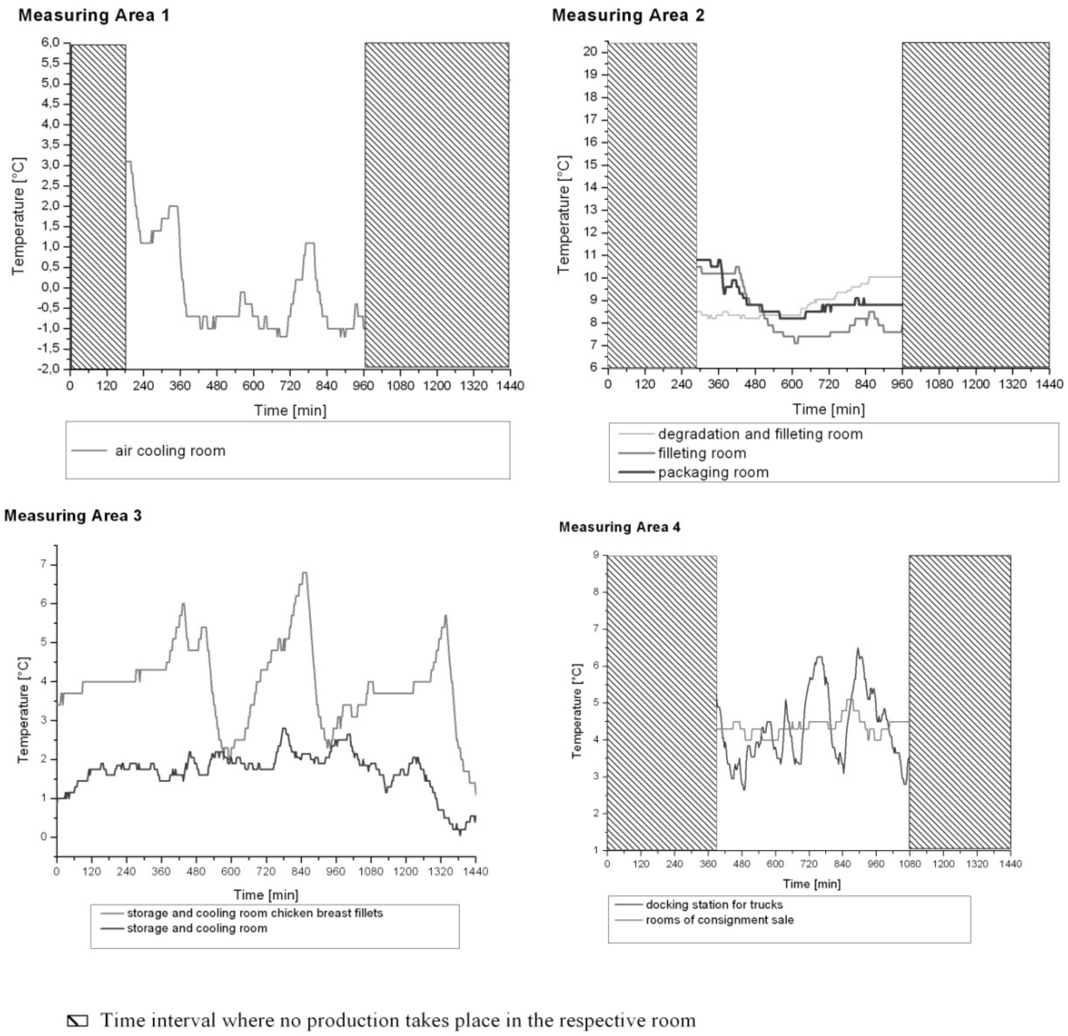

Figure 3.10: Temperature mapping of different process stage in the production chain of chicken parts and chicken breast fillets

The highest temperature measured inside the truck during transportation was 15°C at the door and 11°C at the cooling device. Temperature mapping at three cardboard boxes at different locations in one pallet show that fluctuations of the environmental temperature take place, e.g. at door opening phase after 484 min of 5°C (top level: 6.0°C, bottom level: 11.6°C). Furthermore, environmental temperatures at each of the boxes varied compared to surface and core temperature of the meat within the cardboard boxes.

At the top level of the pallet core and surface temperatures of the meat were more influenced by environmental temperature fluctuations than at the medium and bottom levels. At these lower levels of the pallet the temperature fluctuated between 3.4°C and 4.8°C, whereas more temperature fluctuations took place at the top level (temperature difference between 2.5°C and 4.5°C).

3.4.3 Determination of remaining shelf life on basis of the temperature history of a product

The results indicate that total bacteria growth behaviour and the bacterial growth of *Pseudomonas* sp. were almost identical at every measuring point and for both meat types. Therefore, only the results of the *Pseudomonas* sp. investigations are presented here. Figure 3.11 shows the growth of *Pseudomonas* sp. on poultry and pork at different temperatures modelled with the Gompertz model (Equation 2.2). The graphs show the typical sigmoid bacterial growth curves for both meat types. The growth is faster at increasing temperatures.

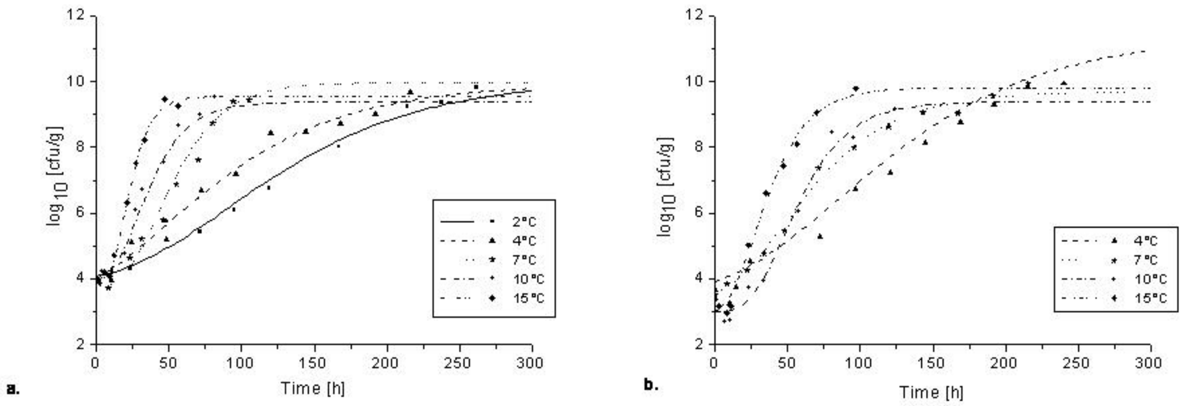

Figure 3.11: Growth of *Pseudomonas* sp. on a) poultry and b) pork at different temperatures with the respective fit using the Gompertz model

The initial bacterial count of *Pseudomonas* sp. on poultry was 3.7 - 1.0 $\log_{10}$ cfu/g and on pork 3.3 +/- 0.5 $\log_{10}$ cfu/g. The parameters calculated from the Gompertz model are presented in Table 3.3 for poultry and Table 3.4 for pork. Shelf life was calculated from time point zero of the laboratory investigations, which means 24 h after slaughtering.

Table 3.3: Parameters obtained from the Gompertz model for poultry

Temperature [°C]	N_{max} [$\log_{10}$ cfu/g]	t_{lag} [h]	μ_{max} [1/h]	R^2	Shelf life evaluated by *Pseudomonas* sp. [h]	Shelf life evaluated by SI [h]
2	10.1	16.52	0.0308	0.978	129.17	154.83
4	9.9	0	0.0381	0.979	94.55	119.49
7	10.0	23.29	0.0955	0.989	61.48	53.18
10	9.7	10.53	0.1166	0.990	40.08	42.34
15	9.6	9.76	0.2120	0.996	25.90	28.21

N_{max} = maximum population level, μ_{max} = maximum growth rate, t_{lag} = lag phase, SI = Sensory index, R^2 = adjusted coefficient of determination

Table 3.4: Parameters obtained from the Gompertz model for pork

Temperature [°C]	N_{max} [log_{10} cfu/g]	t_{lag} [h]	μ_{max} [1/h]	R^2	Shelf life evaluated by *Pseudomonas* sp. [h]	Shelf life evaluated by SI [h]
4	11.1	7.97	0.0376	0.990	110.51	148.72
7	9.7	7.39	0.0586	0.993	71.45	111.03
10	9.4	23.76	0.0988	0.985	65.77	68.71
15	9.8	8.471	0.130	0.988	40.62	44.43

N_{max} = maximum population level, μ_{max} = maximum growth rate, t_{lag} = lag phase, SI = Sensory index, R^2 = adjusted coefficient of determination

Based on the coefficient of determination the Gompertz model is applicable for describing the growth of *Pseudomonas* sp. on both meat types (R^2 = 0.978). The final maximum bacterial count is about the same at all temperatures and for both meat types. For the length of the lag phase no trend can be established, although it would be expected that the length of the lag phase decreases with increasing temperature. At any given temperature the maximum growth rate on poultry is higher than on pork meat. The higher growth rate, the higher initial bacterial count and the lower tolerance level of poultry in comparison with pork results in a shorter shelf life of poultry meat at any given temperature.

The maximum growth rate of *Pseudomonas* sp. on poultry and pork meat is clearly temperature dependent and can be described using the Arrhenius Equation (Equation 2.5). Figure 3.12 shows the Arrhenius plots for μ_{max} for the growth of *Pseudomonas* sp. on poultry and pork meat. The activation energy for growth of *Pseudomonas* sp. on poultry is 100.65 kJ/mol and on pork 76.00 kJ/mol.

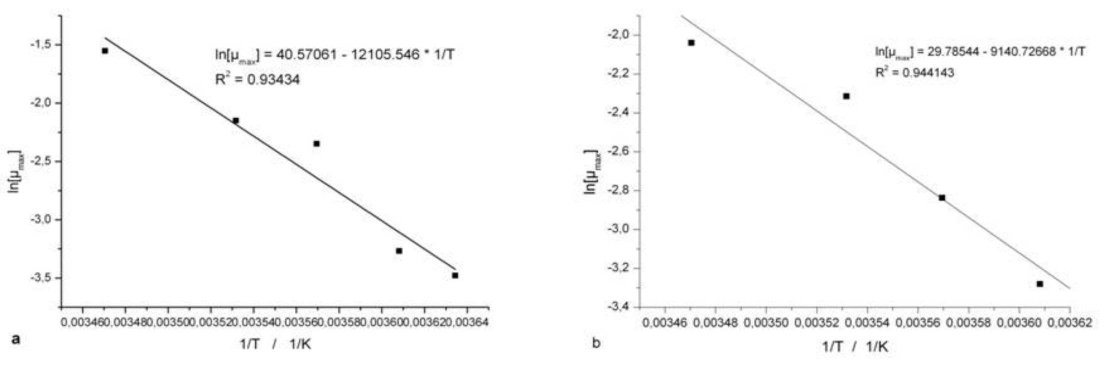

Figure 3.12: Secondary modelling of the temperature dependency of max for a) poultry and b) pork meat using Arrhenius Equation

To validate the application of the Gompertz model, the growth of *Pseudomonas* sp. under dynamic temperature conditions (4 h 12°C / 8 h 8°C / 12 h 4°C) was evaluated. Figure 3.13 shows the growth on poultry and pork with the dynamic temperature profile.

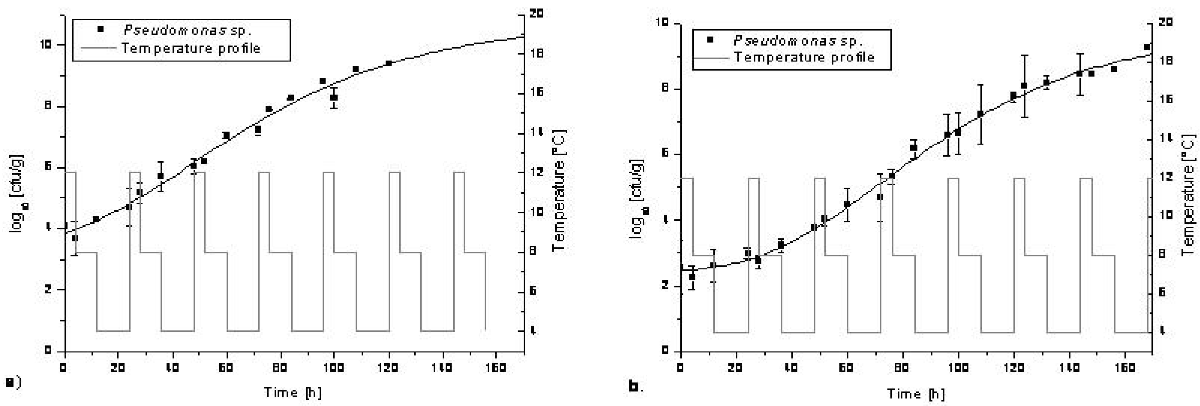

Figure 3.13: Growth of Pseudomonas sp. at dynamic temperature conditions (4 h 12°C / 8 h 8°C / 12 h 4°C) on a) poultry and b) pork meat

Table 3.5 gives an overview of the model parameters obtained from the mathematical model.

Table 3.5: Parameters obtained from the Gompertz model for poultry and pork under dynamic temperature conditions (4 h 12°C / 8 h 8°C / 12 h 4°C)

Meat	N_{max} [log_{10} cfu/g]	t_{lag} [h]	μ_{max} [1/h]	R^2	Shelf life evaluated by *Pseudomonas* sp. [h]
Poultry	10.76	0.20	0.0584	0.986	62.61
Pork	9.82	28.40	0.0621	0.995	104.38

N_{max} = maximum population level, t_{lag} = lag phase, μ_{max} = maximum growth rate,
R^2 = adjusted coefficient of determination

The Gompertz model is also suitable for the mathematical description of the growth of *Pseudomonas* sp. on poultry and pork under dynamic temperature conditions. The coefficient of determination (R^2) is higher than 0.98 for both meat types. It was shown that the shelf life of poultry at constant temperatures is also shorter than the shelf life of pork under dynamic temperature conditions. Based on the developed growth model for *Pseudomonas* sp. a possible practical application scenario was created for a simplified cold chain from the dissection stage to retail. In Table 3.6 the different stages that occur from dissection to the incoming goods department at the retail point are listed with assumed sojourn times and mean temperatures at every stage.

Table 3.6: Parameters used in the predictive model

Meat	N_{max} [log_{10} cfu/g]	t_{lag} [h]
N_0	3.7 log_{10} cfu/g	3.1 log_{10} cfu/g
N_{max}	10 log_{10} cfu/g	10 log_{10} cfu/g
t_{lag}	6.7 h	12 h
A	40.6 1/h	29.8 1/h
E_a/R	-12105.5 K	-9140.7 K

N_{max} = maximum population level, t_{lag} = lag phase

The following assumptions and simplifications were made to create a possible application scenario:

- Initial bacterial count is constant for all temperatures.
- Maximum bacterial count is constant for all temperatures.
- Lag phase is constant for all temperatures.
- Growth of *Pseudomonas* sp. at dynamic temperature conditions is similar to the respective constant effective temperature.
- Only the maximum growth rate is temperature dependent.

The following parameters for the simplified cold chain were estimated on the basis of the presented results (Table 3.7).

Table 3.7: Processing stages in a simplified cold chain from dissection to retail with assumed sojourn times and mean temperatures

Processing stage	**Sojourn time [h]**	**Mean temperature [°C]**
Slaughtering, processing to final inspection	8	4
Transport	12	7
Intermediate storage	5	3
Transport	5	7
Overall	30	5.3

Using the Arrhenius Equation (Equation 2.5) and the above assumptions, the actual bacterial count at the incoming goods department at the retail point can be calculated. After 30 h at a mean temperature of 5.3°C (Table 3.7) a bacterial count of *Pseudomonas* sp. on poultry meat of 4.9 $\log_{10}$ cfu/g is estimated. On pork meat a bacterial count of *Pseudomonas* sp. of 4.1 $\log_{10}$ cfu/g is estimated. Assuming further storage at an optimal storage temperature of 4°C for poultry and pork meat, the remaining shelf life can be estimated. This is done by a parallel translation of the growth curve at 4°C to the left by reducing x_c so that the curve reaches the actual bacterial count at the present storage time.

Using this new equation a remaining shelf life of 52.1 h for poultry and 74.4 h for pork is estimated in this example of a simplified cold chain.

3.5 Three-dimensional generic model for the optimization of cold chain management

The results indicate that the connection of the technical, organizational and functional dimension can delivers an important contribution regarding the optimization of cold chain management of pork and poultry supply chains.

The temperature mapping has shown that fluctuating environmental temperature conditions exist during transport and distribution. Such weak points within cold supply chains are also reported by other authors (Olsson, 2004; Giannakourou et al., 2005). The empirical supply chain analysis revealed that monitoring of temperature conditions in meat supply chains is very heterogeneous and partially not efficient. For example, companies often control temperature conditions based on measurements taken by data loggers, which normally measure the environmental temperature. But environmental and surface temperatures of the meat often differ as shown by the results. Measurement of the core temperature of the meat at the entrance control is only a random measurement. The difference between the environmental and surface temperatures depends on the placement of the logger, packaging material, etc. (Moureh et al., 2002), which have to be taken into consideration.

The empirical supply chain analysis revealed that an effective temperature control over the whole supply chain of companies rarely exists. For the optimization of cold chain management the full temperature history over the entire supply chain is needed, which can only be achieved through comprehensive temperature monitoring along the whole supply chain. Possible solutions could be the integration of Smart Active Labels or time-temperature integrators, which are placed directly on the food. If temperature measurement equipment is not located directly on the meat an alternative to the individual determination of product temperature is the development of a heat transfer model that draws conclusions on the temperature on the meat surface based on ambient temperature. There are several temperature monitoring systems, but to implement them successfully other factors must also be considered like organizational structure (distribution length, packaging material and size, etc.).

Further on, the empirical analysis revealed that several challenges still exist regarding the optimization of temperature monitoring and inter-organizational information management of quality and temperature data. Until now, temperature data are rarely shared with upstream or downstream chain partners as this shown by the questionnaire results. But, the successful collection and management of such data within an inter-organizational information management system will bring added value to all actors. For example, efficient management decisions at important decision and inspection points can only be done by optimal data treatment. Additionally, the prediction of remaining shelf life in each stage of the supply chain is possible on basis of a full temperature history. The development of the shelf life model has shown that it is possible to calculate the remaining shelf life of poultry and pork based on laboratory investigations. This can allow the functional linkage of temperature data with the product quality.

By using the model it is possible to draw conclusions based on the temperature history of a product and the total count of *Pseudomonas* sp. As less than 30% of the surveyed companies analyze the viable count of *Pseudomonas* sp. at the entrance control, the use of the shelf life model in practice requires the optimization of inter-organizational temperature monitoring. As shown by the results, only continuously monitoring of the environmental temperature takes place and heat transfer models are still not used. Conclusions on basis of the environmental temperature history can lead to an underestimation of remaining shelf life and thereby cause economic losses, particularly in chains where transport stages are characterized by several stops with variable door opening times and when temperature loggers are located close to the door.

Based on these results a three-dimensional generic model to optimize cold chain management in different meat supply chains has been developed (Figure 3.14).

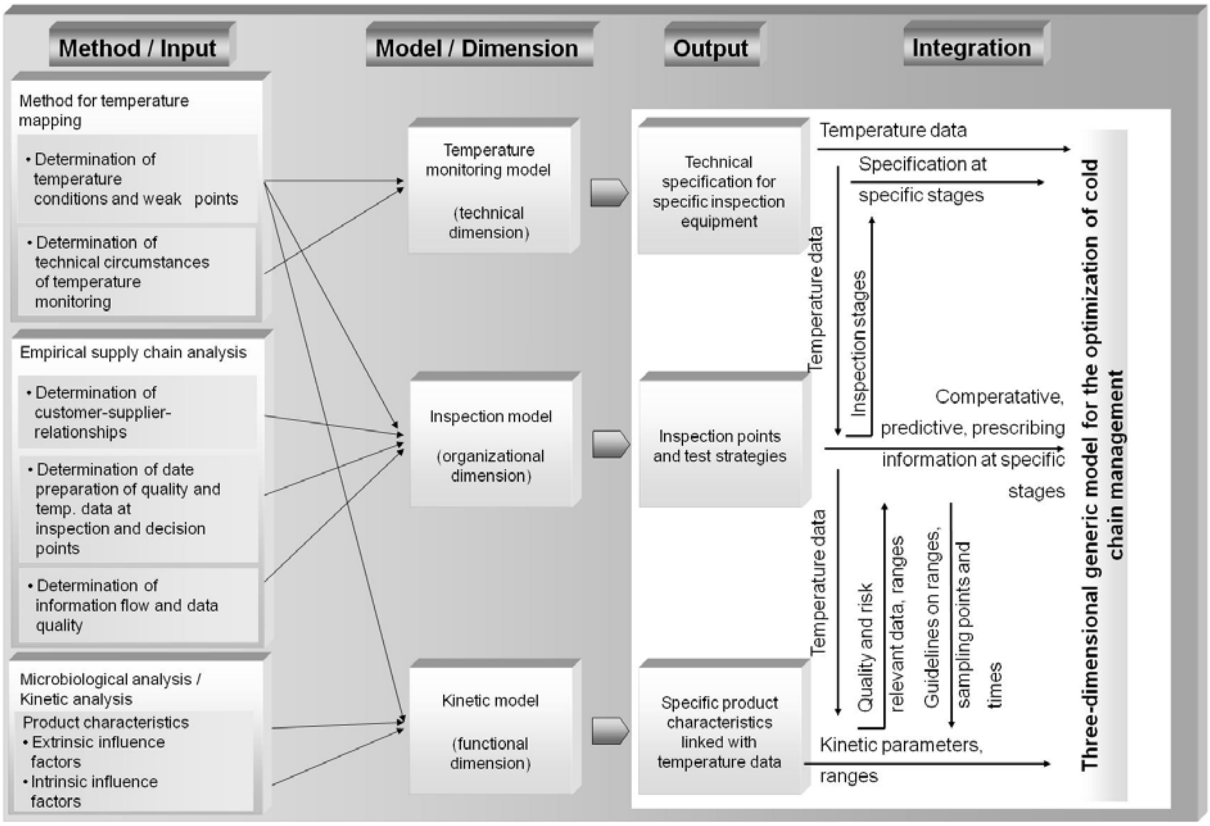

Figure 3.14: Three-dimensional generic model to optimize cold chain management including a technical, an organizational and a functional component (modified after Raab et al., 2008; Kreyenschmidt, 2009)

The three-dimensional generic model consists of three different sub-models: a temperature monitoring model (technical component), an inspection model (organizational component) and a kinetic model, e.g. a shelf life model or a TTI kinetic model (functional component).

The temperature monitoring model includes chain specific information regarding methods of temperature mapping. Further added value may be provided due to the integration of parameters for a heat transfer modelling. Based on all parameters, a description of optimal technical implementation of innovative solutions and their integration in holistic systems for the particular cold chain will be delivered. The inspection model provides information on all factors related to organizational structure, inspection scheme and information management of the specific chains. The output of the model is the support of intra- and/or inter-organizational inspection and decision. The model generates information on methods and sampling times of microbiological investigations as well as temperature control at specific inspection points. The use of a shelf life model or another kinetic model is one important step in linking product characteristics with temperature data.

3.6 Conclusion

The results indicate the important contribution of efficient temperature monitoring in meat supply chains to the whole concept of cold chain management. It becomes apparent that mainly inter-organizational temperature monitoring is a major challenge in the optimization process. The collection of a temperature history along the whole supply chain will allow the linkage of temperature data with product quality, e.g. due to a combination of predictive models with novel temperature monitoring solutions. Thus, the three-dimensional generic model will support actors by providing information for their decision management; it will reduce cost through a systematic inspection scheme; and it will also make an important contribution to improving meat quality. The empirical supply chain analysis revealed that in practice there still exists an optimization potential regarding temperature monitoring. Therefore it is necessary to support the chain actors in finding the most appropriate solution regarding their needs and to develop implementation concepts for the usage of innovative solutions.

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4 Validation and application of a novel temperature monitoring solution in inter-organizational cold chain management of a poultry supply chain

4.1 Introduction

The improvement process of cold chain management in whole supply chains has to consider the implementation of novel temperature monitoring solutions as well as the optimization of information handling of temperature data along the supply chain (Chapter 3). As it is detailed in Chapter 2, several different temperature monitoring solutions have been developed to support comprehensive temperature monitoring within a single company as well as at the chain level (Kreyenschmidt et al., 2005; Kerry et al., 2006; Ellouze and Augustin, 2009).

One possibility is the use of time-temperature indicators (TTIs) which provide the option to continuously monitor and record the temperature history along the entire cold chain in a simple and cost effective way (Taoukis and Labuza, 1989; Labuza and Fu, 1995). The possibility for the use of TTIs has been studied in the laboratory and details published by many researchers (Chen and Zall, 1987; Wells et al., 1987; Fu et al., 1991; Shellhammer and Singh, 1991; Riva et al., 2001; Kreyenschmidt, 2003; Smolander et al., 2004). Furthermore, several authors have described different requirements and implementation challenges regarding the practical use of TTIs in food supply chains (Fu and Labuza, 1992; Kreyenschmidt et al., 2005; Hauser et al., 2005; Kerry et al., 2006; Kreyenschmidt, 2007; Taoukis, 2008; Tsironi et al., 2008, Vaikousi et al., 2008; Kreyenschmidt et al., 2010a). However, only a few studies have been published to date regarding field testing of TTIs in real food supply chains. Giannakourou et al. (2005) investigated TTIs as shelf life monitors for fresh fish within a Greek distribution chain. The same chill chain management system on the basis of TTIs was investigated by Taoukis (2006) in a retail transportation route scenario involving fresh pork cuts. Within these studies, the applicability of TTIs in food supply chains was investigated and potential improvement possibilities in cold chain management were raised. However, mainly the functional requirements are taken into concern e.g. correlation of the response with the product quality.

The development of the three-dimensional generic model (chapter 3.5) has shown that also organizational and technical requirements should be taken into concern. Taking this three-dimensional view into concern, it can be distinguished between the following technical, organizational and functional requirements regarding the implementation of TTIs.

Technical requirements regarding TTIs as temperature monitoring solution are e.g. the choice of the placement of TTIs at the logistic unit. The placement should be chosen according to the placement where the temperature correlates mostly with the temperature of the food. This requirement is in close connection to a functional requirement regarding the definition of the smallest traceable unit. Further on, the correct initial settings and the choice of an accurate reading accuracy belongs to this group of requirements. Such technical implementation challenges regarding optimal temperature monitoring are considered within the temperature monitoring model described in chapter 3.5. The temperature monitoring model can be used for the development of chain specific implementation concepts and thus, for an optimal implementation of innovative tools like TTIs.

Thereby, organizational requirements occur due to intra- and mainly inter-organizational degree of complexity. The willingness to exchange information within the supply chain as well as the definition of access privileges to the collected temperature data, due to different cooperation levels and trust between the chain actors (Schulze Althoff et al., 2005) can be described as organizational requirements. With regard to TTIs, the organizational requirements as well as challenges vary regarding the application scenario: if a TTI is used within a mutual chain relationship, within a whole supply chain or network or until the consumer. Additionally, TTIs can also be used to monitor only the logistic ways e.g. the OnVu^{TM} logistic label (Ciba Specialty Chemicals & Freshpoint, Basel, Switzerland). In combination with matrix codes, containing information regarding enterprise resource planning (Raab et al., 2010), or standard international logistic labels (GS1, 2008), the degree of traceability regarding temperature data can be enhanced.

Functional challenges can be defined as all challenges, which deal with the optimal integration of TTIs linking the temperature with the product's quality. For example, the information collected by using the TTI and the remaining shelf life of the product at important inspection and decision points within the supply chain. In addition, the correct estimation of remaining shelf life using the TTI under dynamic temperature conditions within all stages of food supply chains has great importance as otherwise an under- or overestimation of the shelf live can result (Kreyenschmidt et al., 2010a).

By taking into account all three dimensions of requirements and challenges, TTIs may facilitate the improvement of the collection of a temperature history along the entire supply chain. This will allow on the one hand an optimization of inter-organizational inspection and decisions and will provide on the other hand added value for the actors e.g. the linkage of temperature data and product characteristics.

Chain information management concepts and models are an important contribution to solving such challenges (Schulze Althoff et al., 2005; Schulze Althoff, 2006; Petersen et al., 2007), e.g. the three-dimensional model described in chapter 3.5. Within the proposed inspection model, the theoretical concept of the process model (Schulze Althoff, 2006) and the closed loop system (Petersen, 1985) can be used. The process model describes the product and optimal information flow, e.g. of temperature data. It postulates that detailed data analysis and data processing at the entrance control, during processing and at final inspection are an important decision-making factor within the company's cold chain management. This also includes the continuous improvement of inter-organizational management aspects involving buyers and suppliers. Such continuous improvement within the whole supply chain requires a substantial degree of monitoring in combination with systematic evaluation at important inspection and decision points. In terms of temperature monitoring, limits for analysis and evaluation of the temperature data are needed in complex systems, which can be specified using the closed loop system (Petersen, 1985). Both models combined denote how to actuate, react to, and manage processes at important intra- and inter-organizational decision points (Petersen, 1985; Schulze Althoff et al., 2005; Schulze Althoff, 2006). Through the use of these theoretical concepts in terms of intra- and inter-organizational temperature monitoring, warning and action control limits can be set at which the TTIs can actuate as a monitoring instrument.

For the calculation of warning and action control ranges, the development of a validated kinetic model is a prerequisite (Taoukis et al., 1999, Nuin et al., 2008; Kreyenschmidt et al., 2010a). A kinetic model allows the determination of limits of the discoloration of the TTIs at important inspection and decision points and therefore a control of the measured response of the TTIs. The TTI kinetic model allows a fast and flexible comparison of the assumed and measured response of the TTI at any stage of a cold supply chain. This permits an efficient process control that takes into account the discoloration of the TTIs affixed to the products and the drawing of conclusions regarding the temperature conditions as well as the remaining shelf life of the products. Therefore, this will allow linking of the temperature history of the products with the products quality and characteristics.

The aim of the study was to test the possible applications of TTIs for optimization of cold chain management in a poultry supply chain. A prerequisite for the application of TTIs is the development of a kinetic model, predicting the discoloration and the remaining shelf life in any stages of the supply chain, which was done in the first part of the study. In the second part of the study, the usability of the TTIs and the kinetic model, integrated into the three-dimensional generic model supporting cold chain management, was tested within a field trial in a typical poultry supply chain.

4.2 Materials and methods

Figure 4.15 shows an overview of the experimental approach used in the present study. In the first step of the study, the discoloration of the TTIs was investigated under constant temperature conditions. The kinetic study within the laboratory was the basis for developing a reliable kinetic model. The kinetic model ("TTI kinetic model") aims at predicting the effect of non-isothermal temperatures on the discoloration of the TTI within the field trial, as well as to translate the response of the TTI into reliable estimates of the remaining shelf life of the food. Furthermore, a second model ("TTI adjustment model") for the calculation of the initial starting value for the TTI application on different products was developed. A prerequisite for the use of both models in the field application was their validation under non-isothermal temperature conditions (Nychas et al., 2008), which was performed in a subsequent step during the laboratory investigations.

The ability of TTIs to be applied as an efficient temperature monitoring solution, optimizing cold chain management in a poultry supply chain, was tested in a four-week field trial. The technical validation of the TTIs was conducted in the first step whereby the measured response was compared with the predicted response of the TTIs using the validated TTI kinetic model.

The integration of the TTIs as a temperature monitoring solution in the three-dimensional generic model (chapter 3.5), should show the improvement of cold chain management using the model. By using model, the applicability of the TTIs for process control of temperature conditions at important decision and inspection points within the supply chain was determined. As a further development, the architecture of the three-dimensional generic model for cold chain optimization allows the possibility for the addition of a functional component, e.g. to predict the remaining shelf life using kinetic models. Within the field trial, shelf life calculations based on the TTI measurements were compared to the predicted remaining shelf life of the TTI. Furthermore, these results were compared with microbiological studies of the product, which were conducted according to the shelf life model (chapter 3.5).

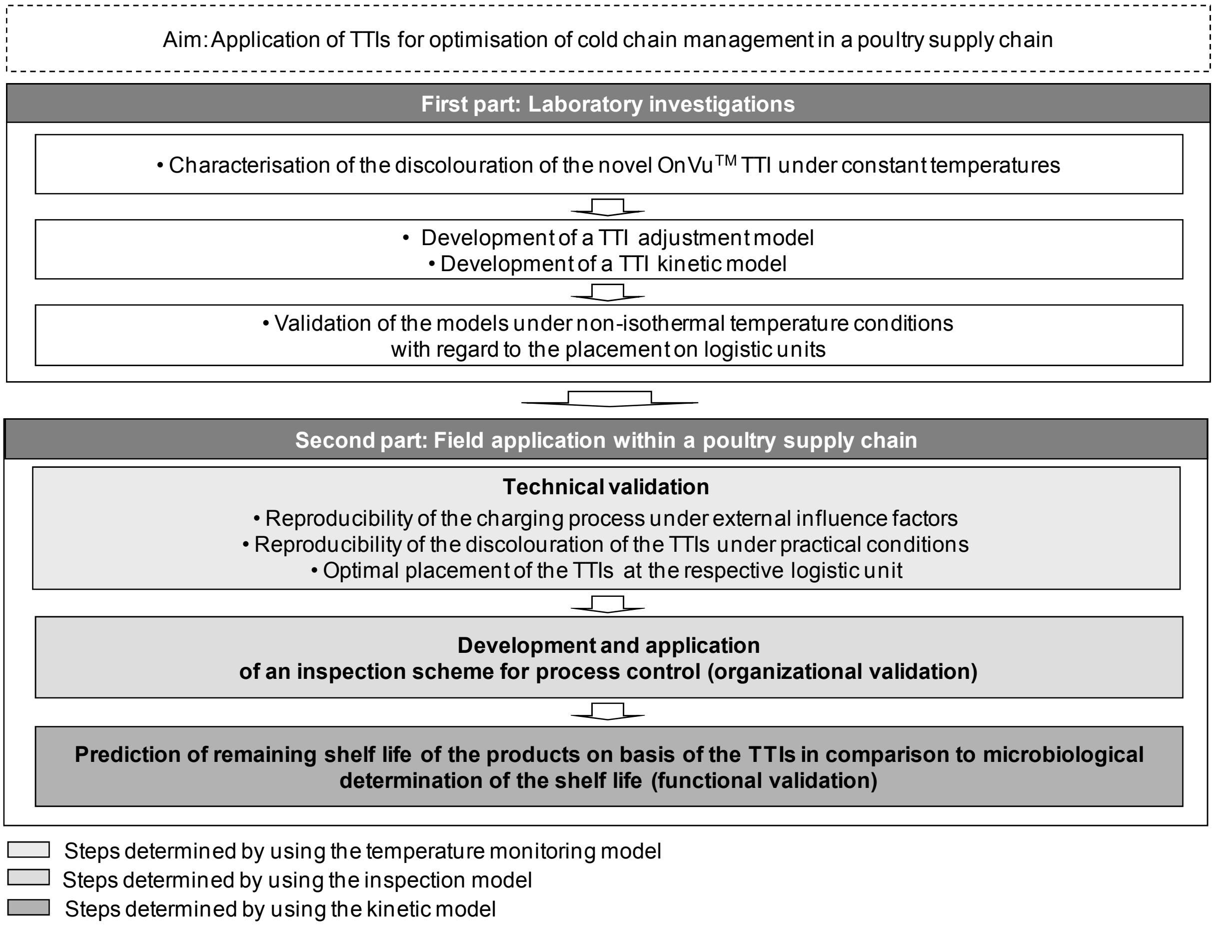

Figure 4.15: Experimental procedure followed in the present study in order to validate and apply time-temperature indicators in poultry supply chains

4.2.1 Characterization of the discoloration of the novel OnVu^{TM} TTI under constant temperatures

The analyzed time-temperature indicator was the OnVu^{TM} label B1+081126 (Ciba Specialty Chemicals & Freshpoint, Basel, Switzerland, patent WO ⁄ 2006 ⁄ 048412). The characterization of the discoloration has taken place in the following way according to Kreyenschmidt (2003) and Kreyenschmidt et al. (2010a): The end of shelf life of the TTI is defined as the time it takes until the color of the blue photochromic spot of the label reaches the reference color, which is surrounding the photochromic ink. An automated UV-light charger (GLP TTI, Bizerba, Germany), was used to activate the labels. The duration of the discoloration time of the labels is proportional to the amount of light used for the charging process, and can be adjusted by varying the duration and intensity of the light pulse (Kreyenschmidt et al., 2010a). The discoloration processes of the labels were measured using a spectrophotometer (X-rite EyeOne i1^Basic, Gretag Macbeth, Regensdorf, Switzerland) and the CIE Lab color system. The discoloration process of the labels during the laboratory investigations and the field trial was investigated by measuring the color changes at defined time intervals of 24 hours. The square value (*SV*, Equation 4.1) was used as a quality parameter to quantify the color changes of the TTI. The experiments were stopped when no color change could be measured within a time frame of 24 hours.

$$SV = \sqrt{L^2 + a^2 + b^2} \tag{4.1}$$

where SV: square Value; L: lightness; a: red and green component; b: yellow and blue component of the label.

Within this study, the effect of the UV charging time and the influence of different environmental temperatures on the discoloration process was investigated using six different charging times (1200 ms, 1350 ms, 1400 ms, 1500 ms, 1650 ms, 1800 ms) and four different isothermal temperatures (2°C, 4°C, 7°C, 10°C). Directly after activation the labels were placed on precooled glass plates (3.5 mm thick), which were covered with multiple layers of white paper to assure a homogeneous and reproducible background for the color measurement (Kreyenschmidt et al., 2010a). The samples with the labels were stored in high-precision low temperature incubators (Sanyo MIR 253, Sanyo Electric, Ora-Gun, Gunma, Japan). The temperature was monitored every 5 minutes in each experiment using electronic data loggers with a resolution of +/-0.5 °C (4K:T, Verdict iButton, Verdict Systems BV, Aalten, The Netherlands).

The data were fitted by nonlinear regression (Levenberg-Marquardt-algorithm) using the Origin 8G software package (OriginLab Corporation, Northampton, Ma., U.S.A.).

4.2.2 Development of a TTI kinetic model and a TTI adjustment model

Development of a TTI adjustment model

The TTI-response was plotted as a function of time and is described using a logistic model (Equation 4.2) as conducted by Kreyenschmidt et al. (2010a).

$$X_t = \frac{A}{1 + e^{-k(t - x_c)}} \tag{4.2}$$

where X_t: TTI response, A: amplitude, k: reaction rate (1/h), x_c: reversal point (h), t: time (h).

Since the discoloration end point, which characterizes the end of shelf life, was known (*SV* = 71), the discoloration time could be calculated. Based on this approach, a TTI adjustment model was developed for the estimation of the discoloration of the TTIs over time. The data obtained from the laboratory study under different isothermal temperatures were the basis for the development of the model. The model was developed in two steps.

In step 1 the discoloration times were converted to log form and fitted by linear regression using the following equation (Equation 4.3):

$$LN(SL) = a + b \cdot SV \tag{4.3}$$

where SL: is the discoloration time of the TTI (h), a: is the intercept and b: the slope of the linear fit. SV: is the initial value of the TTI.

Step 2: For the characterization of the twofold dependency of the discoloration time of initial value and temperature, the slope (*b*) and intercept (*a*) were plotted separately as a function of temperature, and fitted by linear regression. The transforming of the equation and the insertion of the fit parameters of the second model step into Equation 4.4 led to the following equation (Equation 4.4):

$$SV = \frac{LN(SL) - (a_a + a_b \cdot T)}{(b_a + b_b \cdot T)} \tag{4.4}$$

where SV: is the initial value of the TTI, T: is temperature (K), SL: is the discoloration time of the TTI (h), a_a and a_b: are the intercept and slope of the temperature dependent a (model step 1); b_a and b_b: are the intercept and slope of the temperature dependent b (model step 1).

The so named TTI adjustment model allows the calculation of the initial *SV* of the TTI for each specific product at a known storage temperature and storage time.

Development of TTI kinetic model

The Arrhenius equation (Equation 4.5) and the logistic equation (Equation 4.2) were combined following the general procedure of Kreyenschmidt et al. (2010b) to develop a TTI kinetic model for the prediction of the discoloration under non-isothermal temperature conditions. By using the Arrhenius equation, the influence of temperature on relative discoloration can be estimated (modified after Arrhenius, 1889). The reaction rate *k* was plotted as a function of temperature in an Arrhenius plot (Equation 4.5):

$$\ln(k) = \ln(k_0) - \frac{E_a}{R} \cdot \frac{1}{T}$$

(4.5)

*Where k: reaction rate (1/h), k_0: constant (1/h), E_a: activation energy (kJ/mol), R: ideal gas constant (8.314 J/mol*K), T: absolute temperature (K).*

As the kinetic model takes into account varying temperature conditions, each temperature interval is examined individually. For each interval with a specific constant temperature, the parameters *A* and *k* were computed according to the linear temperature dependence of the particular parameter. The *SV* at the end of every interval was calculated using the following equation (Equation 4.6):

$$SV_e = \frac{A_T}{1 + e^{-k_T (t - x_{cT})}}$$

(4.6)

With: SV_e: square value at the end of the particular interval; e=1…n=number of intervals, A_T: temperature specific amplitude of the interval, k_T temperature specific reaction rate of the interval (1/h), $x_{c\,T}$: reversal point (h), t is time (h).

Thereby, the reversal point is calculated with the interval specific values of *A* and *k* (Equation 4.7). Additionally, the *SV* value of the former interval is used.

$$x_c = \frac{\ln(\frac{A_T}{SV_{e-1}} - 1)}{k_T} + t$$

(4.7)

With: SV_{e-1}: square value at the end of the former interval, e=1…n =number of intervals, A_T: temperature specific amplitude of the interval, k_T temperature specific reaction rate of the interval (1/h), x_c: reversal point (h), t is time (h).

By using Equation 4.7, the response of the TTIs can be calculated at each stage within a cold supply chain under fluctuating temperature conditions. The model has been named TTI kinetic model. By transforming the equation, the response of the TTI can be translated to show the remaining shelf life of the food.

For the first interval, no former *SV* value of the previous interval was available. Thus, n(t)=1 is set on the initial value in the first interval.

The TTI kinetic model was evaluated using the performance index R^2 and by comparing the predicted end of shelf life based on the TTI discoloration with the observed one based on the square value using Equation 4.8.

$$R^2 = \frac{\sum_{i=1}^{n}(observed_i - predicted_i)^2}{\sum_{i=1}^{n}(observed_i - mean)^2} \tag{4.8}$$

4.2.3 Experimental design of the validation study under laboratory conditions

Validation of the TTI adjustment model (Equation 4.4) and the TTI kinetic model (Equation 4.7) under dynamic temperature conditions was conducted by simulating the dynamic temperature conditions of the respective supply chain. In total 280 labels were activated with an initial *SV* of 57.9. The initial *SV* was calculated using the TTI adjustment model under the assumption that the remaining shelf life of the products is 144 hours (total shelf life is 168 hours, but the investigation started 24 hours after slaughtering). Directly after activation, the labels were placed on double layers of white paper to assure a homogeneous and reproducible background for the color measurement. The labels (on transparent foil) were placed on the different sides of the respective logistic unit, cardboard boxes containing chicken breast fillet, to investigate the optimal placement. The optimal placement is defined as the placement position at a cardboard box where the temperature conditions are similar to the product temperature.

The layers with 10 labels each were put into the transparent foil and placed at different sides, as well as inside, of two cardboard boxes (40 cm x 30 cm x 10 cm). After labelling, the two cardboard boxes were stored under the following temperature conditions: one cardboard box was stored under temperature conditions simulating temperature conditions in the poultry supply chain in winter. The simulated temperature conditions were measured in a previous study at beginning of April 2008 (Table A-16, Study no. 7) (Raab and Kreyenschmidt, 2008). Therefore, the temperature profile was: one day at 4°C, 2 h at 5°C, 6 h at 1°C, 2 h at 5°C, 12 h at 2°C. Afterwards this box (cardboard box 1) was stored at 4°C until the end of discoloration. One control batch (cardboard box 2) was stored under isothermal temperature of 4°C. Within the investigation, the samples with the labels were stored in high-precision low temperature incubators. Electronic data loggers monitored the temperature every 5 minutes. As stated previously, the temperature was monitored in every experiment using electronic data loggers with a resolution of +/-0.5 °C.

Experimental design regarding the application of time-temperature indicators within a field trial in a poultry supply chain

In order to test the potential use of TTIs as an inter-organizational temperature monitoring solution, a field trial in a poultry supply chain was designed (Figure 4.16). This field trial involved monitoring of aerobe packed fresh chicken breast fillet that was produced in Northern Germany. 8 cardboard boxes were filled with 5 kg of chicken breast fillet, wrapped in transparent foil, and stored for two to ten hours in a cooling chamber within the slaughterhouse. In the four week field trial, every Monday and Tuesday, pre-prepared cardboard boxes were then transported in a first distribution stage to a wholesaler. In the second distribution stage, the cardboard boxes were forwarded to different retailers, butcher shops, restaurants and canteen kitchens. Boxes containing TTI and temperature loggers were carefully marked and always placed at the top of the pallet before being transported by refrigerated trucks. The pallets in the first transportation phase were always placed in the second or third row at the back of the truck. At the end of the storage time at the wholesaler, repacking took place and the cardboard boxes were transported to retail butchers in refrigerated delivery vans. Each cardboard box was stored in a cold store at 4°C until the end of shelf life within a cooled chamber (Viessmann CS 1300 T-111, Viessmann Werke GmbH & Co KG, Allendorf, Germany). The field application has taken place in November 2009. The outside temperature in the weeks of the investigation was in the range of minimum temperatures of -1°C to +12°C and maximum temperatures of +5°C to +15°C.

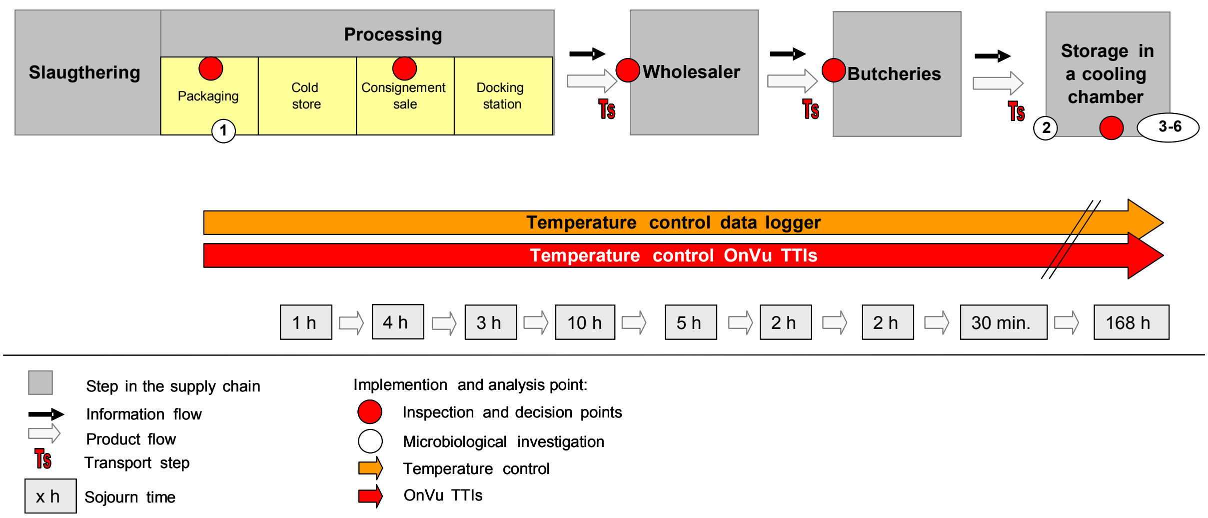

Figure 4.16: Overview of the experimental set-up within the field trial of a typical poultry supply chain

Experimental design to validate the technical component of the three-dimensional generic model using TTIs

To achieve a technical validation of the system, the charging process under external influence factors in a poultry slaughterhouse and the optimal placement at the logistic units were investigated (Malcata, 1990, Labuza and Fu, 1995). To determine the optimal placement of the TTIs, the labels were activated at the time of packaging and placed on different sides of the cardboard boxes. TTI tags were attached to each box at seven different, indicative points, namely at the top (Side 1), the bottom (Side 6) and all four sides (Side 2-5) of the cardboard box as well as inside (on top of the foil) (Side 7) of the boxes (Figure 4.17). Furthermore, the technical validation includes the investigation of the reproducibility of the charging process and the discoloration of the labels within the field trial. Therefore, 10 TTIs were labeled and placed on each side of the cardboard boxes. Electronic data loggers were placed at the same positions as the TTIs. In total 560 TTIs were activated to an initial *SV* of 57.4 (in adjustment on 168 hours shelf life) and placed on, as well as in, the eight cardboard boxes. The initial *SV* was calculated using the TTI adjustment model (Equation 4.4), under the assumption that the remaining shelf life of the products is 168 hours (estimated by the producer and determined in previous studies: Bruckner et al., 2009).

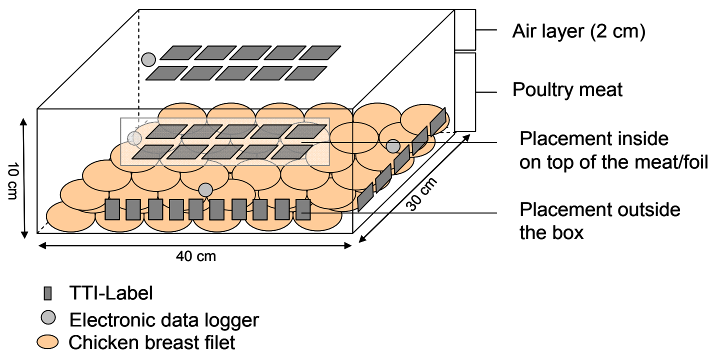

Figure 4.17: Placement of the OnVu™ TTIs and the electronic data loggers at the experimental cardboard boxes

Experimental design to validate the organizational component of the three-dimensional generic model using TTIs

As well as the investigation of technical challenges, organizational challenges like specific adaptation of the needs of the actors within the supply chain and the optimal information management of the data collected using the TTI have been investigated. Therefore the inspection model, which is the organizational component within the three-dimensional generic model (chapter 3.5) is used. Within the inter-organizational inspection model, the theoretical framework of the process model and the closed loop system are combined as described previously. Figure 4.18 shows the schematic diagram of the inspection model adopted regarding the optimization of inter-organizational cold chain management using TTIs as a technical component.

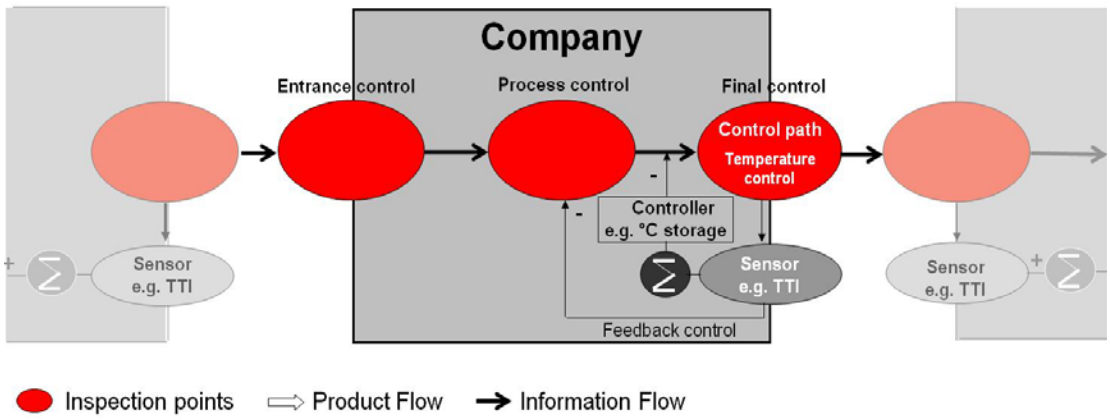

Figure 4.18: Schematic diagram of the inter-organizational inspection model for the case of the implementation of TTIs in the temperature monitoring system of a supply chain (modified after Petersen, 1985)

The inspection model includes as a first step in this example the integration of inter-organizational circumstances within the respective supply chain and, as a second step, the integration of feedback control mechanisms.

According to the defined needed input parameters of the inter-organization inspection model (chapter 3.5), important inspection and decision points within the whole supply chain are determined. At these stages the response of the TTI is measured during this field application of the TTIs. By collecting the response of the TTI at all inspection points, the temperature is controlled over the whole supply chain. Therefore, information about the temperature history is available at each of the inspection points. To gather this data basis, the actual response of the TTI is measured using the spectrophotometer at each inspection point.

For further data preparation, the measured response within the field trial is compared with warning and action control limits, calculated using the TTI kinetic model (Equation 4.7). This provides a data basis for further data preparation regarding comparative, predictive and prescribing information at specific stages of the supply chain. The use of the compiled inter-organizational inspection model for TTIs in combination with the temperature monitoring model was tested at the important inspection and decision points within the field application.

Experimental design to validate the functional component of the three-dimensional generic model using TTIs

As described previously, by collecting the response of the TTI at all inspection points, the temperature is controlled over the whole supply chain. By using the TTI kinetic model, the response of the TTI can be translated to calculate the remaining shelf life of the chicken breast fillet (Equation 4.7). In order to investigate this use of TTIs for shelf life prediction, the discoloration of the TTIs at critical stages within the supply chain is compared with the microbiological status of the chicken breast fillets. Therefore, the samples for microbiological analysis were taken at the same inspection and decision points at which the TTIs were measured (Figure 4.16). The count of *Pseudomonas* sp., as specific spoilage organism (SSO), in the poultry samples was measured at every sampling point. Three samples were taken out of each of the eight boxes at every sample point (altogether 168 poultry samples). The logistic unit of a cardboard box is defined as smallest traceable unit in this field trial. Then, a representative product sample of 25 gram was transferred to a Stomacher-bag. 225 gram chilled saline peptone diluents (0.85 % NaCl with 0.1 % peptone; Oxoid, Basingstoke, United Kingdom) were added and homogenized for 60 s in a Stomacher 400 (Kleinfeld Labortechnik, Gehrden, Germany). Appropriate 10-fold dilution of the homogenate was made with saline peptone diluents. For determination of *Pseudomonas* sp. surface spreading on *Pseudomonas* Agar Base (Oxoid Basingstoke, United Kingdom) plus CFC supplement (Oxoid, Basingstoke, United Kingdom) was used. Petri dishes were aerobe incubated at 25±1°C for 48 h. The spoilage level of *Pseudomonas* sp. for the fresh chicken breast fillet used is defined as 7.5 $\log_{10}$ cfu/g on basis of studies of Bruckner et al., 2009. The level of microbial spoilage was calculated using the Gompertz function (Gibson et al., 1987), which allows a calculation of the remaining shelf life at any assumed average storage temperature using the mathematical approach described in chapter 3.3.3. In all experiments air temperature in the incubators was recorded by the electronic data loggers every 5 minutes.

4.3 Results and discussion

4.3.1 Discoloration of the novel OnVu^{TM} TTI under constant temperatures as a basis for the development of the models

Kreyenschmidt et al. (2010a) have shown that the discoloration process and the charging process of the novel TTI were well reproducible which is mandatory for the application of the TTIs in practice. For the development of the TTI kinetic model, it was necessary to investigate the response of the TTI under constant temperatures. Figure 4.19 shows the discoloration process of the TTIs in dependency of different charging times (*SV* 56.5 – *SV* 59 respectively) at a constant storage temperature of 4°C, which is the legally stipulated maximum storage temperature for chicken breast fillet. The square value was plotted as a function of time.

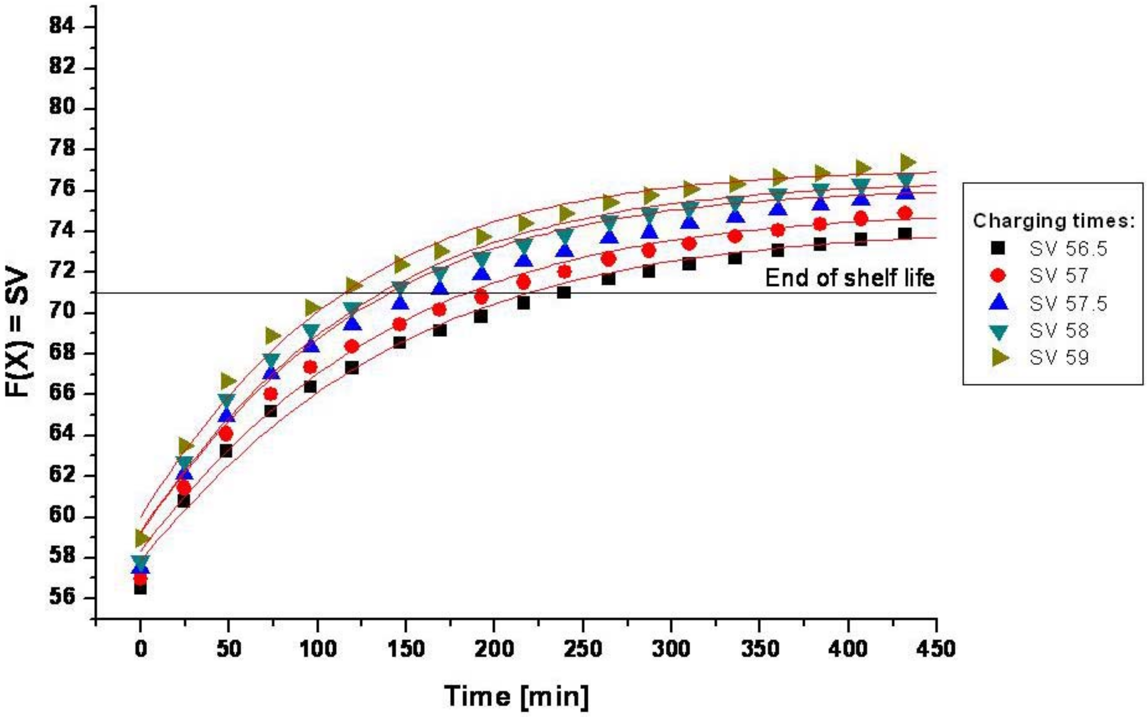

Figure 4.19: Discoloration of the TTI using different ultra violet charging times and stored at 4°C

The discoloration times were converted to log form and fitted by linear regression. On this basis, the TTI adjustment model was developed using the described mathematical approach (chapter 4.2.2). By using the TTI adjustment model an exact calculation of the initial square value of SV_1 = 57.4 and SV_2 = 57.9, which are needed for fresh chicken breast fillet at a storage temperature of 4 °C but different storage times (144 hours, 168 hours), was possible. Figure 4.20 shows the discoloration process of the TTI in dependency of the temperature with an exemplified initial square value of 57.4 (i.e. SV_1 = 57.4).

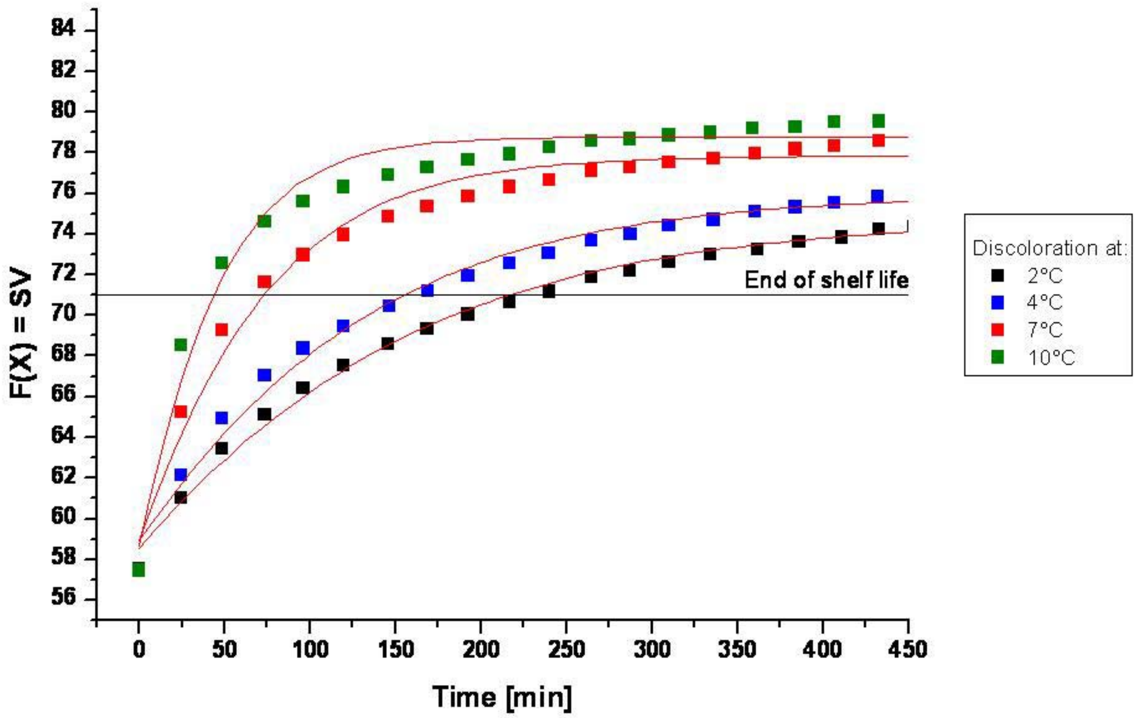

Figure 4.20: Response of the TTI using different ultra violet-charging times stored at different temperatures for an initial square value of *SV* = 57.4

Based on the Arrhenius approach an accurate characterization of the kinetic behavior of the TTI (R^2=0.996). The temperature dependency of the reaction rate constant *k* for different charging times (SV_1 = 57.4 and SV_2 = 57.9) adapted to the respective product under different storage conditions is shown in the Arrhenius plot in Figure 4.21.

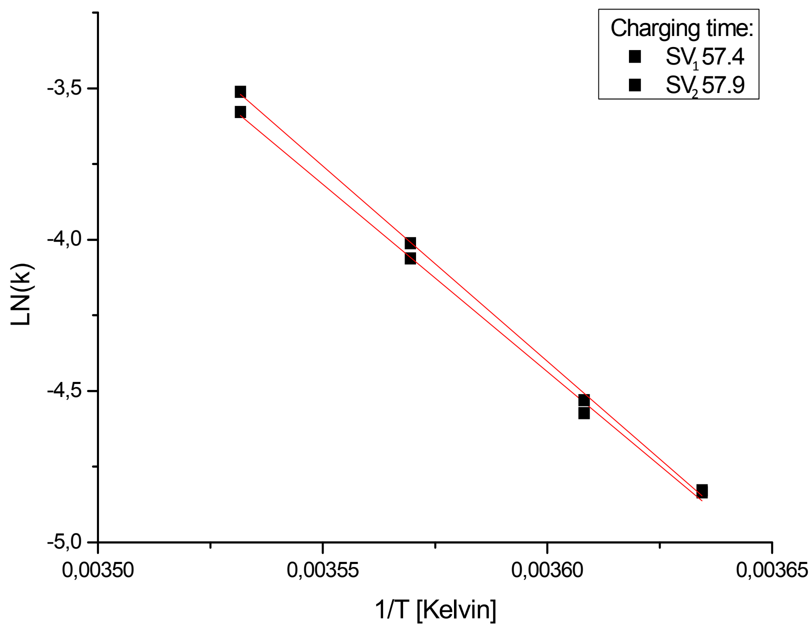

Figure 4.21: Arrhenius plot: Ln of the response rate constant of the OnVu^{TM} time-temperature indicator plotted vs. 1 ⁄ T in K

By using the data from the Arrhenius plot a TTI kinetic model was developed on the basis of the described mathematical steps (chapter 4.2.2). The calculated activation energies for the two charging times were 24.6 and 25.6 kcal mol^{-1}, which is in close agreement to the findings of Kreyenschmidt et al. (2010a). According to Taoukis et al. (1999) the difference between the activation energy of the TTI and of monitored food should be less than 5 kcal mol^{-1}. The activation energies calculated for the TTI response is close to the one calculated for chicken breast fillet spoilage (21 kcal mol^{-1}, Cayré et al., 2003), as found in a previous study and consequently, the requirement for TTI application is met. Through use of the determined TTI kinetic model the discoloration of the TTI under non-isothermal temperature conditions can be predicted. Furthermore, a calculation of the remaining shelf life of the chicken breast fillet is possible.

4.3.2 Validation results of the discoloration process and the TTI kinetic model under non-isothermal temperature conditions

The TTIs were activated with an initial square value of SV_2 = 57.9, which was calculated using the TTI adjustment model. The discoloration time of the TTIs within the non-isothermal and the 4°C control temperature scenario was similar for all TTIs comparing the calculated shelf life time on each side, which is caused by a similar mean temperature within the whole storage time. Comparing the observed response of the TTI with the ones predicted using the TTI kinetic model, there is a nearly perfect agreement, as all observed data points were within a tolerance level of +/-5 % (Figure 4.22). In general, the TTI kinetic model fitted the data well as the R^2 was higher than 0.971 on all sides of cardboard box 1 and higher than 0.968 on all sides of cardboard box 2. The percentage difference in shelf life time of the TTIs in the non-isothermal scenario in comparison with the shelf life time in the control scenario (constant storage temperature of 4°C) was +7.25 %, which is acceptable according to Taoukis et al. (1999).

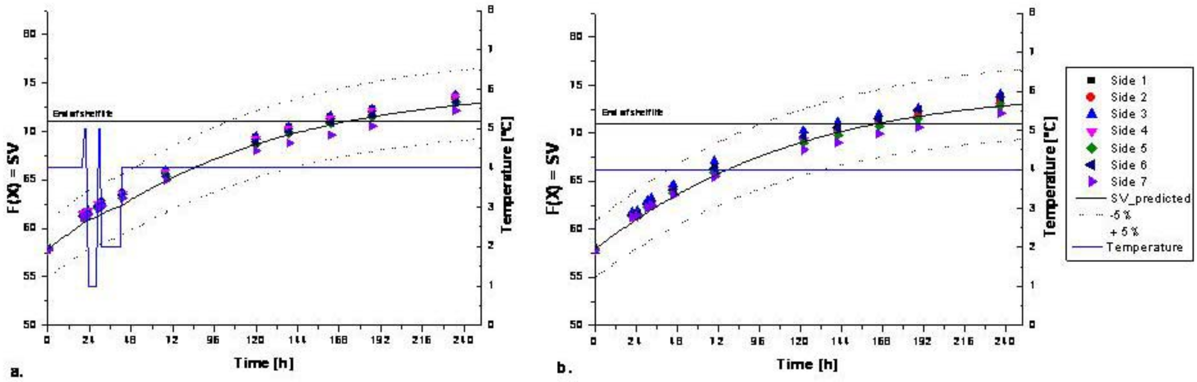

Figure 4.22: Observed (data points) and predicted response of the TTI under non-isothermal temperature conditions at cardboard box 1 (a.) and under isothermal temperature conditions of 4°C at cardboard box 2 (b.)

Regarding the choice of the correct placement of the TTI, it can be concluded that the TTI should be placed on one of the outer sides of the box (side 7), as the response of the TTI inside the box differs from the predicted discoloration using the measured temperature profile within the box. The temperature conditions on all outer sides (side 1 to 6) were similar within this laboratory experiment and therefore no conclusions regarding the best placement on one of the outer sides for TTIs could be made.

Therefore, it can be concluded that the labels reacted properly under temperature fluctuations simulating the temperature conditions in the pilot supply chain in the winter. The comparison of the predicted and measured values for the responses of the TTIs has shown a good level of agreement. Furthermore, the results indicate that the calculated initial *SV* was chosen appropriately because the response in the control scenario was in close agreement to the assumed response.

The successful validation of the TTI kinetic model has confirmed the feasibility of the practical use and the use within three-dimensional generic model.

4.3.3 Field application of the temperature monitoring solution in a poultry supply chain

Activation of TTI labels took place in a cooling room (2 to 5°C environmental temperature) within the slaughterhouse and processing factory, respectively. As described in chapter 4.2.3 the technical validation of the system was investigated as a first step of the field trial. As stated by Kreyenschmidt et al. (2010a) constant environmental temperature conditions during the charging process are mandatory, which were achieved during the field trial. The charging process showed a very low standard deviation as the initial square value at the point of the activation of the labels is 0.03 for a total of 560 TTIs.

Figure 4.23 shows the reproducibility of the initial square value for the activation of different boxes.

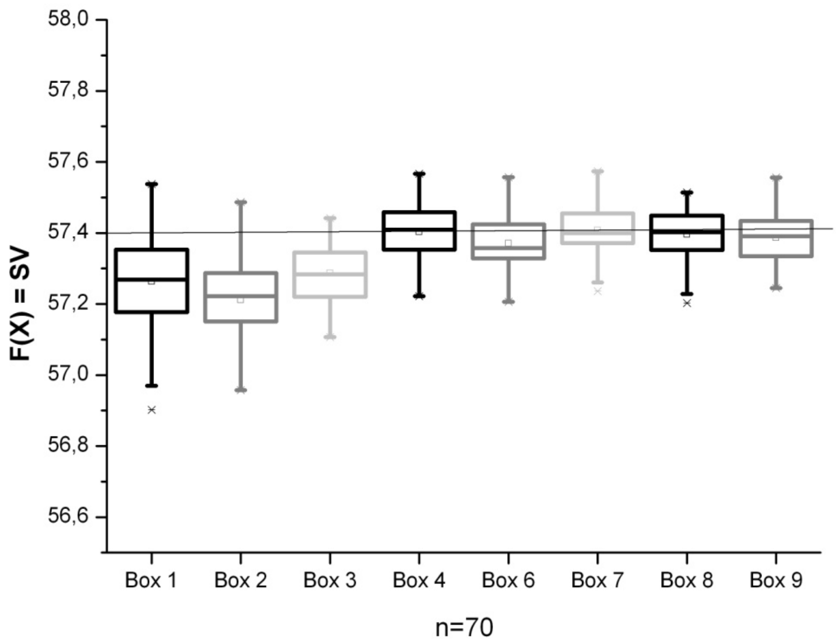

Figure 4.23: Reproducibility of the activation process for different boxes

The results in Figure 4.23 show, that the charging process is highly reproducible under constant environmental temperature conditions within the packaging room. The standard deviations of the square values ranged from 0.06 to 0.87 for different timestamps of the eight cardboard boxes.

Inspection and process control using the inspection model (organizational component)

One requirement for the integration of the TTI kinetic model into the inter-organizational inspection model is a good agreement between the measured response and the predicted response of the TTIs within the field trial.

In Table 4.8 the measured square value after assumed end of shelf life of 168 hours is compared with the predicted square value. Differences in observed and predicted *SV* are shown as percentages.

Table 4.8: Comparison of measured and predicted *SV* using the TTI kinetic model at the end of the assumed shelf life of 168 hours

	Box 1	Box 2	Box 3	Box 4	Box 5	Box 6	Box 7	Box 8
M SV S1	69.45	70.14	70.91	70.93	69.69	70.64	71.60	71.19
P SV S1	-*	70.14 (0 %)	69.93 (- 0.69 %)	70.04 (- 0.63 %)	69.51 (- 0.12 %)	70.43 (- 0.15 %)	70.22 (- 0.98 %)	70.03 (- 0.82 %)
M SV S2	68.83	69.23	69.89	70.44	69.64	70.92	71.70	71.38
P SV S2	70.29 (+ 1.01 %)	70.21 (+ 0.68 %)	69.95 (+ 0.04 %)	70.19 (- 0.17 %)	69.41 (- 0.16 %)	69.72 (- 0.85 %)	70.11 (- 1.14 %)	70.33 (- 0.75 %)
M SV S3	70.15	69.53	69.90	70.55	69.53	70.54	71.41	71.28
P SV S3	70.11 (-0.03 %)	70.18 (+ 0.45 %)	70.05 (+0.10 %)	70.13 (- 0.30 %)	69.41 (- 0.08 %)	-*	70.07 (- 0.96 %)	70.72 (- 0.40 %)
M SV S4	69.77	69.33	70.02	70.43	69.61	70.80	72.05	71.43
P SV S4	70.29 (+ 0.36 %)	70.07 (+ 0.51 %)	69.9 (- 0.08 %)	70.16 (- 0.19 %)	70.06 (+ 0.31 %)	69.76 (- 0.74 %)	70.09 (- 1.41 %)	70.7 (- 0.52 %)
M SV S5	69.89	68.97	69.81	70.28	69.91	70.48	71.53	71.65
P SV S5	70.16 (+ 0.19 %)	70.02 (+ 0.72 %)	69.88 (+ 0.05 %)	70.19 (- 0.07 %)	69.4 (- 0.36 %)	70.38 (- 0.07 %)	70.17 (- 0.97 %)	70.62 (- 0.74 %)
M SV S6	70.03	69.34	70.36	70.62	69.79	70.08	71.21	71.11
P SV S6	70.16 (+ 0.09 %)	70.18 (+ 0.58 %)	70.04 (- 0.22 %)	70.21 (- 0.29 %)	69.43 (- 0.25 %)	70.15 (+ 0.05 %)	70.21 (- 0.71 %)	70.09 (- 0.73 %)
M SV S7	68.11	68.61	69.48	70.25	69.15	70.05	70.79	70.73
P SV S7	68.76 (+ 0.45 %)	70.26 (+ 1.13 %)	69.94 (+ 0.32 %)	69.42 (- 0.58 %)	70.05 (+ 0.62 %)	70.11 (+ 0.04 %)	70.14 (- 0.46 %)	70.74 (+ 0.01 %)

* Temperature data not available - defect of data logger, M SV S: Measured SV at the respective Side S, P SV S: Predicted SV at the respective Side S

The comparison of the measured and predicted *SV* on each side of the boxes after 168 hours has shown a good agreement, as most differences in *SV* estimation were less than 1 % from the measured *SV*. The small differences in *SV* estimation depend not only on the model used but also on the activation energy difference, as well as the use of different batches of the OnVu^{TM} label B1+081126 labels (cardboard box 7 + 8). These results lead to the conclusion that the TTI kinetic model can be used as a valuable tool for temperature control at important decision and inspection points within the respective supply chain.

The TTI kinetic model was used to calculate limits of the square value by taking 4 °C as the reference temperature into account. By using this approach, efficient and effective process control was generated, as the observed square values could be easily monitored at the important inspection and decision points (Figure 4.24).

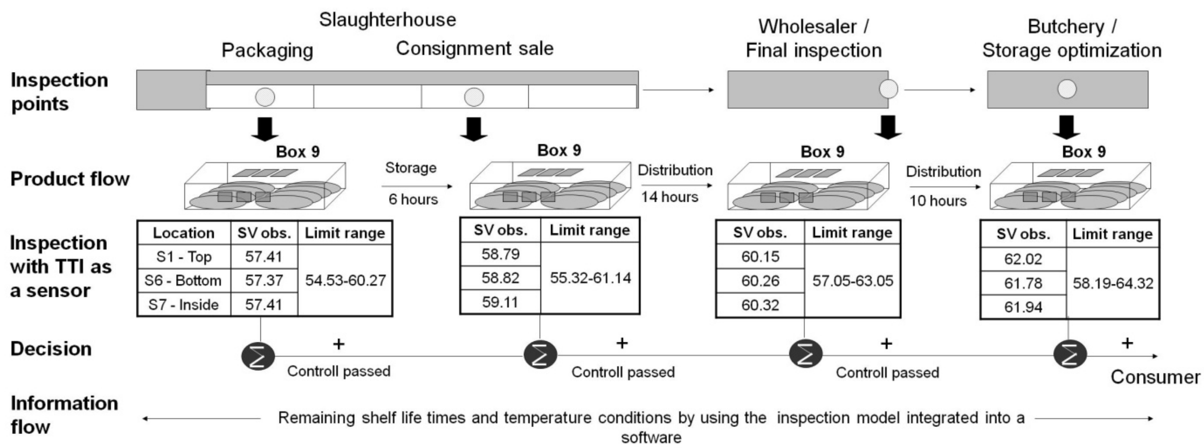

Figure 4.24: Field application of the inspection model using TTIs as sensor at selected inspection and decision points (limit is therefore a +/-5 % tolerance level calculated by using the TTI kinetic model)

Through use of the inspection model, decision making is simplified regarding the control of the temperature maintenance in the upstream stages of the supply chain. In addition, process control as well as a feedback control is facilitated, as further information can be obtained by comparing estimates with values found. Further recommendations can be generated on the basis of the outcome of the inter-organizational inspection scheme, e.g. to lower the temperature during transport and storage.

Prediction of remaining shelf life using the inspection model in combination with the shelf life model (functional component)

In addition to the use of the OnVu^{TM} TTI labels as well as the TTI kinetic model in terms of temperature monitoring and process control, the efficient use of the inter-organizational inspection model for the determination of the remaining shelf life of the products was investigated. Therefore, as a first step, the response of the TTI was translated into remaining shelf life using the TTI kinetic model. In a second step of this part of the study, the predicted response at different stages of the supply chain was compared to the measured response. In a third step, the microbiological shelf life of the chicken breast fillet was compared with the calculated shelf life on the basis of the TTIs.

In the first step, the shelf life times of the TTIs on each side of the boxes were calculated using the TTI kinetic model and the measured temperature profile of the electronic data loggers. Figure 4.25 shows the observed and predicted data points as well as the recorded temperature profile of the top and the bottom of a typical sample cardboard box (cardboard box 6).

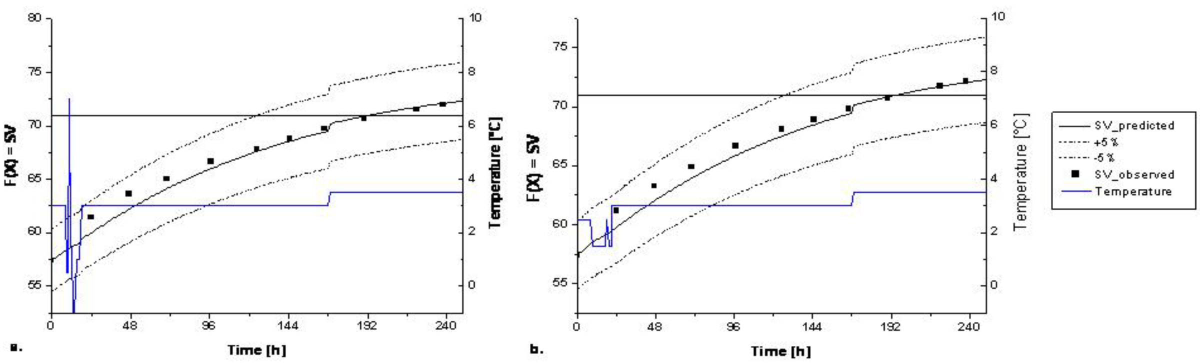

Figure 4.25: Example of observed (data points) and predicted response of the TTI within the field trial at cardboard box 6: a. top of the box, b. bottom of the box

The results indicate a good level of agreement between the predicted and measured response of the TTIs. Thus, the measured response of the TTI can be used as a suitable data basis for the calculation of the remaining shelf life of the chicken breast fillet using the TTI kinetic model.

In a second step, the calculated shelf life times on the basis of the TTIs were compared with the growth of the specific spoilage organism *Pseudomonas* sp. to investigate the reliability of the TTI as a freshness indicator. The observed initial bacterial count (N_0: microbial count at time t=0) of *Pseudomonas* sp. at the beginning of storage for fresh chicken breast fillet varied between 2.2 to 3.9 log_{10} cfu/g. At the end of storage, *Pseudomonas* sp. reached a maximum between 9.2 to 10.2 log_{10} cfu/g which is in agreement with other studies (Bruckner et al., 2010).

Figure 4.26 shows the growth of *Pseudomonas* sp. on poultry in all investigated cardboard boxes fitted with the Gompertz model. The graph shows the typical sigmoid bacterial growth curves.

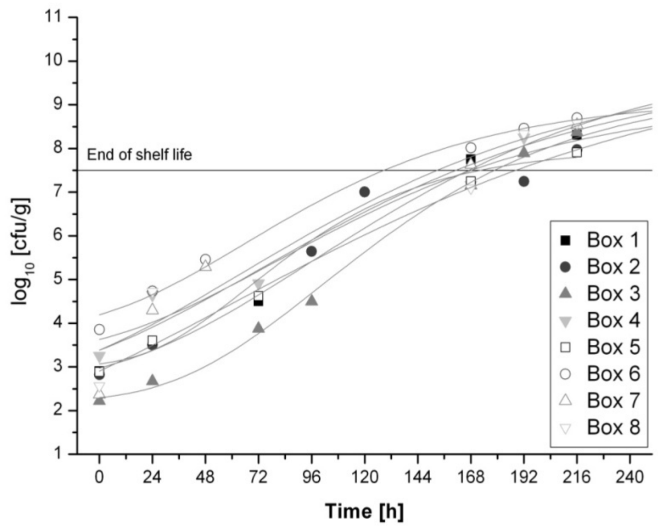

Figure 4.26: Growth of *Pseudomonas* sp. on poultry meat at each cardboard box with the respective fit using the Gompertz model

Calculated shelf life based on the growth of *Pseudomonas* sp., the shortest shelf life calculated was 128 h (box 6) and the longest shelf life was 188 h (box 5). Growth parameters of *Pseudomonas* sp. on fresh chicken breast fillet obtained with the Gompertz model are listed in Table 4.9.

A comparison of the calculated remaining shelf life of the products on the basis of the TTI using the TTI kinetic model and the shelf life on the basis of *Pseudomonas* sp. was conducted. Figure 4.27 shows the observed and predicted response of the TTI at the top and the bottom of cardboard box 2 in comparison to the growth of *Pseudomonas* sp. on poultry meat within this box.

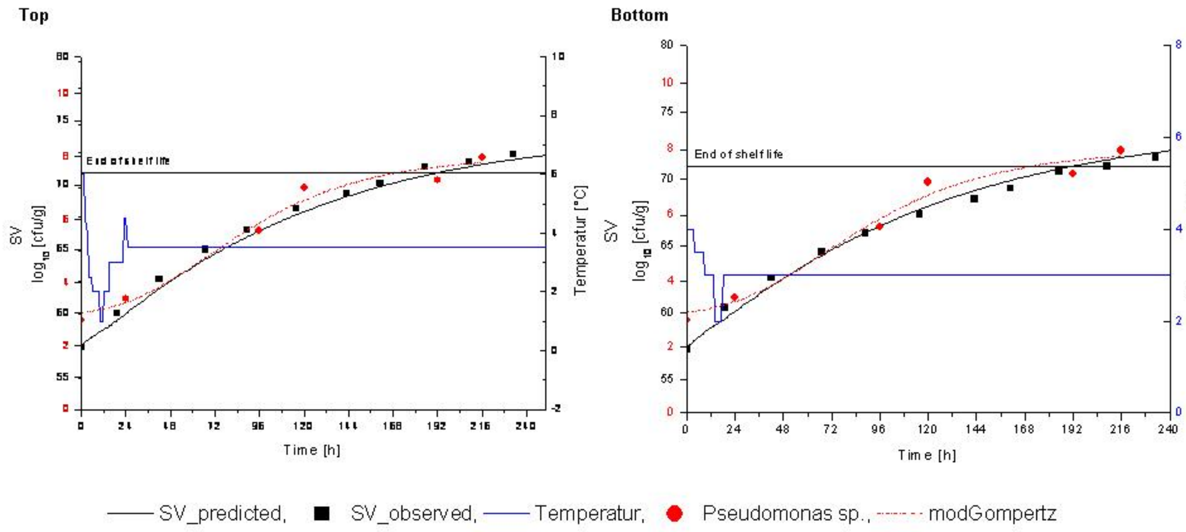

Figure 4.27: Example of the response of the TTI, the predicted response of the TTI and growth of *Pseudomonas* sp. on poultry meat with the respective fit using the Gompertz model (cardboard box 2)

Mean shelf life evaluated by *Pseudomonas* sp. in all boxes was calculated as 165 hours, which is in close agreement with the assumed shelf life of 168 hours determined in previous studies (Raab et al., 2008), which corresponds to the shelf life that is given by the producer. The predicted shelf life times using the TTI kinetic model and the measured shelf life times of the TTIs differ in general less than 20%. As previously stated, Taoukis et al. (1999) noted that ranges of less than +/-20% differences are acceptable in practice. Just at cardboard box 8 the difference is higher at all sides as the measured shelf life time due to a slightly higher initial square value. In general, by taking into account the ranges provided by Taoukis et al. (1999), smaller differences were evaluated in this study (top: seven boxes are in range, bottom: six boxes are in range).

Despite this, the predicted shelf life times on the basis of the TTIs and the microbiological investigations differ with most of the boxes by less than 24 hours (Table 4.9).

Table 4.9: Parameters obtained from the Gompertz model for the different cardboard boxes

	N_0 [log$_{10}$ cfu/g]	N_{max} [log$_{10}$ cfu/g]	μ_{max} [1/h]	R^2	Shelf life evaluated by *Pseudomonas* sp. [h]		Shelf life evaluated observed TTI response [h]	Mean product temperature until end of shelf life [°C]
					Top	Bottom		
Box 1	2,60	10,17	0,03	0,99	166,95	198,20	184,90	3,05 +/- 0,55
Box 2	3,00	8,00	0,04	0,97	172,80	180,50	201,00	3,37 +/- 0,40
Box 3	2,22	9,40	0,04	0,99	178,64	175,80	188,70	3,10 +/- 0,51
Box 4	3,26	9,16	0,03	0,95	168,19	168,80	172,90	3,01 +/- 0,63
Box 5	1,20	10,20	0,03	0,97	188,36	197,70	195,00	2,89 +/- 0,69
Box 6	3,86	9,15	0,03	0,99	128,72	170,80	187,60	3,33 +/- 0,36
Box 7	2,37	9,87	0,03	0,94	152,79	144,30	150,90	3,56 +/- 0,25
Box 8	2,56	9,80	0,03	0,91	161,32	156,50	158,10	3,00 +/- 0,26

N_0 = initial bacterial count, N_{max} = maximum population level, μ_{max} = maximum growth rate

The TTI prediction slightly overestimates the remaining shelf life, evaluated on basis of the growth of *Pseudomonas* sp. According to various authors, an overestimation is critical as risks in quality and safety occur (Labuza and Fu, 1995; Giannakourou et al., 2005). However, the overestimation at box 1 and 2 can be explained by a slower discoloration of the TTIs due to slightly lower initial square values (box 1: SV_1 = 57.29, box 2: SV_1 = 57.24). Furthermore, the short microbiological shelf life at cardboard box 6 can be explained due to a higher initial bacterial count of *Pseudomonas* sp. The results show varying initial bacterial counts between 1.20 $\log_{10}$ cfu/g and 3.86 $\log_{10}$ cfu/g. Such varying bacterial counts have an effect on the remaining shelf life of the products (Kampmann, 2010; Bruckner, 2010). This could explain the difference in shelf life time evaluated on the basis of *Pseudomonas* sp. and on the basis of the discoloration of the TTI. This leads to the conclusion that the TTI can only be used as quality indicators if the process is well controlled and product stability analysis shows minimal fluctuations in the initial quality of the products (Labuza and Fu, 1995). It also leads to the conclusion that a shelf life determination is generally possible, however a number of requirements must be secured prior to the use at company as well as on chain level.

4.4 Conclusion and future prospects

The field application of TTIs including a validated TTI kinetic model within a poultry supply chain showed that the TTI is a potentially valuable management tool. However, different technical, functional, and organizational requirements have to be assured prior to its integration within the supply chain. The study has shown that the TTIs, as well as the TTI kinetic model, are a useable and useful tool for temperature monitoring during process and for the prediction of the remaining shelf life in different stages of the supply chain. By integrating the TTI kinetic model into the framework “Inspection model”, comparative and predictive information could be prepared at important inspection and decision points within the supply chain. As the integrated theoretical framework of the process model is limited to the view on the supply chain, an extension by using the netchain model will necessitate including netchain-wide quality information management under complex conditions (Schulze Althoff et al., 2005).

The integration of this approach within a user-friendly software tool may facilitate its practical use in poultry supply chains (Dalgaard, 2002; Nuin et al., 2008). A developed “Web2.0 based software solution” is proposed by Raab et al. (2010) and described in detail by Raab et al. (2011) as well as Ibald et al. (2011). Additionally, the connection with a logistic planning system, a data warehouse or predictive microbiology application software will provide further benefits for each actor (McMeekin et al., 2006). These connections point out the complexity of optimizing cold chain management using innovative temperature monitoring systems. In addition, the study has shown that novel temperature monitoring systems feature several key improvement possibilities regarding optimization of cold chain management.

Once a full temperature history along the supply chain has been collected using TTIs, or other novel solutions, the efficient inter-organizational information management of the collected temperature data is a matter of high importance (Giannakourou et al., 2001; Koutsoumanis, 2001; Koutsoumanis et al., 2002; Koutsoumanis et al., 2006; Ólafsdóttir et al., 2010). As described in chapter 2.4.1, important issues are the linking of the product characteristics with temperature data and the interpretation of such data. Within this study, this functional challenge was met by using the developed approach of the integrated approach for optimization of cold chains. Taking into account different requirements, e.g. consistent initial quality of the products, prediction of remaining shelf life at important inspection and decision points is generally possible. However, it has to be put into perspective that a high level of accuracy and reliability in the discoloration of the TTIs is needed (Labuza et al., 2003). In this study, the calculation of remaining shelf life times on the basis of TTIs was always within an acceptable range but higher accuracy is probably needed regarding the requirements of the actors in the supply chains.

Taking into account these criteria, actors can be supported in finding the most efficient temperature monitoring solution optimizing their cold chain management. Such an assessment has to take into account the specific organizational structures and technical and functional needs on company as well as on chain level.

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5 A concept to assess temperature monitoring systems supporting the technology selection process of chain actors in cold supply chains

5.1 Introduction

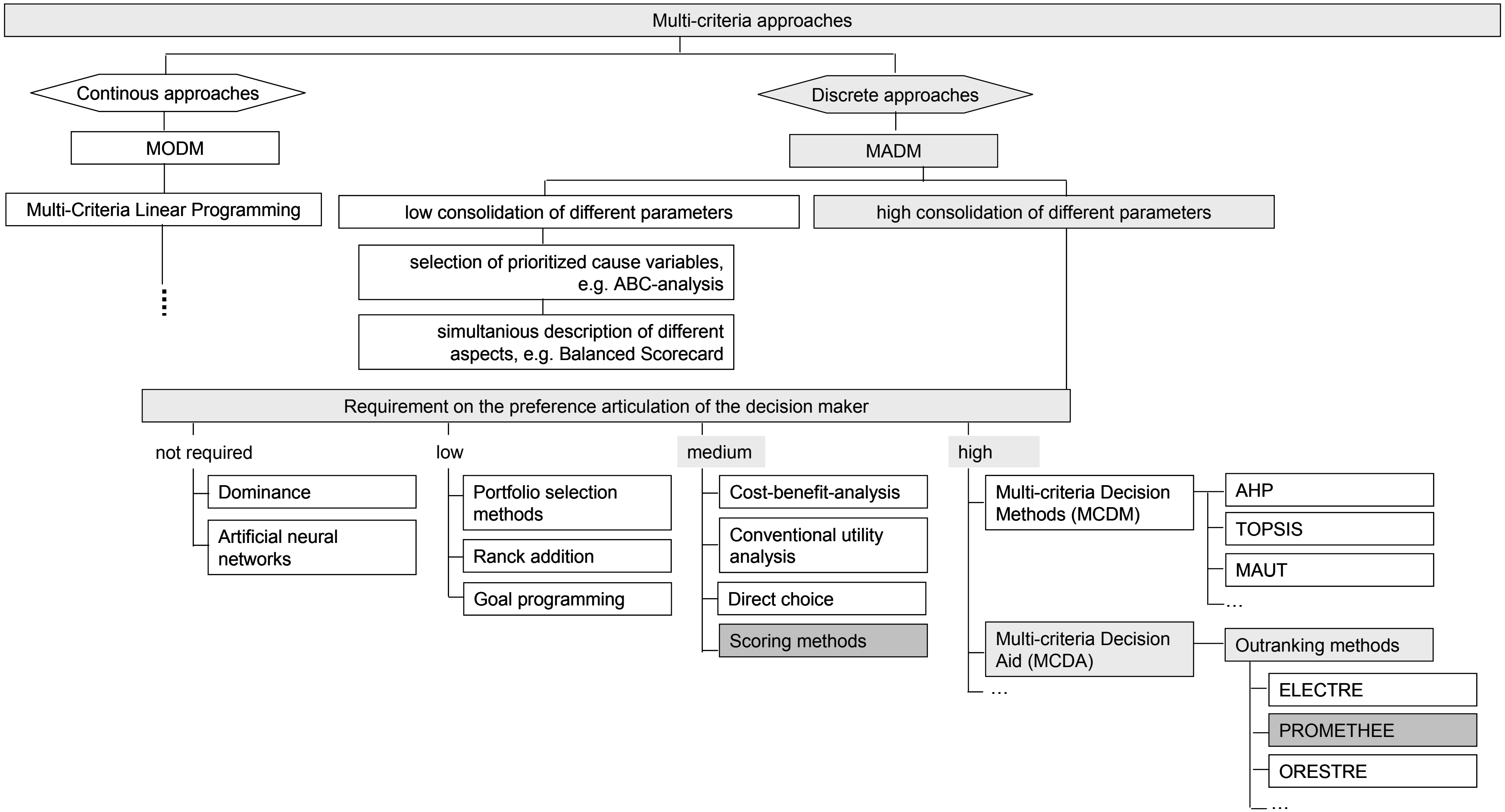
In recent years agri-food companies have shown an increasing interest in improving their overall cold chain management performance. One of the key issues in this process is the optimization of intra- as well as inter-organizational temperature monitoring (Chapter 2). This requires elaborate quality and information systems as well as information links with suppliers and buyers in order to reduce waste and costs and to avoid quality related complaints (Chapter 3). Several authors point out that collaboration at an inter-organizational level yields a competitive advantage for companies and increases the overall performance of a supply chain (Spekman et al. 1998; Christopher, 2002; Akkermans et al., 2003; Petersen, 2003; Bovenschulte et al., 2007; Petersen et al., 2007; Estrada-Flores and Tanner, 2008). The improvement of inter-organizational cold chain management through the use of innovative temperature monitoring systems requires not only a technical but rather an organizational and functional view (as is explained in chapter 3.5).

One important decision problem for chain actors within the improvement process is to decide upon the best system to suit their individual supply chain from amongst several possible temperature monitoring alternatives. As described in chapter 2.3, on the one hand a huge variety of temperature monitoring solutions exist on the market. On the other hand, meat supply chains can be seen as heterogeneous; and complex customer-supplier-relationships exist in agri-food networks. Thus, finding the most appropriate solution for a particular situation is non-trivial due to the huge variety of alternatives and a finite number of criteria. Additionally, the criteria may demand partially conflicting system functionalities with varying degrees of importance and there may be of different degrees of preference for the decision makers.

The aim of this chapter is to present a user-oriented concept of how to assess different temperature monitoring solutions. Within the assessment, various system functionalities of temperature monitoring solutions are examined regarding their potential to improve cold chain management. Therefore, the concept should take organizational, functional and technical requirements from the perspectives of the users into consideration. The assessment tool should support the decision process finding the best temperature monitoring solution within specific application scenarios.

5.2 Theoretical framework

In recent decades several multi-criteria methods and tools have been developed supporting assessment and ranking processes (Vincke, 1986; Behzadian et al., 2010). The proposed methods vary regarding the outline of the model (e.g. linear, non-linear, stochastic), the characteristics of the decision space (e.g. finite or infinite) or the solution process (e.g. prior specification of preferences or interactive) (Vincke, 1986; Kahraman, 2008). Multi-criteria methods are generally divided into Multi Attribute Decision Making (MADM) for discrete problems and Multi Objective Decision Making (MODM) for continuous problems (Zimmermann and Gutsche, 1991; Stewart, 1992; Figueira et al., 2005; Geldermann, 2005). Figure 5.28 gives an overview of multi-criteria methods.



chosen methods for the assessment concept. accompanying class of the chosen methods

MODM: Multi Objective Decision Making, MADM: Multi Attribute Decision Making, MAUT: Multi-attribute utility method, PROMETHEE: preference ranking organization method for enrichment evaluation, ELECTRE: Elimination et Choix Traduisant la Realité, TOPSIS: Technique for Order Performance by Similarity to Ideal Solution, ORESTRE: Organization, Rangement Et Synthese De Donnes Relationnelles, AHP: Analytic Hierarchy Process

Figure 5.28: Categorization of multi-criteria approaches (modified after Roy, 1991; Dyer et al. 1992; Schuh, 2001; Geldermann, 2005)

Within each group of methods a huge variety of approaches exists. The MADM approaches can be categorized according to the priorities of the decision maker. Detailed descriptions of the categorized methods are given by Siskos et al., 1984; Steuer, 1986; Vincke, 1986; Roy, 1990; Keeny and Raiffa, 1993; Roy and Vanderpooten, 1996; Martel, 1999; Figueira et al., 2005 and others.

In the area of agricultural science several authors have proposed approaches to support decision processes in food supply chains (Table 5.10). A quantitative approach of Schulze Althoff (2006) permits a decision, based on planning steps for inter-organizational information management in supply chains and networks (Schulze Althoff et al., 2005; Schulze Althoff, 2006). Mack (2007), Ellebrecht (2008) and Schütz (2009) propose different approaches, in which planning steps are combined with different multi-criteria methods, e.g. portfolio selection methods, utility methods and newly developed scoring methods for decision making in complex situations in information management, risk and preventive health management in agri-food chains.

These methods of the aforementioned authors were based on an approach by Petersen (1985). She examined decision theory (Bühlmann et al. 1975; Bamberg und Coenenberg, 1981; Raiffa, 1973) to solve multi-criteria decision problems in the preventive health management context. Petersen (1985) also combined the approaches of decision theory on the basis of the theorem of Bernoulli with the theoretical information management concept of Shannon (1948) to rank information gain. Strotmann (1989) used both approaches for decision making situations regarding the choice of the best fitting predictive health management system.

An extension of these approaches in cold chain management requires the further specification of the role of each individual criterion. According to Fülöp (2005), Multi-Criteria Decision Aid methods (MCDA) permit such extensions and involve the making of decisions under conflicting objectives. These methods consider a finite number of criteria and alternatives under the assumption that the alternatives are explicitly determined.

MCDA methods or even outranking methods are based on the assumption of uncertainties during the decision making process. As the decision makers may not be fully aware of their preferences, the outranking methods should support the decision maker by showing the consequences of the choice using different weights for individual criteria (Geldermann, 2005). Therefore MCDA approaches focus on the decision making process itself and the modelling of the decision maker’s preference. In contrast, MCDM (Multi-Criteria Decision Making) methods focus on finding a solution to a multi-objective optimization problem and consists in representing preferences by means of a utility function (functional modelling) (Siskos et al., 1984; Roy, 1990).

Outranking methods are based on the principle that one alternative may have a degree of dominance over another due to comparison of the performance of alternatives and the identification of the extent to which a preference for one over the other can be asserted (Linkov et al., 2006; Linkov et al., 2007). By using different methods pair-wise comparison of alternatives or a ranking of alternatives is possible due to the aggregation of the preference information across all relevant criteria and attempting to seek to establish the strength of evidence favoring one alternative over another (Linkov et al., 2007).

Well known methods in this area are PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation) and ELECTRE (Elimination et Choix Traduisant la Realité) (Buffet et al., 1967; Roy, 1968; Brans et al., 1986; Vincke, 1986; Brans and Mareschal, 1994; Roy, 1996; De Boer et al., 1998; Vincke, 1999; Araz et al., 2006). Within this framework, the PROMETHEE method has been proposed as an outranking method. Several authors propose modelling options and at least two model levels (first and second level models) which must be chosen before PROMETHEE can be implemented on any raw data matrix (Guitoni and Martel, 1998; Bouyssou et al., 2002; Rousis et al., 2008). In particular, Rousis et al. (2008) describe in detail the steps which have to be taken into account by using PROMETHEE, following the mathematical approach of Brans et al. (1986).

PROMETHEE allows the choice of an appropriate preference function and the weight given to each variable. By using PROMETHEE a finite number of alternatives can be ranked in view of several, partially conflicting criteria (Rousis et al., 2008). The preference function defines how one object is ranked in relation to another and translates the deviation between the evaluations of two samples on a single parameter into a preference degree. The preference degree represents an increasing function of the deviation; hence smaller deviations will contribute to weaker degrees of preference and larger ones to stronger degrees of preference (Lahdelma et al., 2000; Higgs, 2006). The calculation of outranking flows (positive and negative) leads to the possibility of ranking a finite number of temperature monitoring alternatives (Brans and Mareschall, 1994). In combination with GAIA (Geometrical Analysis for Interactive Assistance), PROMETHEE allows a graphical representation of up to five dimensions. In the last decades several software packages have been developed facilitating the PROMETHEE process like PROMCALC (Brans and Mareschal, 1986), DECISION LAB (Visual Decision, Canada, Version 1999, Version 2000) and D-Sights (Decision Sights, Universite Libre de Bruxelles, Belgium, Version 2009 - 2011).

Table 5.10: Overview of selected Multi-criteria approaches

Ranking value	Application fields	Elements of the approach	No. of assess-ment criteria	Scoring system	Authors
Information gain $I_{B,T} = \sum_{i=1}^{m}\sum_{j=1}^{m} P(R_i,T_i) x \log_2 \frac{P(R_i,T_j)}{P(R_i) x P(T_j)}$ $I_{B,T}$ = mutual information, *T* = Test result, *R*= Risk regarding the decision	Ranking of test strategies	■ Methods of decision theory • Decision tree models • Probability calculation • Shannon model	5	0-1	Petersen (1985), Strotmann (1989)
Ambition steps	Ranking of information and communication systems	• Process model • Netchain model • Closed-loop-system • Scoring model (quantitative)	3	Low, medium, high (qualitative)	Schulze Althoff (2006)
Service indices $DI = dk * di = \left[\frac{f(a+d)}{f\max(a\max + d\max)} * \frac{h * m}{h\max * m\max}\right] * 100$ *di* = service intensity, *dk* = service complexity, *a* = audit typ combination, *d* = document type documentation, *m* = quantity of service users / per year, *f* = function combination, *h* = audit quantity per service user / per year	Ranking of service strategies	• Conventional portfolio selection technique ■ Scoring model	7	1-4, 2-8, 50-300	Mack (2007)
$NI_{tec} = \frac{(ZG + ZE + IZ)}{3}$, $NI_{org} = \frac{(GB + GIR + GNE)}{3}$ *GB* = Degree of willingness to exchange information, *GIR* = degree of traceability, *GNE* = Degree of utility, *ZG* = Gain in time, *ZE* = Time frame for decision, *IZ* = Growth in information	Ranking of technology functionalities of service organizations	• Modern Portfolio selection technique • Conventional Utility analysis ■ Scoring model	100	0-100	Schütz (2009)

Ranking value	Application fields	Elements of the approach	No. of assess-ment criteria	Scoring system	Authors
User-specific utility indices $$\frac{ZG(1+\Delta d)xIZx\ddot{U}G}{ZE(d)}$$ *ZG* = Gain in time, *ZE* = Time frame for decision, *IZ* = Growth in information	Ranking of specific technical functionalities and communication systems	• Conventional Utility analysis ☐ Scoring model	4	0-100	Ellebrecht (2008)
Outranking flows Positive outranking flow: $\phi^{+}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(a, x)$ Negative outranking flow: $\phi^{-}(a) = \frac{1}{n-1} \sum_{x \in A} \pi(x, a)$ Partial ranking: $\begin{cases} a P^{I} b \text{ iff } \begin{cases} a S^{+} b \text{ and } a S^{-} b, \\ a S^{+} b \text{ and } a I^{-} b, \\ a I^{+} b \text{ and } a S^{-} b, \end{cases} \\ a I^{I} b \text{ iff } a I^{+} b \text{ and } a I^{-} b, \\ a R b \text{ otherwise.} \end{cases}$ Complete ranking: $\begin{cases} a P^{II} b \text{ iff } \phi(a) > \phi(b), \\ a I^{II} b \text{ iff } \phi(a) = \phi(b). \end{cases}$ *a* is a set of n possible decisions or alternatives which are evaluated through k criteria f , , . . . , fk.	Outranking of a finite set of alternative actions to be ranked and selected among weighted criteria, which are often conflicting	☐ PROMETHEE I* (partial ranking) ☐ PROMETHEE II (complete ranking) • PROMETHEE GDSS*** • (group decision making) • PROMETHEE TRI (sorting problems) • PROMETHEE CLUSTER (nominal classification) ☐ GAIA** (Graphical visualization)	Finite	Various	Brans, 1982; Brans and Mareschal 1992; Mareschal & Brans, 1986; Brans and Mareschal, 1994; Brans and Mareschal, 2005; Figueira et al., 2004;Rousis et al., (2008)

* PROMETHEE: Preference Ranking Organization Method for Enrichment Evaluation, ** GAIA: Geometrical Analysis for Interactive Assistance, ***GDSS: Group Decision Support; ☐ Chosen methods within the assessment concept

5.3 Research design

In order to develop an assessment concept, several research studies have been conducted to determine the elements of the concept and to gather the required data input for each individual element.

In order to form the phases, steps and elements of the assessment concept, a total of ten temperature mappings have been performed. The mappings involved different data loggers, six field trials with Time-Temperature-Indicators (TTIs), two field trials with RFIDs with a temperature sensor, conduct in national, international and global poultry, fish, pork, beef and cooked ham supply chains (Table A-16). One selected temperature mapping and one selected field trial are described in chapter 3.4.2 and 4.3.3. The focus of the research studies was based on the determination of assessment criteria and the weighting of the criteria to assess temperature monitoring technologies (Table 5.12). Further on, detailed knowledge could be gathered as to the exact needs for different application scenarios (Table 5.15). The knowledge regarding needed system functionalities and as to needed decision support could be complemented due to gathered technical expertise in meetings with system developers. Table 5.11 gives an overview about the determination of key improvement functionalities for the assessment of temperature monitoring technologies in different research studies.

Table 5.11: Determination of key functionalities for the assessment of temperature monitoring technologies in different research studies

Type of supply chain	Supply Chain characteristics	Conducted trials	Key improvement functionalities		
			Organizational	Technical	Functional
National poultry supply chain	• Strong customer-supplier-relationships • High level of transparency • 1 Network coordinator (medium sized company) • Minimum 2 other chain actors (Wholesaler / Butcher's shops) • Innovative company • Own distribution network	• 2 Temperature mappings (Inv. of summer and winter conditions • 4 Field trials with TTIs • 1 Field trial of with Tracechill-System of the EU-project Chill-On	• Intra-organizational investigation of weak points, placement of the devices within processing and storage rooms • Inter-organizational investigation of weak points, temperature fluctuations through door openings • Inter-organizational information exchange through strong customer-supplier-relationships possible • Temp. mon. on netchain domain possible	• Easy-to-handle temperature monitoring solutions • Easy integration into the available system architecture • Digital data + descriptive information are needed • Temp. mon. on pallet level due to temperature fluctuations within the truck • Short measuring intervals needed due to temp. fluctuations in summer • Temperature mon. on single product level only by very cheap devices / chicken breast filet • Potential advantage: TTIs on single product level as chicken breast is a highly perishable product with short shelf life • High service provision needed due to small QM/IT-department	• Draw back conclusions on the shelf life of the meat • High quality ambitions • Avoidance of temperature abuses during summer • Return system of cost-intensive devices possible • Legal obligations • Training of staff members in questions of temperature monitoring and CCM
National sliced ham* and pork supply chain	• Strong customer-supplier-relationships • High requirements due to delivery to the huge retailers • 1 Network coordinator (large processing company) • Min. 5 other chain actors (Logistic companies, Gathering center, Retailers / Discounters) • External distribution	• 1 Temperature mapping • 1 Field trial with TTIs • 1 Field trial with RFIDs with temp. sensor	• Less intra-organizational tasks • Inter-organizational complexity through several un-/reloading and inter-mediate storage within a cold store • Temp. mon. on netchain domain is limited possible	• Integration of complex solutions is possible • Digital + predictive information due to long shelf life of the goods and selling to a discounter • High memory size by measuring on pallet / single level due to long supply chain / shelf life and un-/reloading of the goods • Partially external sensors are needed (e.g. monitoring of product temp. of pork halves)	• Return system of cost-intensive devices difficult • Legal obligations

Type of supply chain	Supply Chain characteristics	Conducted trials	Key improvement functionalities		
			Organizational	Technical	Functional
International beef* and fish** supply chain	• Less strong customer-supplier-relationships • Low level of transparency • 1 Network coordinator • Min. 4 other chain actors (Logistic companies, Gathering Center, Retailers) • Long distribution way • Less door opening phases	• 1 Field trial with TTIs incl. temp. mapping / beef supply chain • 1 Field trial with TTIs incl. temp. mapping / fish supply chain	• Focus on Inter-organizational investigation of weak points, temperature fluctuations through door openings • Temp. mon. until the next stage in the supply chain possible • Less inter-organizational information exchange possible	• Easy-to-handle temperature monitoring solutions • Easy integration into the available system architecture • Digital data + descriptive information are needed • Temp. mon. on truck or pallet level to monitor if temperature abuse takes place • TTIs on single product level for the consumer due to high price / high perishable product • High service provision needed	• Draw back conclusions on the shelf life of the meat • Legal obligations
International poultry supply chain (East Europe to North Europe)	• Strong customer-supplier relationships • Strong market requirements due to selling to powerful retailer • 1 Network coordinator (processing company) • Min. 3 other chain actors (slaughterhouse, logistic company, retailer) • Long distribution way • One transhipment	• 1 Temperature mapping	• Intra-organizational: focus on securing low initial product temperature • Inter-organizational: Temp. is generally secured during transport, monitoring of unforeseen temp. abuse, intensive monitoring at point of transhipment • Inter-organizational information exchange required by network coordinator	• High requirements on maintenance of very low temp. and accuracy of the devices • Digital data + comparative information are needed • Real-time information will allow foresighted planning of further processing • Temp. mon. on pallet / E1 box level needed to monitor transhipment • Less service provision needed	• High requirements on CCM due to selling of the goods to a huge retailer • Quality and CCM Requirements above legal obligations
Global poultry supply chain (South America to Europe)	• Strong customer-supplier relationships • Strong market requirements • 1 Network coordinator (processing company) • Min. 3 other chain actors (slaughterhouse, logistic company, retailer) • Transcontinental shipment	• 1 Temperature mapping (frozen goods)	• Intra-organizational focus on monitoring transover points due to high environmental temp. conditions • Inter-organizational focus on monitoring of reloading at the harbour and several weeks shipment	• Predictive information is a prerequisite to predict the quality and the shelf life at the final harbour • Real-time alerts are necessary due to long shipment of the goods • Monitoring at different places within the container is needed due different intensive solar radiation at each side of the container	• High requirements on CCM due to selling of the goods to a huge retailer • Quality and CCM Requirements above legal obligations

* no personal participation / involvement in research design, planning and data evaluation, ** Personal support of the pilot activity of a project partner

5.4 Phases, steps and elements of the concept

The phases and steps of the assessment concept result from the number of modelling options which must be chosen before the PROMETHEE method can be implemented on any raw data matrix as it is proposed by several authors (chapter 5.2). Taking into account the proposed requirements for using PROMETHEE, the modelling steps should include two levels: First level models have to be chosen for the application of PROMETHEE within a specific research area, which aim at capturing aspects which reflect the worth or value of elements represented in the model of alternatives. Hanne (1998) and Vanderpooten (2002) state that the choice of the best fitting models within the respective application area is the most “delicate” matter. Therefore within this framework, a validated model in the area of cold chain management and a scoring model are chosen for the construction and scoring of the criteria which are relevant for the assessment of temperature monitoring solutions. The second level model “PROMETHEE” is used as multiple criteria, defined at the first level, must be aggregated in order to model overall preferences, taking into account the relative importance of the criteria.

According to this, the assessment concept for temperature monitoring solutions (Multi-Criteria Decision Aid Method for the optimization of Cold Chain Management (MCDA-CCM)) is divided into two phases: “CCM Requirement Creation” as well as “Assessment and Decision” (Figure 5.29). Within the phase “CCM Requirement Creation” two steps are defined, in which assessment criteria of temperature monitoring technologies are determined and scored, according to their importance. In the second phase “Assessment and Decision”, both steps include modelling processes of the PROMETHEE method with the aim of ranking the proposed temperature monitoring alternatives.

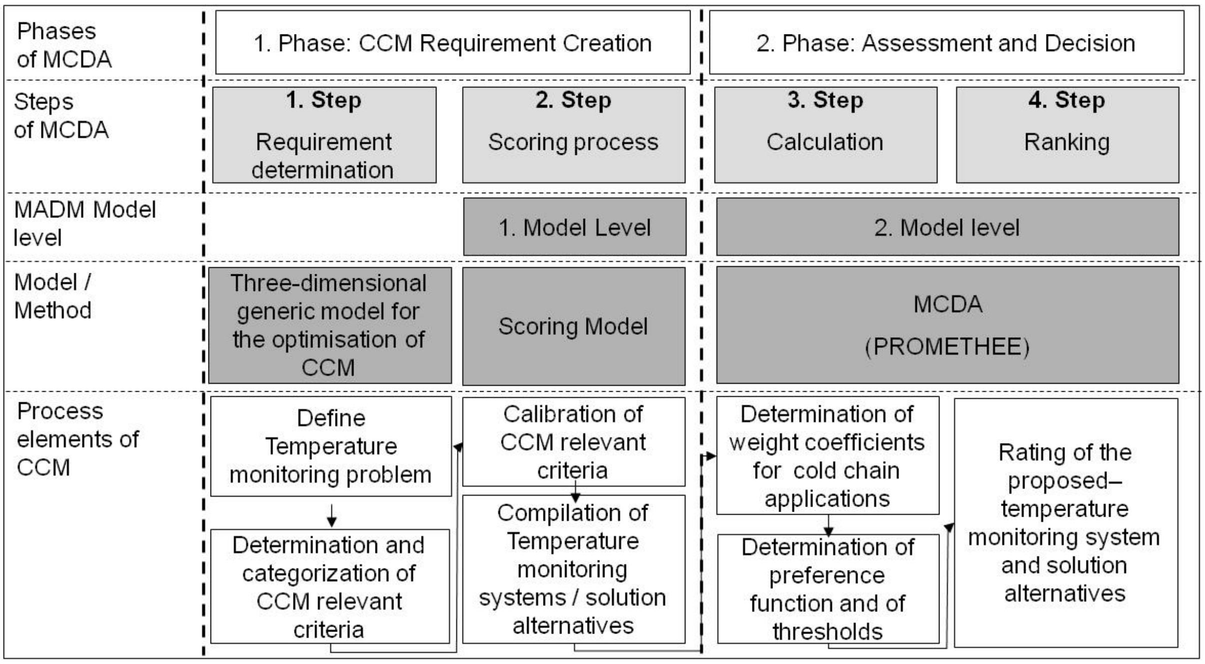


Figure 5.29: Matrix structure of the assessment concept (MCDA-CCM) of temperature monitoring solutions improving cold chain management

Step 1: Requirement determination

In the past mainly the technical requirements were taken into consideration within the assessment of temperature monitoring solutions supporting intra- as well as inter-organizational information management. But taking into account the discipline of information management, several authors have proposed recently that efficient integration of such solutions requires interdisciplinary approaches - including an organizational, a functional and a technical dimension (chapter 3.2). Requirements regarding the use of temperature monitoring solutions can be structured into these three dimensions (chapter 3.5).

In order to proceed with the successful selection of temperature monitoring solutions, it is essential to establish and examine an adequate number of criteria that will give a representative and complete picture of alternative system functionalities divided into the three dimensions. Taking the definition of these classifications into consideration, the criteria of system functionalities of temperature monitoring solutions have been categorized.

In relation to the improvement of cold chain management, 14 individual criteria have been selected in total, categorized in the three dimensions:

Technical dimension:

T1 Measuring unit. Examination of the application level of potential temperature monitoring according to the logistic unit. The smaller the logistic unit, the higher the transparency but also the cost and the amount of data. For example, monitoring on single unit level make sense regarding high price goods and/or by using a very cheap device such as TTIs.

T2 Memory size. The specific memory size of a device varies whether it is a stationary or a moveable device. The memory size is in particularly important for temperature monitoring of long supply chains and of very critical supply chains, e.g. in ground meat supply chains where short measuring intervals are needed.

T3 Measuring accuracy. Measuring accuracy depends on regulatory obligations governing specific application scenarios. For this reason this aspect is a very sensitive criterion for the evaluation of the alternative–proposed temperature monitoring systems.

T4 Reading possibilities. The reading possibilities of a device influence how time consuming this process is for staff members. Particular attention is paid to time critical processes which make a real-time reading of the temperature data necessary, e.g. requires wireless reading and GPRS data transfer. This leads eventually to higher costs due to complex integration issues and roaming fees.

T5 Data format / preparation. The improvement of data collection and preparation at important steps of the cold chain is a very important issue within the assessment. If digital data are provided by a system, further data enhancement in the sense of descriptive, prescriptive, predictive and comparative information is possible.

T6 Maintenance of the system. System developers bring various updates and expansion options for software and hardware components in ever-shorter intervals to the market. Easy maintenance of an installed system with predictable cost and a realistic life-span is therefore necessary.

T7 Service provision. Some temperature monitoring systems require high service provision regarding the installation and use of the system. In particular RFID projects need intensive support e.g. the reading distance depends on the local conditions.

Organizational dimension:

O1 Degree of intra-organizational complexity. Available temperature monitoring solutions vary regarding to their potential for monitoring temperature in cold stores, in processing rooms and during transportation. This potential complexity of the different solutions has a great impact on the quality and consistency of the gathered data.

O2 Degree of inter-organizational complexity. If the improvement of temperature monitoring is undertaken over an entire supply chain, requirements on the system become even higher due to more interfaces, a higher volume of data and even more requirements due to the involvement of additional chain actors. Assessment of possible inter-organizational temperature monitoring aspects of a solution is therefore very important. An important inter-organizational consideration is also that the trust between the actors is not threatened or/and can instead be enhanced or even confirmed.

O3 Degree of willingness to exchange information. Temperature and quality data are very sensitive data within a company’s performance portfolio and even in customer-supplier-relationships. Therefore, the allocation of different user accesses and systems security overall are a very sensitive matter and must be dealt with responsibly and sensitively.

O4 Degree of traceability. In recent years, requirements as to traceability have grown continuously. This criterion of assessment mainly focuses on the design of a temperature monitoring system taking into account the organizational requirements of the chain actors.

Functional dimension:

F1 Functional degree in a quality and health management context. The functional complexity of temperature monitoring must comply with regulatory requirements. Depending on the admission of the chain actors, compliance with different standards and internal quality demands is necessary.

F2 Functional degree in a cold chain management context. Tools and methods are needed that maximise the use of temperature monitoring information for decision making in cold chain management. Further combination with software solutions is possible to build the link to inter-organizational information management, e.g. predictive models of shelf life and risk modelling can support the chain actors in the field.

F3 Integration degree. Each temperature monitoring solution requires a different level of pre-existing system architecture as well as trained staff members regarding the use of the solution. Therefore the functional scope of an implementation of a novel solution or the extension of already existing systems depends on the actual system architecture of one actor or the whole supply chain or network, respectively. Chain actors have to agree on the “smallest identifiable units” that identifies products in the central system at the required level of detail (Vernède et al., 2003).

Step 2: Scoring process

After determination of the criteria according to the three dimensions, their assessment has to be done with regard to their characteristics. Therefore the scoring model of Mack (2007), Ellebrecht (2008) and Schütz (2009) as well as the MADM approach of Petersen (1985) are used.

Calibration of CCM-relevant criteria

The calibration of each individual criterion within the three dimensions (T1-T7, O1-O4 and F1-F3) is based on its characteristics. In particular, all likely cases are covered and a scoring system is applied, with a scale from 1 to 100 according to Schütz (2009). As shown in Table 5.12, the most favorable are allocated with a high mark while the least favorable are given a low mark. Most favorable means in this context the highest level of temperature monitoring consequently improving cold chain management. The highest level is not necessarily the most preferred level for all chain actors. These heterogeneous preferences are taken into account by the determination of weight coefficients (step 3).

In this research study the scoring for each individual criterion was set to take account of the individual input from the case studies within the development of the “Three-dimensional generic model for cold chain management optimization” (Chapter 3.5) and the TTI field trial (Chapter 4.3.3) (Table 5.11), respectively. Table 5.12 shows the scoring for each individual criterion.

Table 5.12: Calibration of the 14 criteria in the (1–100) scale

	Criteria	Specification in sub-criteria	Score
Technical dimension	T1 Measuring unit	Single product level + product temperature	100
		Single product level	75
		Pallet level	50
		Container level	50
		Batch level	25
	T2 Memory size	High memory size	100
		Medium memory size	75
		Less memory size	25
	T3 Measuring accuracy	Very precisely	100
		Precisely	75
		Less precisely	25
	T4 Reading possibilities	Wireless Network	100
		Wireless manual reading	75
		Wired manual reading	25
	T5 Data format / preparation	Digital data + comparative information	100
		Digital data + predictive information	90
		Digital data + prescribing information	80
		Digital data + descriptive information	70
		Digital data	60
		Paper documents	10
	T6 Maintenance of the system	Very good available	100
		Good available	50
		Rarely available	0
	T7 Service provision	Full support	100
		Medium support	50
		No / low support	0
Organizational dimension	O1 Degree of intra-organizational complexity	Storage rooms + Transportation vehicle	100
		Transportation vehicles	50
		Storage rooms	50
		Incoming and outgoing inspection	25
	O2 Degree of inter-organizational complexity	International supply chains	100
		National supply chains	75
		Customer + Supplier	50
		Customer	25
		Supplier	25
	O3 Degree of willingness to exchange information	Unrestricted available	100
		Available	75
		Less available	25
	O4 Degree of traceability	Unrestricted available	100
		Available	75
		Less available	25
Functional dimension	F1 Functional degree in a quality and health management context	Requirements above legal obligation	100
		Legal obligations	50
	F2 Functional degree in a cold chain management context	High requirements	100
		Medium requirements	50
		Less requirements	25
	F3 Integration degree	High actual system architecture	100
		Medium actual system architecture	50
		Less actual system architecture	25

Compilation of temperature monitoring alternatives

In Chapter 2.3 classes of temperature monitoring solutions are summarized. On the basis of the pilot studies and expert discussions with technical developers a huge number of alternative temperature monitoring solutions and systems have been compiled and listed for the assessment within the MCDA-CCM approach. Using the criteria defined in Table 5.12, each alternative solution can be scored according to its actual performance.

By doing so, a matrix of values can be calculated, which is a data basis for a further calculation within the assessment. As described in chapter 2.3, a huge number of temperature monitoring systems and solutions is available on the market. Thus, within this framework of this concept, the scoring of the alternative temperature monitoring solutions will be described in an example. According to this, the scoring template, filled in with scores of exemplified temperature monitoring solutions, is shown in Table 5.13.

Table 5.13: Scoring template of the criteria in the three-dimensions for exemplified temperature monitoring solutions

Alternative solution	Technical							Organizational				Functional		
	T1	T2	T3	T4	T5	T6	T7	O1	O2	O3	O4	F1	F2	F3
Temperature monitoring. solution 1	50	100	50	75	100	75	100	50	75	75	100	50	50	100
Temperature monitoring. solution 2	50	75	25	75	60	75	25	50	50	50	25	50	25	25
Temperature monitoring. solution 3	25	75	75	25	10	100	100	25	25	25	100	100	25	100
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Step 3: Calculation

Determination of weight coefficients for cold chain applications

By using PROMETHEE it is possible to weight each single criterion of the total group of criteria within the respective dimension according to the degree of importance within specific application scenarios. Further on it is possible to weight each group of criteria. The sum of the weight coefficients of individual criteria equals 100%.

For first assumptions within the decision making process the criteria in the three dimensions can be considered of equal importance. However, one main feature of the MCDA-CCM approach should be a flexible adaptation to the heterogeneous requirements in cold supply chains which is possible with a specific weighting of the criteria depending on user specific requirements. For example, within large companies, IT departments exist which have the knowledge to deal with the technical complexity of temperature monitoring solutions but the companies have to deal with high organizational complexity e.g. a large number of suppliers and customers.

Within this framework the weighting of criteria is determined for different application scenarios classified according to diverse categories: the company size, the customer-supplier relationships, the role of a network coordinator or a user of inter-organizational information management, the ambition level regarding the performance of quality and cold chain management, the actual system architecture and the innovative degree. Seven application scenarios represent several types of meat supply chains (Table 5.14).

Table 5.14: Seven application scenarios covering different types of meat supply chains

Different application scenarios	Characteristics of meat supply chains									
	Small or medium sized company	Large enterprise	Service enterprise	Network coordinator	System user	National customer-supplier relationships	Global / international customer-supplier	High ambition level**	Medium to low ambition level**	Innovative company
Application Scenario 1	√	-	-	√	-	√	-	√	-	√
Application Scenario 2	√	-	-	√	-	√	√	√	-	√
Application Scenario 3	√	-	-	-	√	√	-	-	√	-
Application Scenario 4	√	-	-	-	√	√	√	-	√	-
Application Scenario 5	-	√	-	√	-	√	-	√	-	√
Application Scenario 6	-	√	-	√	-	√	√	√	-	√
Application Scenario 7	n.d.*	n.d.	√	√	-	√	√	√	-	√

* not a determining factor for this scenario, ambition level: characterizes the degree of willingness to invest and improve quality management as well as the level of trust between the actors

Within the MCDA-CCM concept the decision maker within each application scenario can chose one of the above described three options: to set all criteria to equal importance, to chose weighed dimension for each single criterion or to group all criteria within one dimension. On the basis of the conducted research studies, the weighting of the criteria and/or the three dimensions is determined regarding the proposed application scenarios in meat supply chains. In Table 5.15 weight coefficients for these different types of supply chains are proposed as a basic feature within the MCDA-CCM concept.

Table 5.15: Weight coefficients for each criterion of each group of criteria

Dimension/Criterion				Appl. Scenario 1		Appl. Scenario 2		Appl. Scenario 3		Appl. Scenario 4		Appl. Scenario 5		Appl. Scenario 6		Appl. Scenario 7	
				Weight coefficient for single criteria (1) and the resulting grouped criteria in the three dimensions (2) [%]													
				1	2	1	2	1	2	1	2	1	2	1	2	1	2
Weight coefficient for single criteria	Technical dimension	T1	Measuring unit	5	1.7	20	4.0	5	2.5	20	8.0	20	4.0	20	4.0	20	8.0
		T2	Memory size	5	1.7	10	2.0	5	2.5	10	4.0	20	4.0	20	4.0	20	4.0
		T3	Measuring accuracy	10	3.5	10	2.0	10	5.0	10	4.0	20	4.0	20	4.0	20	4.0
		T4	Reading possibilities	20	7.0	20	4.0	20	10.0	20	8.0	20	4.0	20	4.0	30	8.0
		T5	Data format / preparation	20	7.0	20	4.0	20	10.0	20	8.0	10	2.0	10	2.0	10	8.0
		T6	Maintenance of the system	20	7.0	10	2.0	20	10.0	10	4.0	5	1.0	5	1.0	0	4.0
		T7	Service provision	20	7.0	10	2.0	20	10.0	10	4.0	5	1.0	5	1.0	0	4.0
		Total		100	35	100	20	100	50	100	40	100	20	100	20	100	40
	Organizational dimension	O1	Degree of intra-organizational complexity	40	10.0	20	8.0	40	12.0	20	8.0	40	16.0	20	8.0	30	8.0
		O2	Degree of inter-organizational complexity	20	5.0	40	16.0	20	6.0	40	16.0	20	8.0	40	16.0	30	16.0
		O3	Degree of willingness to exchange information	30	7.5	20	8.0	20	6.0	20	8.0	10	4.0	10	4.0	0	8.0
		O4	Degree of traceability	10	2.5	20	8.0	20	6.0	20	8.0	30	12.0	30	12.0	30	8.0
		Total		100	25	100	40	100	30	100	40	100	40	100	40	100	40
	Functional dimension	F1	Functional degree in a quality and health management context	40	16.0	40	16.0	30	6.0	30	6.0	45	18.0	45	18.0	35	6.0
		F2	Functional in a cold chain management context	30	12.0	40	16.0	30	6.0	30	6.0	45	18.0	45	18.0	35	6.0
		F3	Integration degree	30	12.0	20	8.0	40	8.0	40	8.0	10	4.0	10	4.0	30	8.0
		Total		100	40	100	40	100	20	100	20	100	40	100	40	100	20
Weight coefficient for grouped criteria		Technical dimension		-	35	-	20	-	50	-	40	-	20	-	20	-	40
		Organizational dimension		-	25	-	40	-	30	-	40	-	40	-	40	-	40
		Functional dimension		-	40	-	40	-	20	-	20	-	40	-	40	-	20

Determination of the preference function and thresholds

According to the described decision problem, a usual or linear preference function is proposed. To take into account the specific preferences of the decision maker, the decision maker can chose thresholds for preference and indifference. These thresholds can be specified for each individual criterion. For example, the decision maker can chose a high preference threshold regarding the criteria “T2 Memory size”, if the decistion maker prefers a temperature monitoring alternative which should have at least a medium memory size.

Step 4: Recommendation

Raking of temperature monitoring system alternatives

By using the PROMETHEE method as a basic method for the MCDA-CCM concept, a partial ranking (PROMETHEE I) and a complete ranking (PROMETHEE II) of systems, taking into account steps 1 to 3, can be performed. Due to the chosen approach, the positive and negative outranking flows (ϕ^+ ,ϕ^-) are calculated and based on the outcomes, the alternatives can be ranked. Figure 5.30 shows an example of a partial ranking of three exemplified temperature monitoring solutions (Table 5.13) using the MCDA-CCM approach within the software D-Sight.

	TM1	TM2	TM3	φ +
TM1	0,000	0,198	0,168	0,183
TM2	0,000	0,000	0,199	0,060
TM3	0,098	0,174	0,000	0,136
φ -	0,049	0,186	0,143	

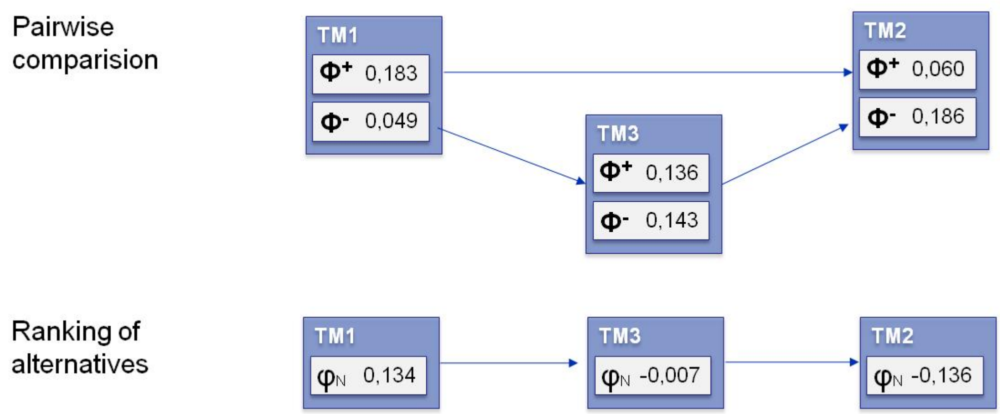


Figure 5.30: Example for ranking three exemplified temperature monitoring alternatives using the MCDA-CCM approach

The criteria were chosen according to Table 5.12 and the weights were chosen assuming application scenario two (Table 5.15). Further on, each single criterion was weighted. The preference flows (expressed as score in the software D-Sight) express the degree of preference: the positive preference flow (ϕ^{+}) expresses the degree to which the sample is preferred over the other alternatives, while the negative flow (ϕ^{-}) expresses the degree to which all the other samples are preferred to the specific alternative. In the example, one temperature monitoring solution has the highest positive preference flow and is thus likely to be preferred by the decision maker.

For a visual projection of the assessed temperature monitoring solutions in the three dimensions, the GAIA plane can be used (Figure 5.31). Within the shown assessment example, each single criterion is weighted and the weight coefficients of application scenario two are used.

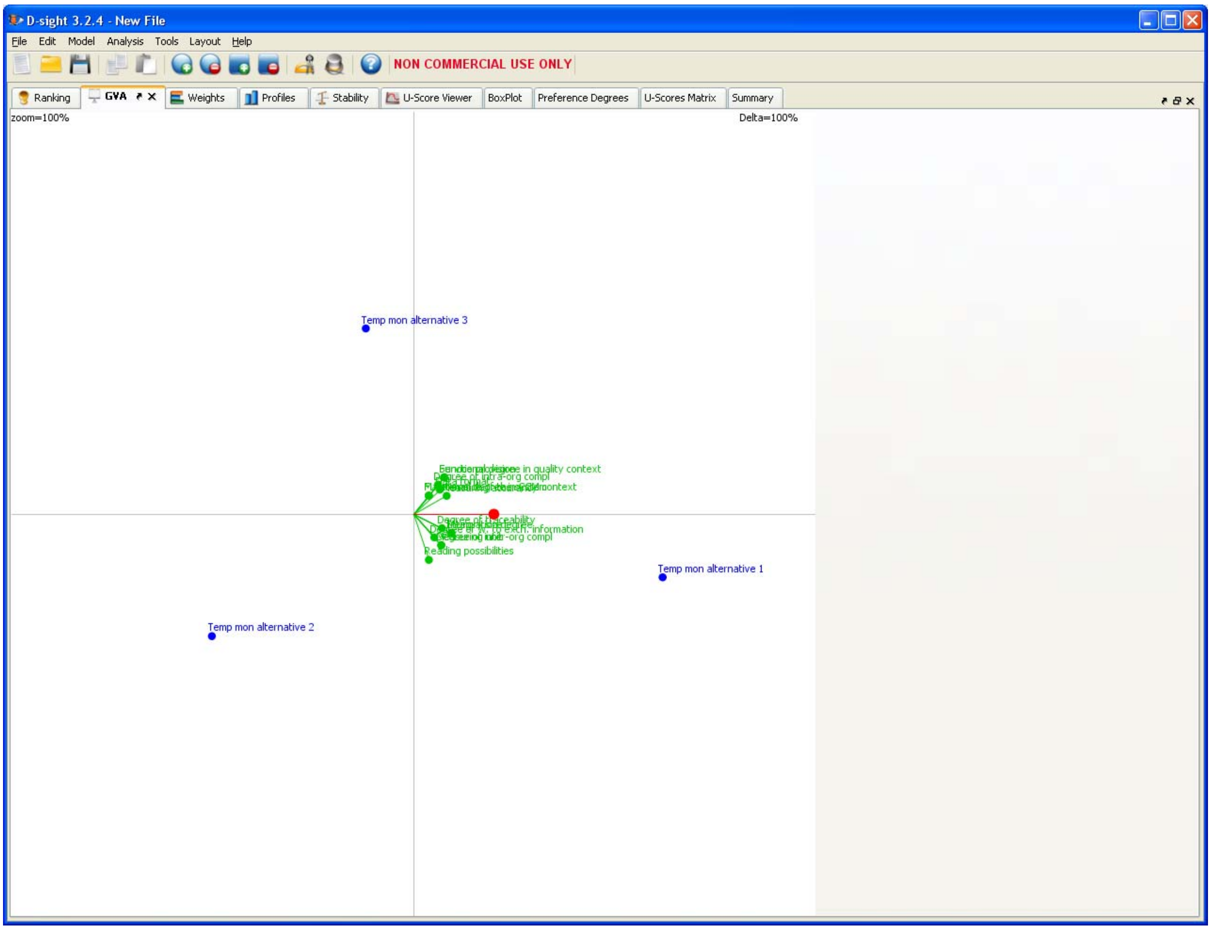


Figure 5.31: Example for the visualization of the three assessed alternative temperature monitoring solutions visualized within a GAIA plane using the MCDA-CCM approach within the software D-Sight

In the calculation in Figure 5.31, within the GAIA plane alternatives are shown as points and the different criteria are shown on the axes. The conflicting character of the criteria appears clearly: criteria expressing similar preferences on the data are oriented in the same direction;

conflicting criteria are positioned in opposite directions. The weights vector in the GAIA plane is shown on the PROMETHEE decision axis (π) (Brans and Mareschal, 1992). The decision-maker is thus invited to consider the alternatives located in the direction of the decision axis. The direction of the decision axis is changing, by modifying the weights. Lenca et al. (2008) describe further features of the GAIA plane in detail: alternatives which have good evaluations on a given criterion are represented by points close to the axis of this criterion. Similar alternatives are close to each other in the GAIA plane and if the π axis is long, it has a strong decision power. The decision maker should choose alternatives which lie in the direction and the sense of the axis. If the π axis is short, it has a weak decision power. This means that for this configuration of weights, the criteria are conflicting, and a good compromise can be found at the origin of the plane.

5.5 A MCDA-CCM Web based software solution

As described in the introduction, a large number of alternative temperature monitoring solutions exist on the market. The MCDA-CCM concept allows a ranking of these temperature monitoring solutions as related to the determined and scaled criteria. The aim of the concept is the support of the decision making process of chain actors in food supply chains. Therefore it is necessary to integrate the MCDA-CCM concept into user friendly software. In general, different MCDA software solutions exist, like the software Decision Lab 2000 or D-Sights. However, this software and also other commercially available software packages allow only general-purpose decision support. An MCDA-CCM software solution will permit the specific support of chain actors within cold supply chains through the integration of the defined criteria, the scoring of the criteria (Table 5.12), the weight coefficients of the criteria for specific application scenarios (Table 5.14) and the matrix for the rating of the proposed–alternative temperature monitoring solutions (Table 5.15). Additionally, a continuous update of the list of alternative temperature monitoring solutions has to be conducted according to ongoing innovations in the sector. By integrating these features into Web based software, chain actors can assess and rank alternatives related to their specific applications and requirements. Therefore the user has to define the respective preferences regarding the defined criteria. This allows the use of the concept in different situations, such as before the implementation of an inter-organizational temperature monitoring system or when extensions of pre-existing solutions are planned.

5.6 Conclusion and possible future developments

The proposed MCDA-CCM concept describes an approach supporting the decision process optimizing cold chain management. A crucial component within the concept is the integration of the three dimensions of observation: the technical, the organizational and the functional perspective. Further on, heterogeneous application scenarios in cold supply chains and varying requirements of the chain actors are taken into account due to the definition of weight coefficients and the definition of thresholds of preference and indifference. By future implementation of the concept into Web based software, a large number of existing temperature monitoring solutions can be ranked for different types of cold supply chains. This will allow a user-orientated support of decision making of the chain actors in finding the best temperature monitoring system to improve test strategies at important inspection and decision points.

The combination of the proposed MCDA-CCM concept with approaches regarding “Group decision making” might allow further added value for decision making in agri-food chains.

Due to complex customer-supplier-relationships and the presence of various actors within a supply chain or netchain, several chain actors decide on improvement strategies. A group decision situation involves multiple chain actors (decision makers), each with different skills, experience and knowledge relating to different aspects (criteria) of the problem (Fülöp, 2005; Shyur and Shih, 2006). Petersen et al. (2007) describe “netchain coordinators” in agri-food chains which have to take the final decision derived by aggregating the opinions of the group members. Thus, the advancement of the MCDA-CCM concept with PROMETHEE GDSS (“Group Decision Support”) (Banville et al., 2000; Rogers et al., 2004) is also of great interest.

Through a detailed view as to the organizational dimension, the potential for applying the concept to risk orientated mutual control strategies can be determined. In this context, Petersen et al. (2011) propose the approach “Alliances for the Mutual Organization of Risk orientated control strategies (AMOR)”. AMOR proposes a development of concepts that will motivate actors involved in quality management in food chains to mutually coordinate such strategies. Thus, product and process quality will be continuously improved from the perspective of the supply chain.

With regard to cold chain management, the coordination of such mutual checking strategies can also be outsourced to a mutual service provider (Kockelkoren, 2006; Kockelkoren et al., 2010) in the supply chain. To determine whether the outsourcing of the coordination of the process of temperature monitoring to an appropriate service provider is the best alternative, the previously assessed criteria can be used. Each contract alternative can imply a specific contract cost and service quality characteristic (de Almeida, 2007) which can be integrated into the concept.

Additionally the factor of “cost” is less integrated within the concept. Only due to the scoring of a few parameters, e.g. high costs for the monitoring of single units by a high score for this criterion. By taking cost-benefit rankings into account, a further critical factor could be integrated into the concept.

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6 Summary

The objective of this thesis was the development of a concept to assess temperature monitoring innovations in cold chain management. The focus was to prove how to facilitate efficient applications of temperature monitoring systems. This necessitated the compilation of a huge volume of research results, which was the basis for solving four research questions.

The first research question focused on the determination and categorization of temperature monitoring solutions and systems. The solutions were arranged in the following categories: Contact thermometer, Infrared thermometers (Non-contact thermometer), Graphic records, Electronic data loggers and wireless technologies with integrated temperature sensors, as well as Smart Active Labels and Time-Temperature Indicators (TTIs). The allocation of key system functionalities within each category is an important contribution to the assessment of the efficient implementation and application in different types of meat supply chains. Furthermore, the main intra- and inter-organizational challenges were met regarding the practical implementation, such as the linking of the product characteristics with temperature data, the measurement procedures and the interpretation of temperature data, the availability and handling of temperature data, the choice of the correct system and training and education of employees.

A major conclusion from this comprehensive literature review and from meetings with meat industry experts was, that a technical, organizational and functional dimension should be considered when attempting to optimize cold chain management.

Considering the previous definition of cold chain management (chapter 1.1), a main challenge regarding the optimization of cold chain management is that a number of disparate disciplines have to be linked together. Therefore, research question 2 is aimed at ascertaining how temperature monitoring solutions can support the improvement of cold chain management. In order to answer this research question, a three-dimensional generic model for the optimization of cold chain management was proposed. The technical component "Temperature monitoring model" describes necessary technical specifications, the optimal technical implementation of innovative tools and the method of temperature mapping at important inspections and decision points over the entire supply chain. The "Inspection model" (organizational component) provides information on all factors related to organizational structure, inspection schemes and information management of the specific cold chains. To generate the linkage of product characteristics with temperature data, kinetic models are considered as a functional component. This component is integrated into the three-dimensional generic model, taking shelf life modelling as an example, as it allows the calculation of remaining shelf life at specific inspection and decision points. Due to the connection of the three disciplines, descriptive, prescriptive, predictive or comparative information on temperature and quality data can be provided at specific points in cold supply chains. This can allow the optimization of logistic processes and storage concepts, the determination of weak points and therefore an attainment of higher quality and the minimization of risk and food wastage.

The third research question was - which derivations of improvement processes in real meat supply chains have to be taken into consideration within the assessment of the technologies? In consequence a four week field trial was conducted using Time-Temperature Indicators (TTIs) as an example. As a prerequisite for the application of TTIs, a TTI kinetic model predicting the discoloration and the remaining shelf life in every stages of the supply chain was developed. Moreover, a TTI adjustment model for the calculation of the initial starting value for the TTI application as applied to different products was deduced.

The practical use of this temperature monitoring solution was conducted taking the three-dimensional view of requirements into account. Therefore it was simultaneously tested whether the three-dimensional generic model could support the improvement process in a real-life meat supply chain. This field test has shown that it is necessary to have a very high degree of accuracy regarding the initial setting and the measuring of the response of the TTI. Less precise measuring results in erroneous calculation of remaining shelf life when using the TTI kinetic model. Through testing the system at several stages of a supply chain, the degree of inter-organizational complexity using such a device became obvious. Due to a high level of transparency between the chain actors, the reading of the discoloration of the TTIs was possible in each stage of the supply chain. Therefore, the testing strategy of cold chain relevant parameters at important inspection and decision points could be enhanced in the poultry supply chain that is used as an example.

On basis of these results, as well as from the results from a total of ten “Temperature mappings”, six field trials with Time-Temperature-Indicators (TTIs) and two field trials with RFIDs with a temperature sensor, 14 criteria for the assessment of temperature monitoring systems could be undertaken. This resulted in poultry, fish, pork, beef and cooked ham supply chains were investigated on a (German) national, international and global scale.

The final research question was concerned with how different temperature monitoring systems could be assessed taking into account the multi-objective nature of technology selection and heterogeneous user perspectives in cold supply chains. To facilitate the assessment of temperature monitoring systems, a scheme involving five levels and five columns which contain different phases, steps and elements is proposed. Core elements of the so named “Multi-Criteria Decision Aid (MCDA)-CCM” concept are the three-dimensional generic model for cold chain optimization, the “Scoring model” and the Multi-Criteria Decision

Aid method “PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluation)”.

By using these approaches and the gathered data from the research studies, the 14 defined criteria were categorized into a functional, technical and organizational dimension. The determination of organizational criteria was facilitated through the huge variety of organizational structures within the meat supply chains investigated in the different field trials. As different electronic data loggers, a thermal imaging camera, TTIs, RFIDs with temperature sensors and WSN were used, suitable criteria in the technical dimension could be determined. The proposed kinetic shelf life model and the developed TTI kinetic model allowed a linkage of temperature data with the product’s quality. Due to the use of the kinetic models, the needed functional degree of temperature monitoring systems could be determined.

By using the “Scoring model” the criteria could be weighted on a scale from 1-100. Weight coefficients of the criteria for specific application scenarios were determined on basis of previously cited research studies. This allows an assessment of alternatives according to the preferences of the decision maker within respective application scenarios. As meat supply chains were determined as being heterogeneous (chapter 3.4.1), the needs and requirements in these perishable food supply chains differ, which makes this element of the concept crucial. Additionally, the matrix for the ranking of the proposed alternative temperature monitoring solutions is proposed, according to categorization of temperature monitoring solutions in chapter 2.3. Due to aggregation and the calculation of negative and positive outranking flows, a ranking of proposed temperature monitoring alternatives is possible. The previously mentioned huge variations concerning the organizational, technical and functional components within the conducted research studies allows a transferability of the proposed MCDA-CCM concept for a range of types of meat supply chains.

A future integration of the MCDA-concept into Web based software is proposed, integrating the described features. This will allow decision makers in cold supply chains to assess and rank alternatives depending on their specific requirements. This facilitates the use of the concept in different situations, such as before the implementation of an inter-organizational temperature monitoring system is being considered, or when extensions to already existing solutions are being planned.

Within the proposed MCDA-CCM concept, it was for the first time describing an approach, which integrates three dimensions: the technical, the organizational and the functional perspective in an assessment concept for cold chain management innovations. Taking into account these three dimensions, testing strategies of cold chain relevant parameters at important inspection and decision points could be enhanced due to finding the best fitting temperature monitoring system for particular customer-supplier relationships or even whole cold supply chains. Through the three-dimensional view, a methodically and theoretically sound concept is developed, which can be used with other multi-criteria decision problems in agri-food chains.

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List of abbreviations

General abbreviations:

a_w-value	Activity of water
CCM	Cold Chain Management
cfu	colifom building units
DIN	Deutsches Institut für Normung e.V.
EN	Europäische Normung
FIFO	First In - First Out
LSFO	Least Shelf - Life First Out
MCDA	Multi-Criteria Decision Aid
MODM	Multi Objective Decision Making
MCDM	Multi-Criteria Decision Making
pH-value	negative logarithm (base 10) of the molar concentration of dissolved hydronium ions (H_3O^+)
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
RFID	Radio Frequency Identification
SCM	Supply Chain Management
SL	Shelf life
SV	Square Value
TTI	Time-Temperature Indicator
WLAN	Wireless Local Area Networks
WSN	Wireless Sensor Networks
WWAN	Wireless Wide Area Networks
t	time
T	Temperature

Physical units:

°C	degree Celsius
g	gram
h	hours
K	Kelvin
M	molar (mol/l)
m	meter
min	minutes
Mol	Mol
ppm	parts per million
sec	seconds

Prefixes:

k	kilo (10^3)
m	milli (10^{-3})
µ	mikro (10^{-6})

Appendix

Table A-16: Overview about the conducted field studies in real food supply chains

Study	Type of field study	Type of food business / supply chain	Period of time	Place
1.	Temperature mapping	Poultry	June 2007	Germany
2.	Temperature mapping	Poultry	Beginning of August 2007	Germany
3.	Temperature mapping	Sliced ham	End of August 2007	Germany*
4.	Temperature mapping	Sliced ham	November 2007	Germany*
5.	Temperature mapping	Poultry	March 2008	Brazil to Belgium*
6.	Temperature mapping	Poultry	September 2008	Poland to Northern Ireland
7.	Temperature mapping + Field trial / TTIs	Poultry	Beginning of April 2008	Germany
8.	Field trial / TTIs	Poultry	End of April 2008	Germany
9.	Field trial / TTIs	Beef	Beginning of July 2008	France to Germany
10.	Field trial / TTIs	Sliced ham	End of July 2008	Germany
11.	Field trial / TTIs	Poultry	November 2008	Germany
12.	Field trial / TTIs	Fish	February 2009	Germany**
13.	Field trial / TTIs + RFIDs	Poultry	November 2009	Germany
14.	Field trial / Temp. sensors + RFIDs with temp. sensor	Pork	February 2010	Germany
15.	Field trial / Holistic TraceChill system of the EU Project Chill-On incl. various innovative solutions and the connection within an inter-organizational information management systems	Poultry	October 2010	Germany
16.-36	Expert meeting with system developers	Poultry / Fish / Sliced ham / Beef	June 2006 to December 2010	Various

** no personal participation / involvement in research design, planning and data evaluation,
** Personal support of the pilot activity of a project partner

Figure A-0.32: Overview about the Questionnaire used within the empirical supply chain assessment (example for the poultry supply chains / English version)

Questionnaire Tool from Perishable
Food Supply Chain Mapping (SOP)

CHILL-ON

2. Questionnaire Tool

Analysis of structures and demands in poultry supply chains regarding quality and information management

Methodology developed for Task 4.1 Supply Chain Assessment and Task 4.1.1 Information Requirement Analysis

Chief Editor: Verena Raab (UB)
For comments and questions please contact: vraab@uni-bonn.de

QUESTIONNAIRE TOOL_POULTRY UB

Analysis of the organizational structures in poultry supply chains

1. Please describe the organizational structure of your respective poultry supply chain. How many branches/suppliers do you have at each step of the chain? Which institution has the function of a coordinator regarding information exchange and implementation of new solutions? Are there any institutions like an Association of Companies as in the example who has the function of a coordinator in your supply chain?

2. Please describe the structures regarding information management in your supply chain. Which systems do you use? Are the systems used by each branch? Do you have a problem with interfaces between the branches?

3. Please describe the transported unit in your logistic chain and the particular delivery times between each production steps.

4. Please describe the transportation between each step of your respective supply chain regarding the parameters linked to the transportation step (e.g. registration number of the vehicle).

5. In which radius do you obtain the respective poultry products? Please quote in percent respectively the main steps within the supply chain.

6. If you obtain products from foreign countries; which countries are your main distributors?

7. About which distances is the poultry transported from your company to the respective customer? Please quote in percent regarding the given distances.

8. If you supply products to foreign countries; in which countries are your main customers located?

9. How many percent of poultry of your company is transported by truck, by train, via air freight and via sea freight (distinguished regarding incoming and outgoing goods)? Please quote in percent.

10. We would like to get an overview about the type of packaging* between each step of your respective supply chain. Please specify the type of packaging regarding the related step in the supply chain.

Section 1: Questionnaire Quality management & Cold Chain Management

11. Which quality standards are applied in your company?

12. Which methods do you use for the receiving inspection and regarding quality control of the products in your company?

13. Which methods do you use to control and monitor temperature conditions in your company at what place?

14. How are quality control checks linked to the finished product within each production stage? How are they recorded (e.g. on paper, punched into a computer system, automated data gathering)?

15. Do you exchange quality control and temperature data with delivering and receiving companies?

16. As how important do you estimate the inter-organizational information exchange with other partners in the supply chain (please rate according to usage: 1=primarily, 2=occasionally, 3=rarely)?

18. We would like to get a detailed overview about your logistic chain regarding cold chain management. Please define critical points in the logistic chain regarding cold chain management.

19. What kind of cooling technologies are used in the transport vehicles?

20. What kind of storage management do you use (e.g. pick up location, stock room with single access, etc.)?

21. What kind of storage system do you use (e.g. storage system with static or dynamic shelves)?

22. Do you have any of the following systems in your cooling system (e.g. cooling ramps, protecting plate fins)?

Section 2: Questionnaire Information management

Analysis of the Information demand at different steps in the Process

23. As how important do you estimate the following information classified regarding different divisions of your company (please rate according to usage: 1=primarily, 2=occasionally, 3=rarely)?

24. What further kind of information do you require in order to make better decisions in regards to your customer-supplier relationship management?

25. Please estimate critical points in your logistics chain regarding information management and technologies (e.g. EDI-exchange, variety of forms, information about stock).

26. As how important do you estimate the specific requirements and possibilities regarding information accompanying the product (e.g. amendment of delivery time and timeliness; prompt handling of customer complaints)?

27. Please estimate which specific category points (e.g. processing time; stock of inventory; multiple data acquisition) should be improved in the future (please rate according to usage: 1=primarily; 2=occasionally; 3=rarely).

Analysis of structures regarding systems and technologies

28. Do you plan important quality control investments in your company (Please distinguish between short; medium and long-term investments)?

29. Do you use/do you have implemented specific data standards and codes (e.g. from the numbering system of the GS1 or any other barcodes)?

30. With which information- and communication possibilities is your company provided (e.g. internet access; tracing of shipments; Electronic data exchange (EDI), Supply Chain Management Systems)?

31. What kind of information management systems and components are already used in your company (e.g. Enterprise Resource Planning System, Quality Management Data Base, Decision Support System)? By whom are the systems used?

32. Which possibilities regarding IT-solutions do you need in your company at the present time (e.g. Tracking & Tracing, Faster data exchange via Barcode Reader or RFID-Scanner, Customer/Corporate portal with direct connection to data regarding tracking & tracing issues)?

33. Which improvements and which application areas could be interesting for your company in future (e.g. Quality of the Information (e.g. propriety); Quantity of the Information (e.g. grade of accuracy, price ratio))?

Analysis of Interfaces regarding Tracking & Tracing Systems

34. Which kind of „Identification and Registration Hardware“ could be applied directly or indirectly with the systems in the company (e.g. Barcode-/RFID-Reader, Manual input unit (mobile data registration, mobile phone, PDA))?

35. How do you support data for third party systems (regarding data interfaces) (e.g. ASCII (American Standard Code for Information Interchange), Data exchange protocol (EDIFACT, XML))?

36. If a standardised interchange format is supported by the data interface, which data formats/standards are being used (e.g. EDIFACT, XML)?

37. Does your Enterprise Resource Planning systems (ERP)-Solution already support Tracking & Tracing (possible answers e.g. yes only own solution; yes, within integration of the following solutions; No, at present not yet)?

38. How does the connection of Tracking & Tracing Data of systems from third parties take place (e.g. actively: connection upon request of the customer, as service involving costs; cooperative: preparation of a standardised interface)?

39. Additionally we would like to know from which systems do you get Tracking & Tracing data and how do you integrate these data into your own system?

40. If a new IT-system would be able to provide you with on-line tracking information including educated forecast as for the remaining shelf life of each shipment, would you be interested in?

41. If such a system would require training of the employees prior usage, would you will be interested in (Yes/No)?

Inter-organizational Information management

42. Please explain if your IT-solutions allow a data exchange with customers/cooperation partners in the supply chain (e.g. partial, primarily, via individual solutions)?

43. How are you provided with information for an optimal decision-making in case of fresh poultry (e.g. Information overflow, Optimal, Insufficient, Inefficient)? Please specify the chosen answer.

44. Please explain your efforts regarding security aspects regarding inter- organizational information management. Additionally we are interested in current system security and the possibilities to give different users specific access to the system. Would you be so kind to explain current system security and the required security in your company?

45. How important are the following system security categories for your company (Please rate according to usage: 1=high-impact; 2=moderate-impact; 3=low-impact (Please make the specifications in reference to family e.g. Technical (e.g. Access Control), Operational (e.g. Personnel Security), Management (e.g. Certification))

46. Which kind of „Identification and Registration Hardware“ could be applied directly or indirectly with the systems in the company(e.g. Barcode-/RFID-Reader, Manual input unit (mobile data registration, mobile phone, PDA))?

47. Does your ERP-Solution already support Tracking & Tracing (Possible answers e.g. Yes, only own solution; Yes, through interface to third-party provider; No, at present not yet)?

48. How does the connection of Tracking & Tracing Data of systems from third parties take place (e.g., actively: connection upon request of the customer, as service involving costs; passively: preparation of a proprietary interface including documentation; except applicable solutions no further connection is planned)?

g. General information about the company

49. Name and Structure of the company:

Name of the interview partner: ____________________

Position of the interview partner: ____________________

Phone: ____________________

E-mail:

Headquarter: ____________________

In which step of the poultry supply chain ____________________ does your company work?

Number of national branches: ______________________

Branches abroad: ______________________

Number of employees: ______________________

Total: t

Main Products: ______________________

☐ Fresh products: ______________________ %

☐ Frozen products: ______________________ %

For more information please contact:

Verena Raab
University Bonn
Phone: + 0049 228 734931
Fax: + 0049 228 736515
Email: vraab@uni-bonn.de
www.itw.uni-bonn.de

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