Chapter 15

Models and technologies for the enhancement of transparency and visibility in food supply chains

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Abstract

With the increased pressure and challenges of economic, environmental, and social character, the need for innovations (including both the generation and adoption of innovations) that can be implemented in supply chains increases. A number of novel concepts focusing on intelligent logistics and packaging systems are being developed and tested in the food industry, all over the world. Several of these concepts predict quality and product safety of foods for use along the food supply chain (FSC) by the food industry, distributors, and retailers, as well as consumers. In this chapter, the focus is set on models and technologies related to increased transparency and visibility in FSCs for the purpose of lowering food waste, increasing food safety, and increasing overall resource efficiency. An overview of models and concepts for transparency with specific emphasis on food monitoring systems and technologies is presented, together with an in-depth field study of an industry case. The field study covers a whole supply chain in which all actors were provided with real-time data on time and temperature of a product from production until consumption. It is concluded that the use of new technologies holds great potential and huge value in collecting and sharing quality data. However, the main challenges are found in the business relationships where the risks and willingness to share information, i.e., of being more transparent, are the major hurdles in the development of sustainable food supply chains.

1 Introduction

A number of novel concepts focusing on intelligent logistics and packaging systems are being developed and tested in the food industry worldwide. Several of these concepts predict quality and product safety of foods for use along the food supply chain (FSC) by the food industry, distributors, ad retailers, as well as consumers. With such new concepts implemented in FSCs, real-time monitoring will enable the identification of abnormalities, e.g., excessive temperatures, as well as cooperative improvement efforts between supply chain actors. Based on such information, actions can be taken directly. Information can also be provided on documented cold chain data for changes of predicted quality and shelf life. In-house efficiency improvements are possible through the early relocation of products whose shelf life has changed during the management process. Food distribution controlled according to needs and actual quality opens up new business opportunities for both carriers and retail trade. This chapter focuses on the advancements and applications of new sensor technologies, including new insights into how actors in the supply chain can cooperate and utilize each other's information for a more sustainable society. Information is presented on how innovation, traceability, and transparency in the food industry can be used to reduce food waste, increase resource efficiency, and improve food security.

The rest of the chapter addresses the following areas:

- Introduction to the challenges related to food waste/resource efficiency and the need to monitor food quality in the supply chain.
- Overview of models and concepts for increased transparency and visibility.
- Overview of technologies.
- Industry case on cold chain monitoring.
- Value and challenges related to sharing information and providing increased transparency in FSCs.

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2 Resource efficiency and food waste challenges in supply chains

The challenge of sustainable development have been on the agenda for many years, but it is not until recently that they have become of strategic importance for companies. The interest and involvement both from stakeholders concerned about what a firm should do in terms of sustainable practices (Gonzalez-Benito et al., 2011; Gray, 2013), and consumers demanding more sustainable services and products as well as transparency in practices (Trienekens et al., 2012), have all influenced this change. In the food industry, a number of challenges exist in sustainable development, with food waste, food safety, and resource inefficiencies being the major ones. Globally, it is estimated that one-third of all the edible food for human consumption is wasted (Gustavssonet al., 2011), i.e., 1.3 billion tons of food per year. While households are found responsible for the largest amount of food waste (Jensen et al., 2013), supply chain practices cause large amounts of food waste, both directly and indirectly. The set-up of FSCs today, i.e., where retailers have the most power, often leads to cost pressure on suppliers as well as demands on implementing quality and sustainability standards without sufficient support. This leads to short-term solutions and causes unnecessary waste due to liability contracts and reimbursement agreements. For several of the food actors, the waste is handled financially with reimbursements, i.e., the cost of food waste is pushed upstream to the suppliers, while in terms of actual food waste the amounts are high but often unknown. However, with increased understanding of customer behaviors, more efficient and secured FSCs, and more effective communication and information between supply chain actors as well as with consumers, food waste both in the supply chain and among consumers could also decrease.

The segment of chilled food products includes many of the most important food products of the European daily diet, especially for people that live in the northern part of Europe. This segment covers the high value and high environmental impact of products like meat, fish, and poultry as well as bulk products like milk. In order to keep chilled food products safe and healthy, consistent low temperatures are required (Olsson and Skjöldebrand, 2008). The physical and microbial quality is highly dependent on the food product storage and handling conditions, i.e., an intact cold chain with minimal fluctuations of storage temperature. Hence, chilled food products are demanding to manage in supply chains due to their perishability, often short shelf life, and natural variety in quality (Aung and Chang, 2014; Mena et al., 2011). The cold supply chains' complexity increases with the many variants of products, different temperature levels on different products, the coloading of products, and consumer expectations regarding new product launches (Aung and Chang, 2014; Naturvårdsverket, 2013).

Most food products today are labeled with a barcode for identity and a production or use-by date for quality and traceability. While this method of providing product data is efficient, it also has a number of limitations due to the fact that it is static and does not take into consideration what happens to a product during its handling and use. The current date labeling system is also a major reason for returns and rejections at different points in the supply chain. Lindbom et al. (2014) estimate that over 50% of all food waste in the industry derives from expired "best before" dates. Furthermore, two-thirds of household food waste is still fit for consumption (WRAP, 2007). There are significant challenges in being able to detect any deficiencies and manage deviations safely without recalling larger batches, which is critical, especially for food producers and retailers, both for profitability and customer confidence. If the state of food products can be identified in a real-time feed, throughout the whole supply chain, including households, the quality of the food can be assured or appropriate actions taken when needed (e.g., targeted recalls).

Food producers state their products' shelf life, in terms of expiry date label, but nevertheless have no control over how the products are treated downstream in the supply chain. With an intact cold chain and correct handling, most products could in theory still be of high quality after the labeled best before date. Common examples of this are products like milk, which still can be drinkable up to 2 weeks after the labeled best before date. Also eggs, stored in the refrigerator, retain their high quality months after the expiry date has passed. In today's society, it seems that many consumers lack sufficient knowledge of food and food handling. Thus, many consumers seek their safety and reliability information from their purchased products, which some of them find in the date labeling system. The safety is, however, as already stated, somewhat misleading, since many consumers completely depend on the labeled date and consider it a health risk to eat food that has passed its "use by" date (Rahelu, 2009). A number of these consumers do not even trust the date labeling system, leading them to throw away food even before the labeled best before date has passed (WRAP, 2011).

3 Transparency and visibility in food supply chains

The need and demands for information from authorities as well as supply chain actors set the standard for information carriers in packaging. In several industries, barcodes have come to be obligatory in order to identify goods. However, even though barcodes are reliable and easy to use, they have a number of limitations, e.g., being passive, needing manual handling, and only providing limited information. Furthermore, barcodes can also easily be removed and replaced with new ones. The development of other solutions, i.e., auto-ID and other information-enriching solutions that can be integrated with the product and its packaging, has been ongoing during the past 20 years. A number of researchers and practitioners have proclaimed different potentials with radio frequency identification (RFID) and other auto-id technologies. Nonetheless, no widespread effects of RFID have yet been reported in grocery supply chains. However, with advances in sensor technologies and a growing attention to the Internet of Things (IoT), increased visibility and transparency is promising. Today many companies have implemented new solutions or are conducting pilot studies of different auto-ID solutions, e.g., Gillette, Volvo, and DHL. In these cases, packaging should be designed in order to function in any situation, whether the demand is for information in order to track and trace, to follow the temperature of a package in a cold chain, or to inform a customer of containment, origin, and handling tips. The latest advancements, both conceptually and technologically, provide clear opportunities for new ways to identify, measure, and follow in real time what happens to products in supply chains. From this information, necessary adjustments can be made to minimize unwanted losses of food or safety/quality issues that occur.

In terms of traceability, all types of food should be traceable through all stages of production, processing and distribution, where each party is responsible for tracing the food one step back and one step forward. Based on European legislation, traceability for the food industry is defined in Regulation (EC) No 178/2002 as “the ability to trace and follow food, feed, food producing animal or substance intended to be, or expected to be incorporated into a food or feed, through all stages of production, processing and distribution” (EU, 2002). The purpose of this is to secure that the complete history can be restored if needed, which is especially important if the food has been found contaminated. As a part of international standards, Moe (1998) and Olsen and Borit (2013) explain that the traceability definition is found in the International Standardization Organization (ISO) 8402 as “the ability to trace the history, application, or location of an entity by means of recorded identifications” (ISO, 1994).

A traceability system must support both tracking and tracing, where tracking is used to keep records of the product at each stage, and tracing is the process to identify the origin of a product, i.e., reconstructing the history of the data recorded by the tracking process (Pizzuti and Mirabelli, 2015). “Tracking is the informative process by which a product is followed along the supply chain keeping records at each stage [..]. Tracing is defined as the ability of reconstructing the history of a product, identifying its origin through the complexity of resources involved in its lifecycle." (Pizzuti and Mirabelli, 2015, pp. 17–18).

The identity of the product is crucial to conduct traceability within a company. The batch is the most common way to group a certain quantity of the same product, and it is identified by using some type of labeling with a batch number, unique and unrepeatable. This number is the clue to tracing during the processing and to connecting either upstream with the raw material or downstream with the finished product.

Related to traceability is transparency. Traceability for logistics firms is the track and trace services that allow a higher degree of visibility (Hultman and Axelsson, 2007). Doorey (2011) and Mol (2015) define transparency as disclosure of information. Besides information sharing within the supply chain, there is an increased demand for transparency from other stakeholders such as consumers and government (Carter and Rogers, 2008; Doorey, 2011). The potential benefits from transparency are that it can create business opportunities (Svensson, 2009), improve business processes (Carter and Rogers, 2008) and lead to a favorable reputation (Fombrun, 1996) for the firm. Another important aspect of transparency is information asymmetry, meaning that one party to a business transaction has more information than the other party, which makes it impossible to choose the product that is believed to yield greater value (Wognum et al., 2011). Further, in terms of corporate social responsibility (CSR), it is crucial to implement transparency in order to obtain a CSR policy that is sustainable, since a company that perform well in CSR cannot distinguish itself from other competitors without transparency (Dubbink et al., 2008).

One way to ensure food quality and at the same time enable transparency is the use of different types of sensors in the FSC. These sensors can function as adaptive shelf-life indicators in consideration of temperature changes, microbiological growth, quality of raw materials, spoilage indicators, metabolites, harmful/food poisoning bacteria, and the quality of the food handling depending on the sensor level of intelligence. In addition to the food quality assurance brought by the sensors, the introduction of sensors will also increase the traceability and information flow within the supply chain.

This type of technology has advantages compared to barcodes and date labels, especially for microbiologically sensitive products such as chilled food. If the actual state of products can be communicated in an easy way, the “safety scare” among consumers might decrease or maybe even disappear. A new and deeper trust can be built between the producers and the consumers that could result in a decrease of unnecessary food waste on the consumer side. However, in order to implement sensor solutions in FSCs, it is extremely important to find incentives for all the actors involved (Hellström et al., 2011). Recognized and acknowledged actor incentives will enable sustainable development for both the food industry and the environment.

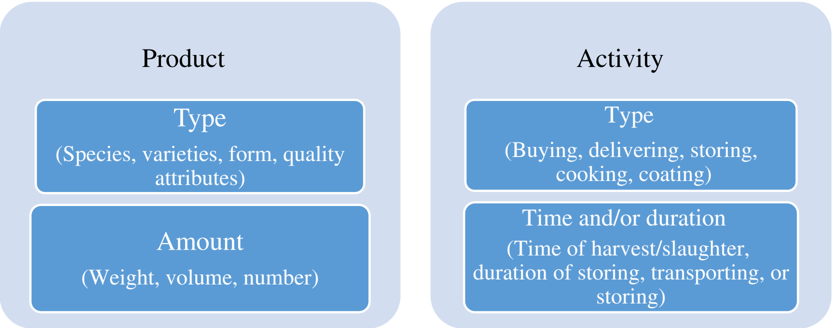
4 Overview of concepts and models for increased visibility and transparency

In FSCs, traceability has become an integrating concept covering several industrial objectives (Coff et al., 2008) and business perspectives (van Dorp, 2002). Some of the central objectives for improved traceability are: risk management and food safety, control and verification, supply chain management and efficiency, provenance and quality assurance of products, and information and communication to the customer (Coff et al., 2008). Traceability has also become a risk management tool that enables governmental authorities to improve safety control over FSCs (Popper, 2007; Banterle and Stranieri, 2008; Thakur and Hurburgh, 2009). A functioning system for traceability is also necessary in order to gain increased visibility and transparency, both being concepts that are essential for competitive advantage and sustainable development. Transparency builds on a willingness to share, to be open, and to communicate. Carter and Rogers (2008), in their concept of sustainable supply chain management, put forward transparency as one of the four key facets. With reference to Hart (1995, p. 1000) who states that "Increasingly, local communities and external stakeholders are demanding that corporate practices become more visible and transparent [...] To maintain legitimacy and build reputation, therefore, companies may need to open their operations to greater public scrutiny," transparency is emphasized as a way to engage stakeholders to build confidence. This is especially central for FSCs due to the many food scandals, which have led to decreased consumer confidence and trust. However, transparency also includes risks related to visibility in the sharing of information in business relationships (Aung and Chang, 2014; Bosona and Gebresenbet, 2013). According to Storøy et al. (2013) the current status of traceability in FSCs is that many food producers have good, often electronic traceability systems internally, but the sharing of information (especially electronic exchange) among actors in the supply chain is insufficient. The diversity and proprietary nature of the actor's internal systems, together with an unwillingness to share information due to business risks, are the main reasons. Nonetheless, the need and demand for increased traceability as well as transparency have triggered a number of projects from which concepts and models been developed and published. In the following sections, some of the frameworks, concepts, and models are presented along with the main findings from these.

4.1 Traceability systems

A number of researchers have provided different aspects of traceability, which have evolved into different frameworks of traceability systems. Bendaoud et al. 2007, (p. 2) define a traceability system as a "system structured in such a way that it allows to totally or partially reconstruct the lifecycle of a given set of physical products." Moe (1998) provides in Fig. 1A system description that allows tracing of both the product and the activities (core entities) that should be included in a traceability system. Both of them have essential descriptors to be traced, such as type of product, type of activity, amount of product, time and/or duration of the activity. The information related to these must be collected or measured and stored.

FIG. 1 Fundamental structure of a traceability system (Moe, 1998). Specific examples of the descriptors are presented in this figure including quality attributes and/or environmental factors.



The four pillars of the traceability framework proposed by Regattieri et al. (2007) coincide with Moe's point of view regarding product identification and data to trace the product's routing or processes (activities). In addition to these shared dimensions between the frameworks, the framework by Regattieri et al. (2007) is broader since it also includes tools to achieve the traceability. Technical solutions and operative resources, such as alphanumerical codes, bar codes, or RFID, are included for the proper functioning of a traceability system.

Another framework that focuses on the way traceability systems can be designed, assessed, and managed is presented by Bendaoud et al. (2012). Unlike the previous frameworks, this takes on a generic approach with specific emphasis on the surrounding environment for a traceability system. The essential aspects of the surrounding environment to understand and include are the supply chain actors, regulations, standards, products, government bodies, and internal beneficiaries. The framework is exhaustive and based on known systematic frameworks, such as the FAST (Function Analysis System Technique) (Bytheway, 2005). The surroundings are evaluated from three complementary points of view:

1. the functional point of view, by focusing on what the traceability system is expected to perform. The generic primary function is "to provide the beneficiaries of the traceability system with data on product traceability," where the beneficiaries are the entities that surround the traceability system and the data comprises the upstream (origin of input material), internal, and downstream traceability (destination(s) of output products).
2. the technical perspective, by focusing on how the traceability system should work, the technical functions needed to do so, and which technical criteria allow them to be assessed.
3. the informational point of view, which is considered in order to build a generic traceability data model; thus it is defined by the different data to be taken into account for the good performance of this system.

Nevertheless, a traceability system alone is not sufficient to achieve safety requirements in the supply chain; it should be seen as a complementary tool to quality safety activities (Bosona and Gebresenbet, 2013).

4.2 Traceability concepts and projects

The CATRENE PASTEUR project, a European research consortium of academic and industrial partners (2009–12) set out with the aim of tracking and displaying food quality and the actual remaining shelf life (Pasteur Project, 2012). With empirical studies on meat and fruit products, a wireless sensor platform and tags were developed during the project. The Pasteur sensor tag combined RFID with sensors measuring, e.g., temperature, humidity, and quality. According to the Netherlands Packaging Centre, NVC, which coordinated the project, all firms along the supply chain would gain benefits from the Pasteur sensor technology. For the producer it would be easier to be certain about the product quality. For freight forwarders the evaluation of correct temperatures during transport would be enabled. The retailers would be able to check and control the product quality on the shelves. Lastly, if sensor tags were placed on each package, the consumer would be able to see the product's quality at home with their cell phone (NVC, 2012).

The DynahMat project (dynamic shelf life for minimized food waste) set out to develop and provide road maps and implementation strategies for an open system solution that enables the integration and interconnection of different sensor solutions, food quality prediction, communication solutions, databases, business systems, and user applications. With specific focus on the static date-labeling system, the project has explored ways to minimize food waste and supply chain inefficiencies, and to contribute to a more sustainable food industry.

The DynahMat concept (see Fig. 2 for an illustration) entails an infrastructure for reliable, safe, and certified sensors attached to a food product (primary or secondary packaging) that provide data (position, time, identity, temperature, mechanical impact, etc.) to a cloud-based information system. The data is processed with, for example, prediction models for dynamic shelf life and other information that can be gained from the data and then communicated to the supply chain actors involved in the product flow, as well as the end customer/consumer through different digital interfaces (Web pages, mobile apps, business systems).

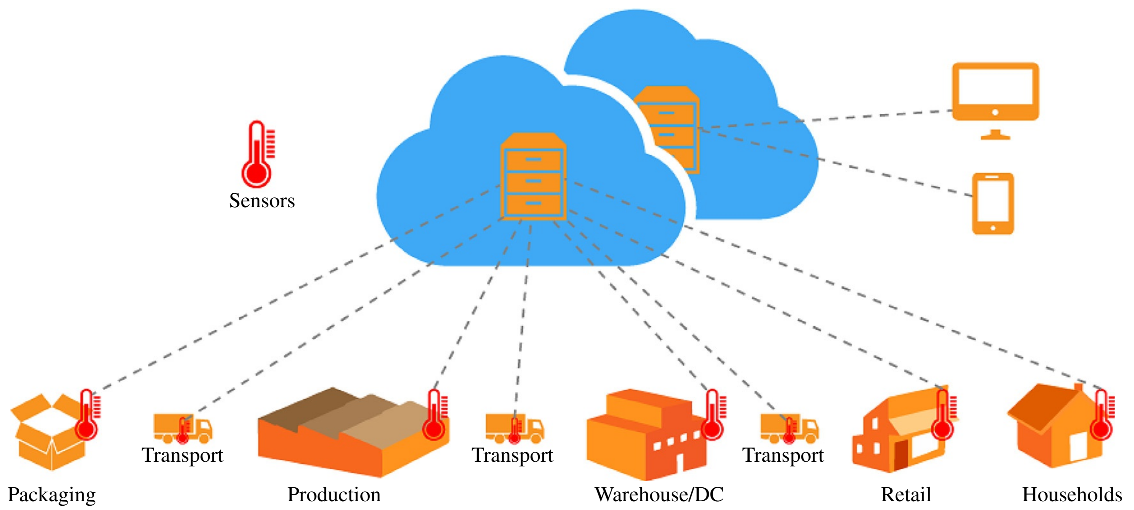


FIG. 2 An illustration of the DynahMat concept. *(Source: DynahMat Final Report 2017.)*

The main learning outcomes from the DynahMat project were that a secured, stable, and cold food supply chain enables longer shelf life for the products investigated as most product flows are below recommended temperatures. However, it would need real-time monitoring in order to identify abnormalities; i.e., if too high a temperature is registered it would enable actions to be taken directly as well as provide registration of documented cold chain data for updates on predicted quality and shelf life. A second key outcome relates to a supply chain vs. consumer solution, where it was found that in terms of implementation potential and food waste reduction a supply chain solution on secondary packages shows the greatest potential. Furthermore, the actual measuring of goods temperatures at every step of the supply chain for every delivery takes quite a lot of time. A central area of efficiency improvements was found from having a unified and automatic way of measuring temperature in the supply chain in terms of time reduction related to temperature controls.

5 Overview of technologies

5.1 Time and temperature indicators

The examples of time and temperature indicators (TTIs) have increased since 2000. Several companies provide TTI solutions used to track chill chains worldwide, e.g., ColdStream by SensiTech, SmartTrace by Smart Trace Online Monitoring, and MonitorMark by 3M, among others. TTIs are most commonly used by food producers and distributors who perform random or specific tests to monitor the quality of their cold chain distribution. These types of quality controls are mainly performed using puck-sized data loggers, such as the TempTale4 USB (TT4 USB), which contains microprocessor, battery, and memory with easily accessible data that is transferred through an integrated 2.0 USB. This can be connected to a server at the final destination (SensiTech, 2018). The increasing interest in rigid cold chain quality control has increased demand on the service and technology levels of TTI solutions. Smart Trace Online Monitoring has developed a transportation monitoring system that notifies time, temperature, and location of the products distributed with only minutes of online delay. The Smart Trace indicator is a small nonreturnable tag placed on the pallet level. After the tags are activated, they continuously upload time and temperature information to a gateway placed in the transportation unit. The data analyzed is customized to suit the needs of the sender (SmartTrace, 2018). This type of monitoring system can be valuable for food producers supplying perishable food products sensitive to temperature changes, such as meat, fish, seafood, and ready-to-eat products. Time and temperature indicators are mainly used between producer and wholesaler, i.e., during transportation, and few of these indicators can be seen or used by the retail staff or the end consumers.

5.2 Biosensors

Biosensors are physiochemical detectors that measure and/or categorize biological material (Rodriguez-Mozaz et al., 2004). Biosensors can detect specific microorganisms by containing active sites that bind to target molecules such as specific enzymes, DNA sequences, antibodies, or proteins (Zhou and Dong, 2011). Up to now, biosensors that target specific microorganisms only exist in the laboratory. However, upcoming biosensors within the food industry are promising, especially those that have the possibility of determining pathogenic microorganisms in food products (Rodriguez-Mozaz et al., 2004). Biosensors with more general biochemical mechanisms have come further in research development and there are several research projects around the world, developing biosensor concepts for food quality control (Pasteur Project, 2012; Fraunhofer Press, 2011). General biosensors detect and categorize chemical changes in food, such as conductance, pH, or gas composition. These chemical changes in food are due to biochemical breakdown or changes or to an increasing amount of microbial growth (Loessner et al., 2005). Examples of biosensors for food products are RipeSense (RipeSense, 2018), and the biosensor film developed by the Fraunhofer Research Institution for Modular Solid State Technologies EMFT (Fraunhofer Press, 2011).

5.3 Internet of things

The Internet of things (IoT) is a collective term for the development of connected devices, i.e., machinery, vehicles, goods, household appliances, packages, and other things equipped with small built-in sensors and computers. These devices can perceive their surroundings and communicate with other devices or humans, thus creating a situational behavior, and they can help to create smarter, more attractive, and more helpful environments, goods, and services. It is proclaimed that the IoT can create prosperity through efficiencies and innovations in various industries, as well as novel usages for consumers, e.g., health, facility management, and personal security and convenience. Verdouw et al. (2016, p. 129) state that, based on

IoT, "food supply chains can be monitored, controlled, planned and optimized remotely and in real-time via the Internet based on virtual objects instead of observation on site."

With sensor technologies connected to the Internet that register, monitor, and transfer food quality data as well as logistics data, advanced solutions that not only can track and trace but also reallocate, optimize, or manage deviations in ongoing product flows can be implemented. The latest advancements in IoT include the release of new standards. The Narrowband Internet of Things (NB-IoT) standards introduced in 2017 represent one example of technological development that enables new ways to implement traceability systems. The NB-IoT is connected to 4G and the coming 5G system for telecommunication and enables small, battery-efficient sensors that directly communicate through the base stations instead of being dependent on different gateways to send data to cloud servers. The communication advancements with NB-IoT implies that the substantial costs of investing in and installing gateways in each supply chain facility can be reduced.

5.4 Block chain technologies

One technology that has been given much attention during the last few years, which can offer both traceability and transparency, is blockchain technology (Yli-Huumo et al., 2016), which initially was invented to support the digital currency of Bitcoin (Nakamoto, 2008). The blockchain technology is designed to store data in blocks; placed in chronological order and based on a mathematical trapdoor (Brennan and Lunn, 2016) the data stored in the blocks is impossible to alter or remove (Nakamoto, 2008; Fanning and Centers, 2016). Copies of the chain of blocks (hence the term blockchain), and thereby the information, are distributed among the participants in the network (Tsai et al., 2016). The copies of the blockchain are then updated when a new block of information is added to the chain (Swan, 2016). While initially research conducted related to blockchains has focused on digital currencies (e.g., Bitcoin) (Yli-Huumo et al., 2016), the increasing usage in other industries to handle transactional information is growing, especially as a recordkeeping technology (Lemieux, 2016). The irreversible data-storing technology that blockchain enables has made the food supply chain industry an interesting application area (Tian, 2016), where the technology could support traceability and thereby achieve transparency (Hancock and Vaizey, 2016).

From a consumer perspective, blockchain technology could open up new possibilities for the food supply chain actors. By reading a simple QR code with a smartphone, data such as an animal's date of birth, use of antibiotics, vaccinations, and location where the livestock was raised can be presented and conveyed to the consumer in a reliable way. For food suppliers a traceability system based on blockchain technology would enable source information about the origin, condition, and movement of food, and contaminated produce could be quickly traced. According to IBM, a major opportunity with blockchain technology is to provide transparency across entire business ecosystems. They have announced blockchain collaboration projects with major food actors, including Nestle, Unilever, and Walmart. Tian, 2017 argues that the centralized traceability systems of today are monopolistic, opaque, and asymmetric, which could cause trust problems. The author (Tian, 2017) argues that the decentralized set-up of blockchain technology together with IoT applications shows great potential for increased transparency and openness among supply chain actors, as well as in consumer relations. However, it is also proclaimed that the technology and its applications are new and further developments are needed.

6 Industrial field studies—Putting concept and models into reality

In order to increase understanding and explore the "real" challenges as well as opportunities with new concepts and models for increased tractability and transparency, a number of field studies have been performed (Göransson et al. 2018a). In this section, a specific study within the DynahMat project is presented, based on two field tests in which all actors had real-time information about the time and temperature of a product from production until storing and consumption in a household. The field studies were performed during the summer of 2016 (field test 1) and the summer of 2017 (field test 2). The supply chain scope covered production until consumption in the home of a consumer. The outside temperature during these periods ranged between 17°C–26°C during the daytime.

The product used in the field study was smoked sliced ham, consumer packed in a modified atmosphere and distributed in plastic return crates stacked together on returnable EU-pallets (see Fig. 3). The printed shelf life was 2016-07-03, i.e., 25 days for field test 1 and 2017-07-26, i.e., 27 days for field test 2. The time range of the field tests started with the production day until up to 36 days after labeled shelf life on the package, i.e., 71–73 days. Perishable food products like smoked sliced ham are primarily spoiled by the growth of microorganisms forming compounds (both volatile and/or particle-bound) that cause off odor and/or taste. Thus, the number of microorganisms is indicative of the quality of the food product. However, this number does not necessarily correlate to the presence of pathogenic microorganisms and the risk of food poisoning.

FIG. 3 Image of the primary packages of sliced ham and the return crates (secondary packaging) they were distributed within.

For the field tests, Bluetooth Low Energy sensors (nRF51822, Nordic Semiconductor) were used for measuring the temperature in the FSCs (20 sensors per test). The sensors were placed on the outside of the primary packages in close connection but not on the content. The temperature history being monitored is thus not exactly that in the proximity of the microorganisms, which affects their growth. However, based on other studies (Göransson et al., 2018a) the difference of product surface temperature compared to the surface of the ham is small. The temperature measurements were continuously broadcasted by the sensors and collected by Sony Xperia mobile phones every 10 minutes. The mobile phones transmitted the sensor data, including time stamps and position data (GPS), to a web server, where the data were stored in a relational database and were made available in real time through a Web interface. The data could be retrieved anytime via a PHP-based application and imported to a data analysis tool (e.g., Excel). The calibrations of all sensors were controlled in a thermal incubator and data adjusted based on the calibration results.

The shelf life of the product was predicted from the temperature sensor data using models that first predict microbial growth, which was thereafter secondarily decoded to food quality and remaining shelf life. Thus first the number of microorganisms were predicted from the logged storage temperature and then the days remaining of shelf life were calculated from the number of predicted bacteria and an assumed future storage at +8°C (maximum storage temperature for this product in Sweden).

A set of published candidate prediction models were identified, investigated, and validated concerning functionality for use in the prediction of dynamic shelf life (Kreyenschmidt et al., 2010; Mataragas et al., 2006; Devlieghere et al., 1998, 1999). The selected models all describe how the growth of spoilage bacteria of modified atmosphere packed (MAP) ham, lactic acid bacteria, is affected by storage temperature. Important issues addressed during validation were how well the growth rate of spoilage microorganisms corresponded between the predictive model and the actual product used in the field tests, as well as how initial status in terms of microflora concentration and composition influenced the prediction accuracy.

The validation storage studies were conducted at +8°C. In order to be generally applicable, in this study, assumed best- and worst-case scenarios of the ham product, i.e., before and after a deacidification process during a normal week of production, were compared. From the maximum specific growth rate values for bias (Bf) and accuracy factor (Af) for the selected models were calculated according to Ross (1996) (Table 1).

The model published by Kreyenschmidt et al. (2010) gave a slight underprediction of 13% (B_f), whereas the Mataragas et al. model overestimated bacterial growth at 18%. The model proposed by Devlieghere et al. (1998) gave a strong overprediction. The model by Mataragas et al. (2006) was selected as the most applicable model for the field studies. This decision was based on the fact that it is better, from a consumer point of view, to have an overprediction by the model, since the risk is minimized that the consumer will get a spoiled product even though the dynamic shelf-life labeling says that the ham is of good quality.

TABLE 1 Calculated bias and accuracy factor for modified atmosphere packed (MAP) smoked ham validation data vs. predicted model data at 8°C

	Kreyenschmidt et al. (2010)	Mataragas et al. (2006)	Devlieghere et al. (1998, 1999)
B_f	0.87	1.18	2.54
A_f	1.14	1.18	2.54

6.1 Field study set-up and process

The specific supply chain started at the production site (see Fig. 4) when the ham was sliced (product temperature at 0°C) and packed and placed for storage/dispatch. The packages were then picked up by a transport company and delivered to a wholesaler. After receiving the pallets, the wholesaler stored them (the pallets were split while crates were kept intact). When an order was received from a retail outlet, the number of ordered crates were placed on a new pallet (with other products) and placed for distribution. Another transport company then picked up the new pallet and delivered it to a retail outlet that placed them in storage, followed by placement on retail shelves in the retail outlet (i.e., the primary packages removed from the crates).

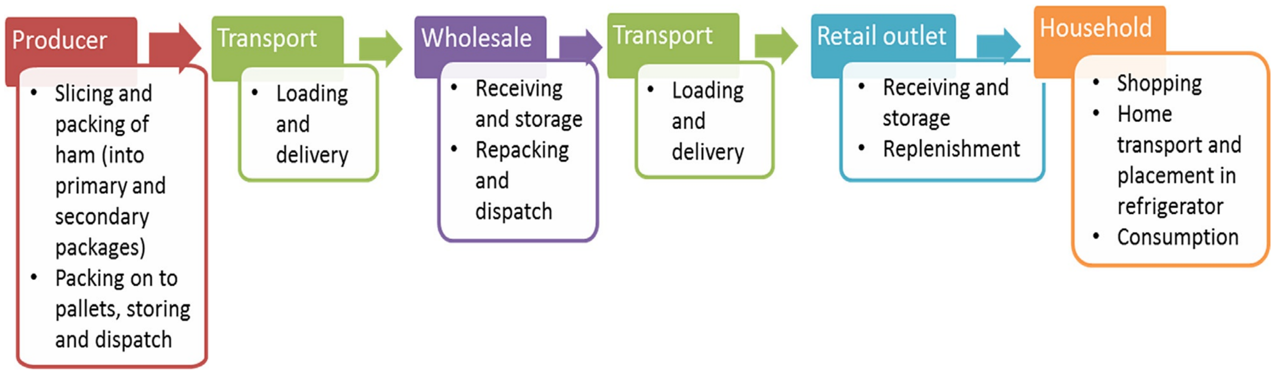


FIG. 4 The supply chain scope, from production to consumption, and main processes covered in the field studies.

At the retail outlet a consumer picked the product off the retail shelf, placed it in a shopping cart, and continued shopping. After paying for the groceries collected, the consumer loaded the products in the trunk of a car and drove home. After arrival at the home, the consumer placed the ham in the refrigerator. In our set-up, half of the packages (20 packages of ham) were then opened and "consumed" while the other 20 were kept in the refrigerator unopened during the field study. The consumption of the ham followed a "typical" breakfast routine, i.e., for time periods between 20 minutes ("normal breakfast") to 2 hours ("weekend breakfast") the ham packages were placed on a kitchen table at normal (20°C–23°C) in-house temperature and then put in the refrigerator again. The "breakfast" procedure was carried out five times during the tests within the first 10 days. See Table 2 for the process steps and the time slots of the field study.

The rationale behind the field study design to open half of the packages and keep half of them sealed was to investigate differences between supply chain and consumer solutions. There are a number of time-temperature solutions on the market for consumer products (e.g., Tempix, 2018) as well as reported research focused on the supply chain part of the cold chain (e.g., Göransson et al., 2018b; Aung and Chang, 2014) that target the reduction of food waste. However, most solutions and studies are only suitable for sealed packages, while most food wastage in the consumer stage relates to packages being opened (Silvenius et al., 2014). Hence, we set out to measure the difference between quality indicators of temperature loading for sealed packaging in the case of the packages being opened vs unopened.

TABLE 2 The process steps and time slots covered in the field study

Supply chain actor	Main processes	Time slots Field test 1	Time slots Field test 2	Process description
Producer	Slicing and packing of ham	June 08 2016 9.00–11.00	June 28 2017 12.00–14.00	45 packages were used in each test (three full secondary packages). Additional six packages were taken for laboratory analysis (initial bacterial load)
	Packing, storing, and dispatch	June 8 11.00–20.00	June 28 14.00–20.00	20 sensors were placed on half of the primary packages and 3 sensors on the outside of the three return crates used. They are then placed on a pallet together with other orders
Transport company	Loading and delivery	June 8 20.00–22.00	June 28 20.00–22.00	The full pallet is loaded as normal on the truck, together with other chilled meat products
Wholesaler	Receiving and storage	June 8 22.00–06.45	June 28 22.00–06.45	Products placed in storage for the night
	Repacking and dispatch	June 9 6.45–8.00	June 29 6.45–8.00	The secondary packages are packed on new pallets together with other chilled products and placed for pick-up
Transport company	Loading and delivery	June 9 8.00–9.30	June 29 8.00–9.30	The transport company distributes the goods
Retail outlet	Receiving and storage	June 9 9.30–11.55	June 29 9.30–14.45	A retail outlet receives the goods and puts them in storage
	Replenishment	June 10 11.55–15.30	June 29 14.45–15.30	In field test 1 the products are kept one day in storage before placed in the store. In field test 2 the products are replenished the same day as arrival
Consumer	Shopping	June 12 15.30–16.00	June 29 15.30–15.45	Shopping is carried out
	Home transport and placement in fridge	June 12 16.00–16.30	June 29 16.30–19.00	In field test 1 the transport took 30 minutes. In field test 2 it took 2 hours (longer distance and stops on the route)
Consumer household	Consumption	June 12–Aug 8	June 29–Aug 16	Half of the packages were opened and half were kept intact and not removed from the refrigerator
	Breakfast 1	June 13 30 min	July 1 120 min	All opened packages were placed on a kitchen table in room temperature at five occasions with different time periods. For the microbiological analysis of the actual bacteria load on the ham, samples were taken out on several occasions and placed in a freezer
	Breakfast 2	June 14 20 min	July 2 30 min	
	Breakfast 3	June 15 90 min	July 4 60 min	
	Breakfast 4	June 16 30 min	July 5 20 min	
	Breakfast 5	June 17 90 min	July 6 30 min	

During the field tests, packages of ham were taken at specific time points and frozen in an ordinary consumer freezer (see Table 3). At the end of the field test, all samples were transported to a microbiological laboratory, thawed slowly at refrigerator temperature, and evaluated for the number of lactic acid bacteria. Lactic acid bacteria were grown on MRS (De Man Rogosa Sharpe, Oxoid) for 3 days at 30°C. Freezing inactivates, but does not necessarily decrease, the bacteria present in food. Once thawed, however, the bacteria can again become active and multiply. The effect of freezing on bacteria varies greatly between species, physiological state, food composition, and the rate of freezing and thawing. In this study we are interested in studying the number of lactic acid bacteria and these microorganisms are considered resistant and most probably only slightly decreased when foods are frozen (Lopez et al., 2006).

TABLE 3 Samples taken out for analysis

Samples taken during field test 1	Comments	Samples taken during field test 2	Comments
June 9 2016	Production day	June 28, 2017	Production day
July 3	Date for static shelf life	July 14	Half-time for the static shelf life
July 13	10 days after ssl	July 26	Date for static shelf life
July 25	22 days after ssl	August 6	11 days after ssl
August 8	36 days after ssl	August 16	21 days after ssl

ssl stands for static shelf life and refers to the printed best-before date on the packages.

6.2 Field study findings

Based on follow-up discussions with involved actors (producer, logistics service provider, wholesale and retail outlet), a number of issues were reflected upon and insights gained. A uniform, quality-assured way of measuring temperature along the supply chain from production to retail shelves was found valuable for all parties in the chain as it is now, despite industry recommendations, clearly handled in different ways. In these tests, the inclusion of the consumer fridge was also found interesting but challenging in terms of real applications that could be considered and used, due to several technological and integrity related aspects. However, data provided by a system like the one in this field study were seen to be valuable for further research and development, especially in how the food is really affected throughout the supply chain, and they contribute to FSC research and development.

In both field tests, the overall logistics was efficient. From production to retail outlet via the retail distribution center (a distance of 174 km) took 22 hours in field test 1 and 20 hours in field test 2 (see Fig. 5). Initial surrounding temperature levels, that is, when the products were placed in the dispatch area at the producer, were high and it took almost 6 hours until the temperature of the sensor was below the threshold of +8°C. Transport, storage at wholesale, and distribution to the retail outlet were all at well below the required temperature and most of the time below 4°C.

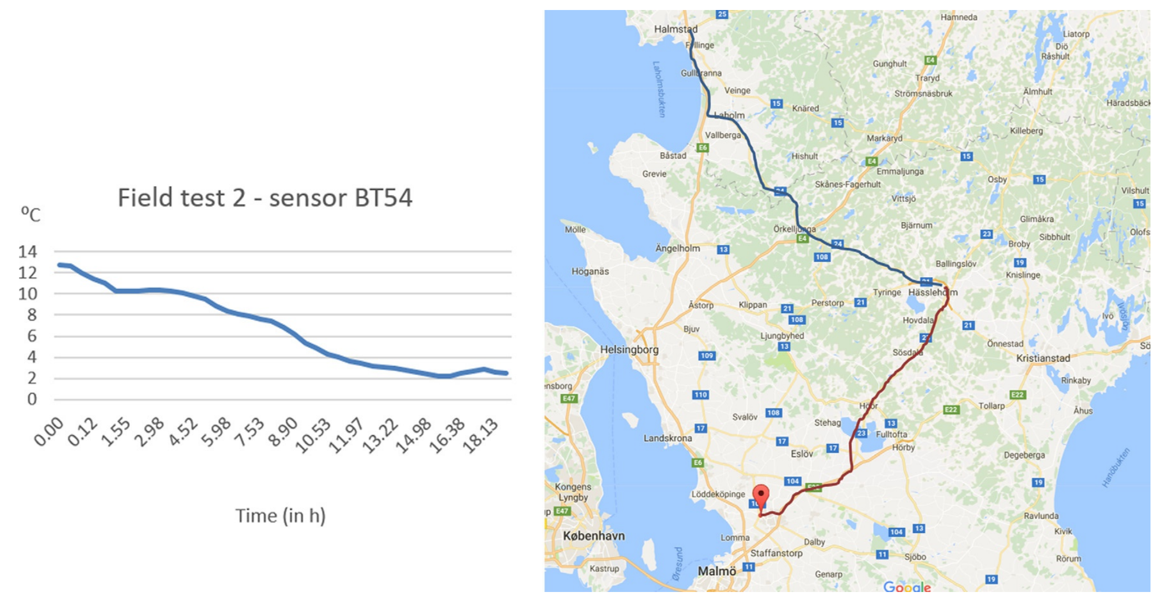


FIG. 5 Distance, time, and temperature from field test 2, for sensor BT54, from production through a distribution center, including night storage, and delivery to a retail outlet.

During the field tests, all the involved supply chain actors had access through a Web interface (see Fig. 6 for a screenshot of the Web interface) to the time and temperature data (dark gray line) for the product, as well as its position. Two dynamic predicted best-before dates were also presented, based on actual temperature impact, and predicted whether kept at the same temperature (in each moment) (light gray line) or if kept at the highest recommended temperature (gray line), i.e., +8°C for the ham.

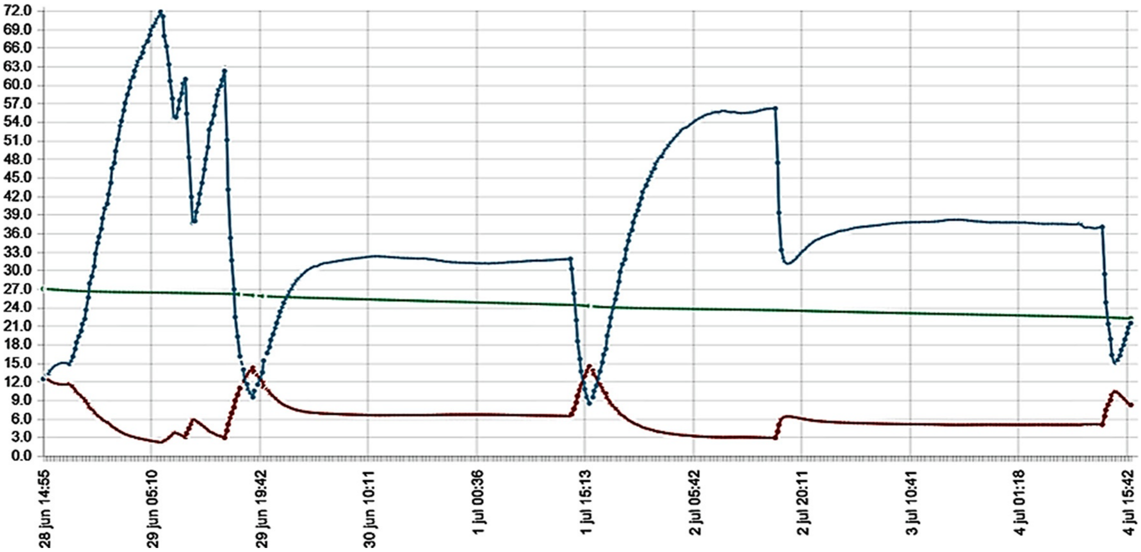


FIG. 6 Screenshot from the Web interface during the field test, where each of the actors in the supply chain could, in real time, follow the temperature and get new predicted best-before dates based on a prediction model. The *dark gray line* shows the actual temperature at each time slot, the *gray line* shows the predicted best-before date if kept in 8C and the *light gray line* shows the predicted best-before date if kept in the actual temperature.

The actors all agreed that monitoring the goods in real time enabled more responsiveness to upcoming deviations of either temperature or position, leading to more effective handling and mitigation of losses, conceivably reducing both direct and indirect costs. Examples of direct costs associated with these kinds of deviations are claims and customer compensation for damaged goods, both economic compensation as well as purchasing and shipping costs for replacement products. Based on more accurate and reliable data, indirect costs such as administrative costs in finding out what, where, and who, i.e., costs for troubleshooting and internal/external follow-up, could be minimized. Also, deductibles and insurance costs were mentioned along with lost sales and dissatisfied end costumers.

The continuous updates of predicted shelf life based on the actual temperature measured, i.e., dynamic shelf life of the product in the tests, were found interesting by the actors. While the applicability of such information for the consumer was reflected upon, a dynamically updated label on each package was found neither feasible nor viable. Instead, based on accurate and reliable information on real temperature exposures of the products in the supply chain, input on how to determine shelf life of the product could be used, and is better aligned to reality. However, such changes would demand a system that could handle abnormalities (e.g., too high or too low temperatures) in order to secure safe products to the consumers.

In Table 4, the dynamically predicted best-before date is presented for one product kept in the refrigerator all the time, and one used for "breakfast," i.e., placed on a kitchen table five times (see Fig. 7 for the time temperature curve of both samples). When comparing the products that have been exposed to a higher temperature impact (e.g., product 1A and 1B in field test 1) both products have longer estimated shelf life but also differences due to the accumulated temperature impact (see Table 4).

Table 4 shows that, due to the initial impact of higher temperature that was measured during field test 2, a shorter shelf life than the static one printed on the package was initially predicted. However, due to low temperature in the rest of the supply chain as well as in the refrigerator, the dynamically predicted shelf life for the ham was prolonged up to 30% longer (11 days) than the static one labeled on the package.

Worth mentioning in relation to the numbers in Table 4 is that, in both field tests, the products used for "breakfast" were also opened, i.e., the microbiological circumstances changed and the protective modified atmosphere was spoiled. Hence, the proclaimed increase in shelf life for product 1B and 2B based on the prediction model is actually shorter than presented in Table 4. The microbiological analysis is presented in the next section.

TABLE 4 Dynamic shelf life in comparison with static (i.e., printed) shelf life for the ham products in the field study based on the prediction models used

		Dsl at wholesale day 2	Dsl during shopping day 3	Dsl in fridge day 7	Dsl in fridge day 16	Dsl in fridge day 23
Field test 1 – ssl 25 days	Product 1a (bt75)—kept in fridge	2017-07-05	2017-07-06	2017-07-10	2017-07-20	2017-07-28
	Change of predicted shelf life	8%	12%	28%	68%	100%
	Product 1b (bt98)—“breakfast”	2017-07-05	2017-07-06	2017-07-10	2017-07-15	2017-07-19
	Change of predicted shelf life	8%	12%	28%	48%	64%
Field test 2 – ssl 27 days	Product 2a (bt54)—kept in fridge	2017-07-25	2017-07-25	2017-07-27	2017-07-31	2017-08-03
	Change of predicted shelf life	−4%	−4%	4%	19%	30%
	Product 2b (bt22)—“breakfast”	2017-07-25	2017-07-25	2017-07-26	2017-07-29	2017-07-31
	Change of predicted shelf life	−4%	−4%	0%	11%	19%

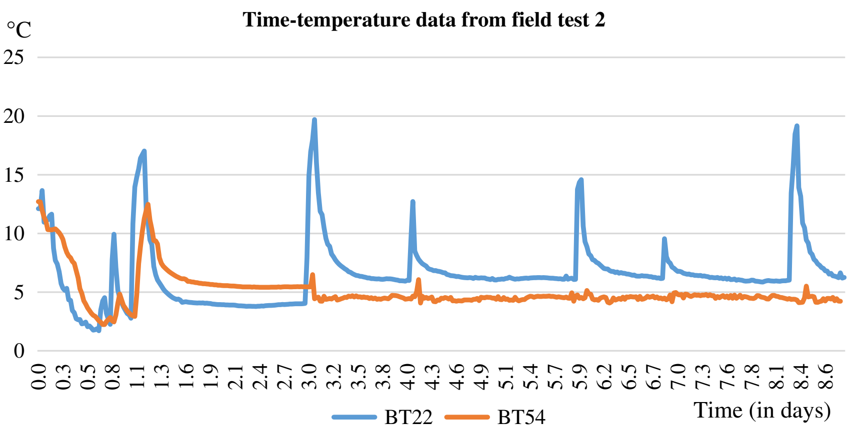


FIG. 7 Time temperature data from two of the sensors, BT 54 for a product being kept in the refrigerator at the consumer level and BT22 being placed at room temperature five times, representing a “breakfast” scenario.

6.3 Results from the microbiological analysis

The results of field test 2, performed in the summer of 2017, are shown in Table 5. The static shelf life (ssl) is set by the producer based on a storage at maximum +8°C (standard storage temperature in Sweden); however, data from the field test illustrates that, due to the low mean temperature along the whole supply chain, a much longer total and/or remaining shelf life than the SSL is predicted based on the prediction models.

As stated previously, the dynamic shelf life is secondarily predicted from the number of spoilage microorganisms which, in the case of MAP sliced ham, is lactic acid bacteria. Thus first the number of lactic acid bacteria is predicted from the logged storage temperature and then the days remaining of shelf life are calculated from the number of predicted

TABLE 5 Field test number 2

Sampling point	Time remaining of static shelf life (days)	Shelf-life prediction (days left until spoilage)	Mean storage temp. (°C)	Prediction no. of lactic acid bacteria (log cfu/g)	Measured no. of lactic acid bacteria[a] (log cfu/g)
Packages taken direct from production					
Production day	28	27	–	1.0	2.0 ± 0.0
Packages keep in refrigerator (unopened)					
Half-time for ssl	12	18	4.2	3.7	5.2 ± 0.8
Date for ssl	0	11	4.5	5.6	7.3 ± 0.5
11 days after ssl	−11	5	4.4	7.2	6.5 ± 0.7
21 days after ssl	−21	1	4.2	8.2	7.0 ± 0.4
Breakfast packages (opened)					
Half-time for ssl	−12	15	6.3	4.5	6.7 ± 0.0
Date for ssl	0	6	6	6.8	7.3 ± 0.2
11 days after ssl	−11	0	6	8.6	7.2 ± 0.8
21 days after ssl	−21	0	6	8.6	7.2 ± 0.1

This table shows the measured mean temperature until sampling point, the remaining days of SSL (a negative value means that shelf life has been passed), predicted shelf life (0 means that the shelf life has been reached), as well as predicted and measured number of spoilage microorganisms, lactic acid bacteria. The data is available for both unopened and opened packages.
[a]*A mean value of five individual samples (packages).*

bacteria and an assumed future storage at +8°C. To evaluate the accuracy of the prediction, the number of lactic acid bacteria was measured during the field test and compared to the prediction. From this comparison two main results were visualized: (1) the number of lactic acid bacteria from the beginning is lower than the dynamic prediction, and (2) the maximum number of bacteria is lower than in the dynamic prediction tool. During the DynahMat project it was realized that fixing the initial number of lactic acid bacteria to a realistic figure is difficult, since the biological variation in-between packages is large. Data from earlier experiments (not shown here) illustrate that the number of lactic acid bacteria in different packages from the same production day and site can vary greatly. It was, e.g., shown that the number of lactic acid bacteria from different packages stored at the same temperature for about 20 days varied from 2 to 7.5 log cfu/g. However, from the same experiment the mean starting number of lactic acid bacteria was 1.1 log cfu/g. It would in the prediction be possible to use, e.g., a Monte Carlo simulation to illustrate this variation; however, being so large the prediction would not be at all useful to the actors of the food chain or the consumer. When bacteria grow, they grow in a logarithmic manner until they reach a stationary phase, the maximum possible number at the set environmental conditions. The stationary phase is limited by nutrients and space, and food spoilage is often reached when the bacteria reach the stationary phase or just after (Adams et al., 2015). The maximum number of lactic acid bacteria in the dynamic prediction was set according to the chosen model (Mataragas et al., 2006) to 8.3–8.9 log cfu/g; however, the field test shows that the actual maximum number of lactic acid bacteria in this ham at these conditions is rather around 7.2–7.3 log cfu/g. Thus this should be investigated further and possibly modified in the dynamic prediction models in order to make more accurate predictions.

6.4 Summary of field study

A starting point of the field study was that the current logic for SSL, i.e., a printed best-before or expiration date labeling, is one of the major reasons for food waste, both in the supply chain and ultimately in households (Lindbom et al., 2014; Rahelu, 2009; WRAP, 2011). The logic guiding the best-before date follows a worst-case scenario in which products are distributed, stored, and handled in the highest allowed temperature, e.g., +4°C, +5°C, or +8°C (depending on national standards and conventions). In this study, it was found that a secured, stable, and cold food supply chain enables longer shelf life for the products investigated. Furthermore, a quality indicator of temperature loading for sealed packaging is not, per se, targeting consumer wastage. With most food waste in households being related to opened packages, other solutions such as smaller-portioned packaging, pricing, and sensors showing how long a package has been opened show more potential to reduce food waste and guide consumers on making better "waste" decisions.

Increased transparency and visibility for supply chain actors regarding actual temperature changes show potential in directly affecting food wastage in the supply chain and potentially also sales in retail stores (e.g., reduced price on products that have passed best-before labeling but still can be sold), and indirectly affecting food wastage by the consumer. This indirect effect is derived from the potential in building trust between food supply chains and consumers (a trust that the many food frauds and scandals have decreased) by being transparent about handling and ensuring cold chains. With increased trust, consumers may consume products over a longer time span. However, as the results from this field study as well as other studies (Göransson et al., 2018b) show, while there are many potentials with new concepts for traceability and transparency in food supply chains, there are a number of organizational and interorganizational challenges that need to be dealt with.

7 Value and challenges with sharing information and providing increased transparency in food supply chains

While technological and conceptual development is a central part of enhanced transparency and visibility in supply chains, the business needs and requirements are the priority for the supply chain actors. Hsiao and Huang (2016, p. 187) state that "Inter-organizational time-temperature sharing could enhance food safety and quality, and further enhance the competitive advantage of food supply chains as a whole." However, Raab et al. (2011) point out that lack of exchange of temperature data between companies is one of the challenges currently remaining in temperature tracking. Furthermore, appropriate alignment among supply chain actors is critical for successful implementation and use of new technology (e.g., sensors) in minimizing waste and increasing safety and quality for consumers. The literature on supply chain alignment, information sharing, and collaboration is vast. While collaboration and information sharing are proven to provide more responsive and agile supply chains that manage changes in demand and meet the customer demand faster (Mentzer et al., 2001), a number of challenges have been reported. Lee (2004) puts forward that lack of alignment is one of the major reasons for failures of supply chain practices, and Lambert and Cooper (2000) argue that risk and gain sharing is critical in supply chain collaboration. Giguere and Householder (2012) discuss supply chain visibility, something that the introduction of new sensors and technologies in one way or another will enable, and conclude that sharing data is primarily a matter of trust, not of technology or data. Furthermore, the alignment of each actor's business strategy with the use and sharing of data in the supply chain is critical for collaboration and in determining on what level the collaboration with different actors should be Giguere and Householder (2012). Hsiao and Huang (2016, p. 186) conclude that interorganizational time-temperature sharing could enhance food safety and quality, and further enhance the competitive advantage of FSCs as a whole.

However, based on a study of information and organization integration in supply chains (Bagchi and Skjoett-Larsen, 2003), it was found that the probable loss of proprietary information and loss of control in sharing business information with suppliers were of major concern for supply chain actors. The main barriers to integration were: (1) the fixed mindset of managers, (2) lack of trust and the fear of sensitive business information falling into competitors' hands; (3) every member of the supply chain not being equally prepared; (4) loss of control; and (5) multiple IT platforms (Bagchi and Skjoett-Larsen, 2003). In their conclusions, (Bagchi and Skjoett-Larsen (2003, p. 104) propose that "the success of a drive to integrate the supply chain depends on the power, influence, motivation and zeal of the prime mover in the supply chain." Kürschner et al. (2008) confirm that collaboration promises mutual benefits for the partners in an SC, but these are rarely realized, due to two main reasons. First, each company has only partial knowledge of other companies' participation, hence incomplete information. Retrieving complete information on the flow of goods requires great effort to locate all actors. Second, the incentives to share sensitive operational data may be lacking. Also, information sharing is usually based on contracts, and to negotiate these contracts with each and every stakeholder, customer, and supplier would be inefficient

(Shah, 2005). Furthermore, Kürschner et al. (2008). (2008) explored possible solutions to work around this problem and find ways to share information between actors in a supply chain. They found that there are five major requirements for a solution for information sharing in an SC: data ownership, security, business relationship independence, organic growth, and quality of service. Hellström et al. (2011, p. 519) state that "even though risk and gain sharing is critical in implementing SCM, there is limited literature on the subject involving more than two supply chain actors."

In line with previous research, it can be concluded that a number of opportunities exist based on more accurate and reliable monitoring of temperature in FSCs. These include systems to handle temperature deviations and alarms quickly and effectively, at the same time as producers base their shelf-life predictions on data obtained from their supply chains. However, for this to happen the protective attitude among FSC actors needs to be reduced and appropriate business models and incentive set-ups developed.

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