Thesis for the Degree of Doctor of Philosophy

Enhancing quality management of fresh fish supply chains through improved logistics and ensured traceability

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ABSTRACT

The aim of the project was to enhance product quality management in fresh fish supply chains through improved logistics management and ensured traceability effectiveness. The study provides insights into seafood companies' perspectives on the benefits of implementing traceability. Knowledge on the net benefits of implementing traceability and the distribution of costs and benefits among actors can support decision making. Comprehensive literature review on the necessary components to ensure traceability and a framework developed to assess traceability system effectiveness enable researchers and practitioners in the food/seafood sector to locate problems and take necessary actions to ensure effective traceability. In addition, more efficient use of recorded data provides an approach to enhance quality management. Data on ambient temperatures during logistics steps can be used to calculate the product warm up time. The results on temperature profiling pinpointed several hazardous steps in air transportation related to handling, storage and transport operations. Pros and cons of two transport modes, air vs. sea, were analysed. Several factors were found to influence product temperature and shelf life during logistics processes, namely, presence/absence of precooling, mode of transport, product location and logistics length. These findings help to improve logistics management as well as to make decisions on transport alternatives so as to improve quality management. The new photochromic time-temperature indicator (TTI) was found to give reproducible responses and reflect well the temperature conditions of fresh fish supply chains. The results show that a right charging time could be defined to suit the shelf life of the fresh fish product concerned. The TTI of a right charging level placed on the bottom surfaces of fresh cod retail packs was found to reflect well the temperature conditions of the product and the shelf life declared by sensory evaluation, except for the case of severely superchilled conditions, and other methods of quality control. The results indicate the potential of using the new TTI to continuously monitor product temperature history, quality and shelf life in fresh fish supply chains.

Keywords: fresh fish supply chain, traceability, logistics, air freight, sea freight, temperature mapping, quality, shelf life, time-temperature indicator.

ÁGRIP (ABSTRACT IN ICELANDIC)

Markmið verkefnisins var að efla gæðastjórnun á ferskum fiski með betri skipulagningu og endurbættum rekjanleika, allt frá veiðum til neytenda. Hluti af rannsóknunum var að fá yfirlit yfir þekkingu forstöðumanna fyrirtækja sem tengjast sjávarútvegi á rekjanleika og kostnaðarmeðvitund þeirra á vali flutningaleiða og umbúða við ákvörðunartöku um val á flutningaferlum fyrir sjávarafurðir. Greining flutningaferla var nauðsynlegur hluti verkefnisins til þess að fá heildaryfirlit yfir stöðu greinarinnar og flutningaferlanna. Niðurstaða greiningarinnar leiddi í ljós hvaða hlekki aðfangakeðjunnar væri hægt að bæta m.t.t. geymsluþols, verklags, búnaðar, umhverfisáhrifa o.fl. Í verkefninu var rannsakað hvernig hitastig þróast í gegnum flutningakeðjuna bæði fyrir flug- og sjóflutninga; flakavinnslu, forkælingu, áhrif mismunandi umbúða, - virkni geymslna og gáma og einnig við tilfærslur vöru í keðjunni. Niðurstöður þessara verkþátta verkefnisins voru notaðar til að meta hitaálag, sem afurðirnar urðu fyrir í ferlunum og nota þá til að spá fyrir um geymsluþol. Afrakstur verkefnisins verður notaður við að taka ákvarðanir um hvaða ferla eigi að lagfæra í aðfangakeðjunni svo að það komi að mestu gagni við bestun á heildarferlinu.

Kostir og gallar flug- og sjóflutnings fyrir ferskan fisk voru greindir. Niðurstöður hitakortlagningar sýndu fram á mun stöðugra hitastig í gámaflutningi með skipum en með flugflutningi. Einkum er hætta á hitaálagi í flugflutningskeðjum þegar vara flyst milli ólíkra hlekkja kælikeðjunnar. Aðrir þættir aðfangakeðjunnar, sem geta haft áhrif á gæði og geymsluþol ferskfisks er forkæling fyrir pökkun, staðsetning kassa á bretti í tilfelli illa hitastýrðra kælikeðja og lengd keðjanna.

TTI (Time Temperature Indicators) var einnig greint í verkefninu þar sem búnaður var prófaður fyrir ferskar fiskafurðir og notkun hans til að meta gæðamörk afurða. Gerðar voru prófanir á TTI í geymslutilraunum til að sannreyna hvort hraði gæðabreytinga afurða væru í samræmi við virkni TTI búnaðarins.

Lykilorð: Ferskur fiskur, rekjanleiki, vörustjórnun, flutningaferlar, skipaflutningar, flugflutningar, geymsluþol, hitaskráning, TTI-vöktun.

LIST OF ORIGINAL PAPERS

This thesis is based on the following papers, referred to in the text by their respective Roman numerals:

I. Mai, N., Bogason, S. G., Arason, S., Árnason, S. V., and Matthíasson, T. G. Benefits of traceability in fish supply chains - case studies. British Food Journal. Accepted for publication 19th October 2009.

II. Mai, N. T. T., Margeirsson, S., Stefansson, G. and Arason, S. 2010. Evaluation of a seafood firm traceability system based on process mapping information - More efficient use of recorded data. *International Journal of Food, Agriculture & Environment*: 8(2), 51-59.

III. Mai, N. T. T., Margeirsson, B., Margeirsson, S., Bogason, S. G., Sigurgísladóttir, S. and Arason, S. 2010. Temperature Mapping of Fresh Fish Supply Chains - Air and Sea Transport. *Journal of Food Process Engineering*. In press.

IV. Mai, N., Margeirsson, B. and Stefansson, G. (2010). Temperature controlled transportation alternatives for fresh fish – air or sea? In J. S. Arlbjørn (Ed.), *Logistics and Supply Chain Management in a Globalised Economy. Proceedings of the 22nd Annual NOFOMA (The Nordic Logistics Research Network) Conference*, June 10-11, 2010. (pp. 147-162). Kolding, Denmark: Department of Entrepreneurship and Relationship Management, University of Southern Denmark.

V. Mai, N., Audorff, H., Reichstein, W., Haarer, D., Olafsdottir, G., Bogason, S., Kreyenschmidt, J. and Arason, S. Performance of a new photochromic time-temperature indicator under simulated fresh fish supply chain conditions. Submitted to International Journal of Food Science & Technology, May 2010.

VI. Mai, N. T. T., Gudjónsdóttir, M., Lauzon, H. L., Sveinsdóttir, K., Martinsdóttir, E., Audorff, H., Reichstein, W., Haarer, D., Bogason, S. G. and Arason, S. Continuous quality and shelf life monitoring of retail-packed fresh cod loins in comparison with conventional methods. Submitted to the journal of Food Control, May 2010.

Abbreviations

ANOVA	Analysis of variance
CBA	Cost-benefit analysis
CBC	Combined blast and contact (cooling)
CFU	Colony-forming unit(s)
EAN.UCC	European Article Number and Uniform Code Council
EPC	Electronic product code
EPS	Expanded polystyrene
GS1	Global Solutions/Global Solutions One
GLN	Global location number
GTIN	Global trade identification number
ID	Identification
LU	Logistic unit
NPV	Net present value
PCA	Principal component analysis
QDA	Quantitative descriptive analysis
RFID	Radio frequency identification
Rf-TTI	Coupled radio frequency and time temperature indicator
RRS	Relative rate of spoilage
RSL	Remaining shelf life
RSS	Reduced space symbology
SSCC	Serial shipping container code
SSO	Specific spoilage organisms
SV	Square value
SVo	Initial square value
TMA	Trimethylamine
TRU	Traceable resource unit
TTI	Time-temperature integrator/indicator
TU	Trade unit
TVB-N	Total volatile basic nitrogen
TVC	Total viable counts

TABLE OF CONTENTS

1 INTRODUCTION

Global demand and consumption of fresh fish have increased (FAO, 2009; Vannuccini, 2004; World Fishing Net, 2010), for instance a significant growth in fresh fish market has been observed in the United Kingdom (UK) during recent years (Seafish, 2010). The world production of fresh seafood has gradually grown from about 45.4 million tons in 1998 to 54.6 million tons in 2007; Of the fish destined for human consumption in 2007 48.1% was in live and fresh form (FAO, 2007). Iced fish export from Iceland has been increasing in recent years, a rise of 43.3% in volume and 37.3% in value in 2008 compared to 2007 (Statistics Iceland, 2009), amounting to about 111.7 thousand tons in 2008 (Statistics Iceland, 2009; Statistics Iceland, 2010). Export of fresh cod and haddock fillets and portions from Iceland was about 11.5 thousand tons in 2008 (Statistics Iceland, 2009), of which about 9 thousand tons were to the UK (Seafish, 2010). Export of fresh fish fillets to the UK almost tripled from 1999 to 2004 for cod and quadrupled from 2003 to 2008 for haddock (Seafish, 2010). All these facts indicate that the supply of fresh fish is increasingly important.

A common (fresh) fish supply chain is shown in Figure 1. The chain is seen as integrated from farm to fork with flows of materials and information.

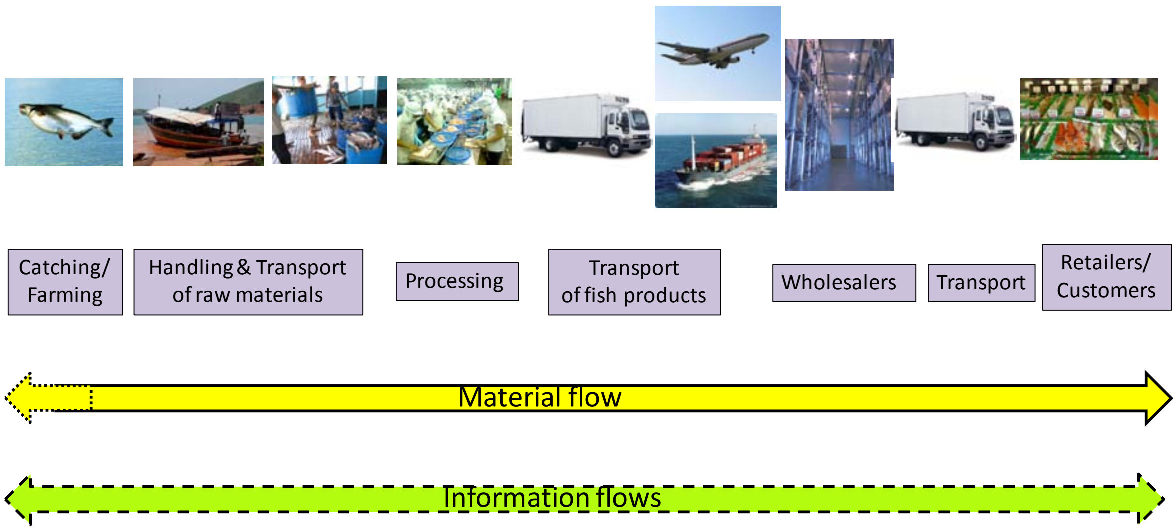

Figure 1. Integrated (fresh) fish supply chain (Adopted and modified from Coyle *et al.* (2003); EAN, (2002)).

From a supply chain management point of view, material flow is an important focus of *logistics* (Coyle *et al.*, 2003), where *quality* of products delivered to the immediate and/or final customers is emphasised. Once a product does not meet market requirements, standards or regulations, it can be rejected (Nunes *et al.*, 2003), returned (Coyle *et al.*, 2003) or even recalled in case of a food safety problem (Buhr, 2003; McEntire *et al.*, 2010). *Fish quality* is a complex concept, which for the consumer may include safety; nutritional and eating quality; freshness; obvious physical attributes of the species, size and product type; convenience and integrity; and availability (Olafsdottir, 2005; Olafsdóttir *et al.*, 1997). *Quality management* (quality assurance), defined as "all the activities and functions concerned with the attainment of quality in a company", would include the technical, managerial and environmental aspects (Huss & Ryder, 2003). The technical aspect is the main focus of quality management in the seafood industry, which includes the management of safety, freshness, shelf life and authenticity (Huss & Ryder, 2003).

Information flow is vital in supply chain management (Coyle *et al.*, 2003). It is a fundamental factor to enable product *traceability*, required by legislations (e.g. EU Regulation 178/2002 and US Bioterrorism Act PL107-188) and markets, tracking and tracing the material flow and history (EAN, 2002). It is also important to fulfil the information requests of actors and consumers in the chain related to product *quality,* e.g. information on the quality itself or on the product origin and/or handling conditions/techniques which affect the quality (Olafsdottir, 2005).

These above facts raise a need for better understanding how traceability and logistics in a fresh fish supply chain are practised, in relation to quality management, and what can be done to improve them. This study focuses on fresh fish export chains from Iceland (cod loins and haddock fillets) and, to a lesser extent, from Vietnam (*Pangasisus* fillets) which have been among the most important chains for the seafood sectors in both countries. Emphasis was to ensure the traceability effectiveness and to improve logistics management of fresh fish by more efficient use of recorded information and continuous monitoring of product temperature conditions along the chain(s) so as to enhance product quality management regarding freshness and shelf life.

1.1 Food traceability

Traceability has emerged as an important concept in food safety since the breakout of the Bovine Spongiform Encephalopathy (BSE) and dioxin crises in Europe in the last decade.

In the fields of animal health and food safety, various definitions of traceability can be found, both in legal and standard texts. *Traceability* is defined by the International Organisation for Standardisation (ISO) as "the ability to trace the history, application or location of that which is under consideration" (ISO 9000:2000 - Part 3.4.2). The term ''ability to trace and follow" is used in the European Union (EU) Regulation 178/2002 (EC, 2002b), while ''ability to follow" is present in Codex standards (CAC, 2008) or ''the creation and maintenance of records" in Bioterrorism Act 2002 of the United States of America (PL107-188, 2002). The ability to trace the product information within a company is referred to as *internal traceability*; while *external/chain traceability* is the ability to trace the product information through the links in a supply chain, or the product information a company gets and gives away (Moe, 1998).

Traceability can be divided into tracing and tracking. *Tracing* (backward or upstream) is the ability to find the origin, attributes, or history of a particular traceable item or product from given criteria, through records, upstream in the supply chain; used to find the source of the problem. *Tracking* (forward or downstream) is the ability, at every point of the chain, to find the products' localisation from given criteria; used in case of product recall and to find the cause of the problem (Bechini *et al.*, 2005; Deasy, 2002; Dupuy *et al.*, 2005; Olsson & Skjöldebrand, 2008; Schwägele, 2005).

In traceability, information accessibility is considered at four main levels: *breadth* or the amount of information the traceability system records, *depth* or how far upstream or downstream in the supply chain the system tracks, *precision* or the system assurance degree of pinpointing the movement or characteristics of a particular product, and *access* or the speed of communicating and disseminating requested information to chain actors or public health officials (McEntire *et al.*, 2010).

1.1.1 Regulations and standards on traceability

EU Regulation 178/2002, US Bioterrorism Act 2002, the 2002 and 2008 US Farm Bills - legislations on traceability of the two most important markets, the EU and the US, for agrifood and particularly seafood products - stipulate “one step back - one step forward” traceability. The regulations require food business operators to be able to know where their supplies come from and to whom their products are sent (EC, 2002b; McEntire *et al.*, 2010; PL107-188, 2002). These and other traceability-related regulations, such as EU Council Regulation 104/2000 (EC, 2002a) and EU Commission Regulation 2065/2001 (EC, 2001a), require identifying and labelling the products by lots. Furthermore, having product recall procedures in place is compulsory for a food business operator in the EU (EU Regulation 178/2002 (EC, 2002b) and Directive 2001/95/EC (EC, 2001b)) while it is voluntarily required in the US (Subpart C of Part 7 of FDA regulations 21 CFR 7.40-59 (FDA, 2003)).

In international standards such as Codex and ISO 22000:2005, traceability is also required at one step up - one step down level and considered as a tool to enable targeted product recall or withdrawal in case of a food safety problem (CAC, 2006; McEntire *et al.*, 2010).
ISO 22005:2007 presents the principles and basic requirements for the design and implementation of a food and feed traceability system. It requires that the organisation should define the information to be obtained from suppliers, to be collected concerning the product and processing history, and to be provided to its customers and/or suppliers (CampdenBRI, 2009).

The GS1 Global Traceability standard (GS1, 2009), a voluntary globally recognised standard, describes the creation of accurate records of transactions to meet the core legislative and business need for one step up-one step down traceability at any point along the supply chain and is compatible with ISO 22000:2005 for product tracing. The GS1 Traceability standard is applied using various GS1 Standards such as Global Trade Item Number (GTIN), Global Location Number (GLN), Serial Shipping Container Code (SSCC), GS1-128 Bar code, Reduced Space Symbology (RSS), Data Matrix and Electronic Product Code (EPC).

TraceFish standard (CEN, 2003; EAN, 2002) was developed by TraceFish, the European Commission funded concerted action project “Traceability of Fish Products”, as a voluntary traceability standard for the fisheries sector, providing separate standards for captured and farmed fish. The standards relate to the information that should be recorded at each stage of the supply chain in order to maintain traceability, such as information on the distribution chain and technical specification for the electronic encoding of data, based on the EAN.UCC (European Article Number and Uniform Code Council)/GS1 numbering system.

More information on traceability regulations and activities in a number of regions and countries as well as other traceability-related standards can be found elsewhere, e.g. in a recent publication of McEntire *et al.* (2010).

1.1.2 Benefits - Incentives for traceability

Food traceability has been perceived and proven to bring both *social* and *industrial* benefits. From the public or social point of view, good traceability practice in food supply chains reduces risks and costs associated with outbreaks of food borne diseases (Hobbs, 2003), e.g. reduce their occurrence magnitude and possible health impact, reduce or avoid medical costs, reduce labour productivity losses, or reduce safety costs arising from a widespread food borne illness (Can-Trace, 2007). Furthermore, readily verifiable traceability information can reduce the costs for consumers in verifying the information associated with food quality (Hobbs, 2004; Hobbs, 2003).

From the industrial perspective, traceability can result in the following benefits:

Market benefits: By implementing traceability, actors of supply chains are able to comply with laws and regulations of the markets and to meet the demands of their customers, which in turn will help them to retain and extend their markets (Leat *et al.*, 1998; McEntire *et al.*, 2010; Olsson & Skjöldebrand, 2008; Smith *et al.*, 2005; Sparling *et al.*, 2006; Wang *et al.*, 2009a). In addition, traceability helps to expand sales of high-value products or products with credence attributes (Golan *et al.*, 2004). Traceability is also found to be beneficial in terms of reducing costs associated with maintaining or enhancing consumer or market confidence in a product (Alfaro & Rábade, 2009; McEntire *et al.*, 2010; Pouliot & Sumner, 2008; Umberger *et al.*, 2003; van Rijswijk *et al.*, 2008; Wang *et al.*, 2009b; Ward *et al.*, 2005).

Benefits from recall savings: Implementation of traceability is considered as a measure to save costs associated with product recalls due to improved recall management efficiency

(Banterle & Stranieri, 2008; Buhr, 2003; Chryssochoidis *et al.*, 2009; Frederiksen *et al.*, 2002; Golan *et al.*, 2004; Hobbs, 2004; Olsson & Skjöldebrand, 2008; Poghosyan *et al.*, 2004; Smith *et al.*, 2005; Sparling *et al.*, 2006).

Benefits from reduction of liability claims and lawsuits: Another economic reason for adopting traceability systems is to reduce liability risks associated with unsafe food problems (Hobbs, 2004; McEntire *et al.*, 2010; Poghosyan *et al.*, 2004; Pouliot & Sumner, 2008; Sparling *et al.*, 2006) which are the penalties, loss of trade, damage to reputation, or loss of a brand name that may result (Frederiksen *et al.*, 2002; Poghosyan *et al.*, 2004).

Benefits from process improvements: Traceability, particularly electronic-based, has the potential to improve supply chain and company management (Poghosyan *et al.*, 2004; Smith *et al.*, 2005; Wang *et al.*, 2009a), increase production and process efficiency (Alfaro & Rábade, 2009; Buhr, 2003; Kim & Sohn, 2009), improve planning and lower cost of distribution systems (Alfaro & Rábade, 2009; Golan *et al.*, 2004) and improve inventory management (Alfaro & Rábade, 2009; Chryssochoidis *et al.*, 2009; Karkkainen, 2003; McEntire *et al.*, 2010). Sharing traceability information along with other relevant information throughout the value chain, e.g. in the cod industry, could improve the catch management and production planning, as well as optimise yields and overall profits (Margeirsson, 2007).

In addition, applying electronic-based traceability systems can also *save in labour costs* compared to paper-based systems (Alfaro & Rábade, 2009; Buhr, 2003; Chryssochoidis *et al.*, 2009).

Cost-benefit analysis (CBA) is necessary to quantitatively estimate the net benefits of traceability. So far, there has not been any scientific publication on the CBA of adopting traceability system(s) in the seafood industry.

1.1.3 Types of traceability systems

Information transfer in traceability can be conducted by several technologies which apply different media and infrastructure. The simplest type of traceability systems is paper-based. Bar codes are also commonly used and radio frequency identification (RFID) is a more recent medium. Besides there are other potential media such as vision/imaging systems, dot peening and laser etching (McEntire *et al.*, 2010).

McEntire *et al.* (2010) have reviewed the advantages and limitations of different types of traceability systems; a summary is presented in Table 1.

Table 1. Advantages and limitations of various traceability system types (Adopted from McEntire *et al.*, 2010).

Type of traceability system	Advantages	Limitations
1. Paper-based	Low cost	Potential illegibility, transposition, language barriers, fading and other physical damage
2. Barcode-based	A substantial amount of information can be contained in the bar code Relatively inexpensive Globally accepted	Need printer and reader/scanner Line-of-sight access to the bar code is required for scanning
3. RFID-based	Line of sight to the tag is not required Multiple tags can be read virtually simultaneously Labour cost savings No manual screening, variable memory Tag memory can be rewritten or appended	May be too expensive for low cost commodities Tags may interfere with recycling and biodegradation processes Radio interference
3a. Active RFID tags Internal battery powered Either transponders or beacons	Range: 1000-1100 m	More expensive, $10 to 50 Limited battery life
3b. Passive RFID tags Tags powered solely by radio frequency No battery, transmitter	Low cost (20-40 cents) No maintenance Can operate at low, high and ultra-high frequencies	Range: several meters
3c. Semipassive RFID tags Internal battery can power sensors	Relatively low cost compared to active tags	Range: several meters Limited battery life

It is worth noting that the type of media for transmitting information is totally independent from the type and quality of information conveyed, meaning that using an advanced medium such as RFID does not guarantee effective traceability if the information is lacking standardisation allowing interoperable exchanges of relevant information along the chain. Regardless of the type of medium selected, the information transmitted along the supply chain needs to be standardised (McEntire *et al.*, 2010).

1.1.4 Traceability effectiveness

Effectiveness of a traceability system is considered as its ability to collect the necessary information (Bertolini *et al.*, 2006).

In general, current traceability regulations (e.g. EU General Food Law Regulation 178/2002 and US Bioterrorism Act of 2002) and standards (e.g. Can-Trace Canadian Food Traceability Data Standard (CFTDS) version 2.0, TraceFish standard, etc.) stipulate one-up-one-down model for traceability. Therefore relevant data must be *collected, kept and shared* by all the participants in the food supply chain to accomplish this.

Three basic elements of chain traceability are (Can-Trace, 2010; CEN, 2003; Derrick & Dillon, 2004; Donnelly *et al.*, 2009; EAN, 2002; ECR, 2004; McEntire *et al.*, 2010):

- *Product, party and location identification*: Every food component from harvest, from farm or sea, and through every stage of its transformation or packaging to a finished consumer product must be uniquely identified at each stage of transformation or possession and these identifiers must be linked.
- *Recording of information*: Effective traceability requires standardising the information that needs to be recorded through each step of the food supply chain. It is required that linkages are maintained, allowing a product to be traced through the supply chain. Each time a lot number is changed, the original and resulting lot numbers must be recorded. If a lot number is unchanged, but the product moves between facilities, this must be recorded in order to follow the path of the product.
- *Linking of information*: Each business operator must transfer information about the identified lot or product group to the next partner in the supply chain or to a central data base or registry to enable information retrieval when necessary. This is to ensure a continuous flow of traceability information.

Mandatory data elements required for traceability are sender identifier, lot number, product description, product identifier, quantity, unit of measure, shipment identifier, ship from and to location identifiers, ship date, receiver identifier and receipt date. There are two types of mandatory data: master and transactional. *Master Data* is information that seldom changes and applies to product, party and location information, including information such as product description, buyer identifier and location. *Transactional Data* is unique to each individual transaction, including information such as quantity, lot number, shipment identifier and shipment date (PMA & CPMA, 2006).

Optional data elements are for enhanced traceability and include information such as best before date, contact information, country of origin (province/state), logistics provider identifier, pack date, receiver name, sender name, shipping container serial number and vehicle identifier (PMA & CPMA, 2006).

As a best practice, the lot number and name of the manufacturing facility should appear on each case of product; and the lot number(s), quantity and shipping location should appear on invoices and bills of lading (McEntire *et al.*, 2010).

The three basic traceability elements are practised with four key traceability principles which are *unique identification* of products, logistics units and locations; traceability *data capture and recording*; *links management* and traceability data retrieval; and traceability *data communication* (ERC, 2004).

To meet the chain traceability requirement, all actors in the chain have to practise well their own traceability. Information related to history (e.g. temperature record, information related to production process), application (e.g. information related to property: weight, species, fat content, etc.) and location (e.g. distribution route) should be recorded and linked to a traceable unit. Each actor is required to record identifications (IDs) of suppliers and transporters of received trade units (TUs) and IDs of buyers and transporters of dispatched TUs. Internal traceability requires all transformations during the production to be recorded (Donnelly *et al.*, 2009; Senneset *et al.*, 2007). For instance, a complete bill of lots of resources contributing to the composition of a product batch has to be registered (Kelepouris *et al.*, 2007). It can be summarised that there are three basic operation types to obtain internal traceability: *recording the unique IDs of traceable resource units (TRUs)*, e.g. IDs of batches of raw materials or ingredients; *assigning unique IDs to new TRUs*, e.g. IDs for products; and *linking* a set of input unique IDs to one or more sets of output unique IDs, e.g. *recording transformations* of raw materials to final products (Derrick & Dillon, 2004; Donnelly *et al.*, 2009; Lindh *et al.*, 2008; McEntire *et al.*, 2010; Senneset *et al.*, 2007; Thompson *et al.*, 2005). Recording of process and transformation information is considered as routine procedures of an internal traceability system (Senneset *et al.*, 2007).

A *traceable resource unit (TRU)* is defined as a batch of any resource (Kim *et al.*, 1999; Thakur & Donnelly, 2010). *Batch* is often synonymous with *lot* (ECR, 2004; Olsen &

Karlsen, 2005) which is a definite quantity of some commodity produced, manufactured or packaged under uniform conditions (Bechini *et al.*, 2005; McEntire *et al.*, 2010).

1.2 Logistics of fresh food, particularly fresh fish; Effect of logistics practice on the product quality

Temperature is considered to be the main factor that affects the quality and safety of perishable food products (Jedermann *et al.*, 2009), particularly fresh fish (Olafsdottir, 2005). Abusive and/or fluctuating temperature accelerates the growth of specific spoilage organisms (SSO) as well as pathogens (Jol *et al.*, 2005; Raab *et al.*, 2008; Rediers *et al.*, 2009), causing quality and safety problems and thus economic losses.

Fresh fish is often stored and/or shipped at melting ice temperature (ATP, 2007; Einarsson, 1992; Einarsson, 1994; Panozzo & Cortella, 2008; Pawsey, 1995) or even below 0 °C, at superchilled temperatures (Olafsdottir *et al.*, 2006; Sivertsvik *et al.*, 2003) to keep it good and safe for a certain period of time. However, the fresh fish supply chains may face certain hazards when the requirements are not fulfilled.

The transportation of perishable products such as fresh fish is very common by air as it is rapid (James *et al.*, 2006; Simpson *et al.*, 2003). However, during loading, unloading, truck and air transportation, storage and holding the product is normally subjected to temperature abuse at un-chilled conditions (Brecht *et al.*, 2003; Nunes *et al.*, 2003), which means that much of its journey, up to 80%, is un-protected (James *et al.*, 2006). The temperature of the hold during flight is normally 15-20 °C (James *et al.*, 2006). Therefore, air freight of perishable food requires some form of insulation around the products as well as precooling/cooling of the products before transportation (James *et al.*, 2006; Laurin, 2001).

Fluctuating and/or high temperatures even for a short time were reported to cause the rejection of a whole strawberry load (Nunes *et al.*, 2003). Results from a study on chilled modified atmosphere packaged (MAP) Pacific hake shows that even a small fraction of storage time (4.3%) at abusive temperature can cause a significant reduction in shelf life (25%) of the product (Simpson *et al.*, 2003).

Another mean of transporting fresh fish is by sea where the product is containerised (Seafish, 2010) in refrigerated containers to maintain the required low temperature for the whole voyage. This mode of transportation, however, takes much longer time compared to air freighting. It is worth noting that the quality of perishables is reduced as time elapses even at optimum conditions of handling (Pawsey, 1995).

The importance of having the food at the correct temperature before loading it into transport containers has been emphasised as refrigeration systems in the containers are designed to maintain the temperature of the load, but not to extract its heat (James *et al.*, 2006).

Air freight has been dominant for fresh fish fillets or portions while container shipping is more common for whole gutted fish (Seafish, 2010). This is because fillet products are more susceptible to microbiological spoilage than whole fish due to the microbial contamination of fish flesh during and after filleting (Einarsson, 1992). However, recently it has been observed that technical developments have also made container transport a feasible option for fillets (Seafish, 2010).

Several studies on the effect of different factors, such as product locations on a pallet, presence of insulating covers and precooling methods, in the cold chains on the temperature distribution and quality of food products have been conducted. Rediers *et al.* (2009) mapped the temperature of fresh cut endive from the point of harvest through the distribution chain to restaurant storage and found that the position of the product on the pallet influenced its temperature, product on the top of the pallet responded more rapidly to environmental temperature changes than those in the middle or at the bottom of the pallet. Similar results were found by Raab *et al.* (2008) during a temperature mapping of a chilled chicken breast supply chain, product temperature at the top level of the pallet was more influenced by surrounding temperature fluctuations than at the middle or bottom of the pallet. Moureh & Derens (2000) have studied and modelled the temperature evolution of frozen fish product at different positions on a pallet during transport, the results of which support previous findings that products/boxes which have more free surfaces to the surroundings, e.g. at the top corners of a pallet, are more sensitive to changes in temperature. Moureh *et al.* (2002) also found that the top corners of a pallet were the most sensitive regions to the surroundings as they had three free surfaces; and studied the use of insulating pallet covers for shipping heat-sensitive foodstuffs in ambient conditions. Laurin (2001) found that precooling methods affected quality of air transported asparagus. Heat transfer models developed by Moureh and Derens (2000) and Moureh *et al.* (2002) can be used to evaluate the product tolerable time for transport and improve packaging design in order to decrease the negative effects of ambient temperature fluctuations on product temperature.

Trade-off between modes of transportation should be made based on the quality and safety perspectives regarding time-temperature history, customer requirement on delivery time, economic efficiency related to cost of transport, cost of more efficient packaging and weighed against the resulting overall environmental impacts. Air transportation is quick, but expensive (Simpson *et al.*, 2003) and with several hazardous steps during ground and flight operations regarding temperature abuse. During passenger flights fish boxes are more exposed to the environment due to the splitting up of pallets. Freighter flights are more fuel efficient than passenger flights, but more affected by fuel prices than passenger flights since their fuel cost is a much larger part of total expenses (Morrell, 2008). Sea transportation is considered to be a cheaper mean of transport. The product temperature is well-controlled during the whole logistics inside refrigerated containers (James *et al.*, 2006). While air transport has several strong, but short lasting, effects on the global temperature, shipping emissions have a cooling effect on climate that lasts 30-70 years due to very high emissions of SO_2 and NO_x, but also with dominating warming effect in the long term because of significant amounts of CO_2 emitted (CICERO, 2008). By optimizing the logistic chain, energy and environmental benefits can be obtained (Panozzo, 1999).

1.3 Time temperature indicators to continuously monitor the quality of food

Time-temperature indicators (TTIs) are small devices that can be attached to the food or the food package which is in close contact to the food. They show an easily measurable, time temperature dependent change which must be irreversible and easily correlated to the food deterioration process and remaining shelf life (Taoukis & Labuza, 1989a).

TTIs have shown a great potential to continuously monitor temperature conditions throughout a chain from packaging to consumption (Kreyenschmidt *et al.*, 2010; Riva *et al.*, 2001; Taoukis & Labuza, 1989a; Tsironi *et al.*, 2008), to indicate the abuse (Labuza & Fu, 1995), as well as to replace direct temperature recordings (Riva *et al.*, 2001).

The operation of a TTI is based on mechanical, chemical, electrochemical, enzymatic or microbiological reaction systems that change irreversibly after being activated (Fu & Labuza, 1992; Giannakouroua *et al.*, 2005; Kreyenschmidt *et al.*, 2010; Labuza & Fu, 1995; Taoukis *et al.*, 1999; Taoukis & Labuza, 1989a; Wells & Singh, 1988). The change rate increases at higher temperatures similarly to most chemical reactions. The change is usually expressed as a visible response, such as colour development and/or colour movement or mechanical deformation.

Some types of TTIs are “partial-history” indicators, responding only after a predetermined threshold temperature has been exceeded (Wells & Singh, 1988); some are “abuse” indicators, showing whether the product was exposed to unacceptably high temperatures (Taoukis & Labuza, 1989a); and many others are full time-temperature history integrators, responding to all temperature conditions (Taoukis & Labuza, 1989a; Wells & Singh, 1988).

1.3.1 Kinetic approach to apply TTI for monitoring food quality

Taoukis & Labuza (1989a) developed kinetic models which allowed the correlation of the response of certain TTI types to the quality change and the remaining shelf life of a product that had undergone the same temperature history (Figure 2).

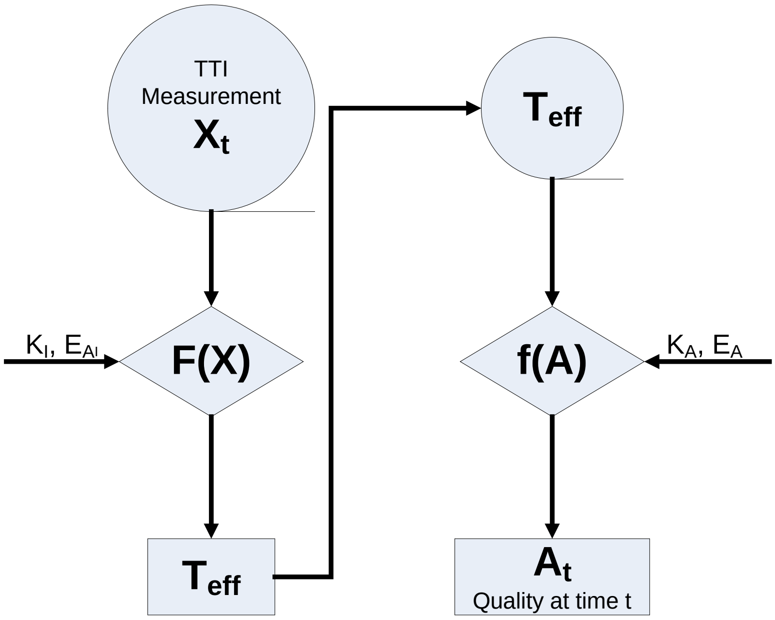

Figure 2. Kinetic approach for applying TTIs to monitor food quality (Adopted from Taoukis & Labuza (1989a)) (see explanations in the text).

A simple form of the quality function showing the change with time of a quality parameter A of a food (such as physical, chemical, microbiological or sensory indices) during a known variable temperature exposure T(t) can be expressed by Eq. 1:

$$f(A)_t = \int_0^t k dt = k_A \int_0^t \exp\left[\frac{-E_A}{RT(t)}\right] dt \qquad (1)$$

where $f(A)_t$ is the quality function of the food; k the reaction rate constant, an exponential function of inverse absolute temperature, T, given by the Arrhenius expression, $k = k_A \exp(-E_A / RT)$, k_A a (pre-exponential) constant, E_A the activation energy of the reaction controlling quality loss, and R the universal gas constant. The activation energy of chemical and enzymatic reactions, as well as microbial growth in food is within the range of 10-120 kJ/mol (Taoukis *et al.*, 1998; Taoukis & Labuza, 1989a).

Introducing the term effective temperature T_{eff}, which is defined as the constant temperature that results in the same quality value $f(A)_t$, as the variable temperature distribution over the same time period, $f(A)_t$ can be expressed as:

$$f\left(A\right)_t = k_A \exp\left(\frac{-E_A}{RT_{eff}}\right)t \quad (2)$$

The same kinetic approach can be used to model the measurable change X of the TTI with a response function $f(X)_t$. When the TTI is exposed to the same temperature history T(t) as the food product, the response function can be expressed by Eq. 3 using the effective temperature concept:

$$f\left(X\right)_t = k_I \exp\left(\frac{-E_{A_I}}{RT_{eff}}\right)t \quad (3)$$

where k_I and E_{AI} are Arrhenius parameters of the indicator (TTI).

As seen in Figure 2, if the change value X of the TTI at time t is measured, the value of the response function can be calculated. By solving Eq. 3, T_{eff} is then derived. With the T_{eff} and the quality loss parameters of the food (k_A and E_A) known, the quality function f(A) is calculated from Eq. 2 and from there the value of the quality index A_t at time t is found. This allows the remaining shelf life of a product to be calculated at any assumed average temperature of downstream distribution and to better manage product quality.

For this effective temperature approach, there is an important underlying assumption, i.e. $T_{eff(food)} = T_{eff(TTI)}$, for a given temperature distribution. This is only true when $E_A = E_{AI}$ and when the temperature is constant throughout the distribution. The smaller the difference in the activation energy of food and TTI, the more accurately the TTI indicates actual shelf life of the food product (Taoukis & Labuza, 1989a). Therefore, the TTI manufacturers are more likely to produce TTIs with appropriate compositions and temperature sensitivities to match the activation energy value of food quality changes.

1.3.2 Applicability of TTIs for monitoring quality of different food products

The applicability of TTIs for safety and quality management and for decision making in meat cold chains has been studied to improve distribution management as well as to replace the current “First In First Out” (FIFO) practice (Oliva & Revetria, 2008). Least Shelf Life First Out (LSFO) TTI-based systems were proposed for chilled (Taoukis *et al.*, 1998) and frozen (Giannakourou & Taoukis, 2003) food products.

Numerous studies have been carried out on the application of different TTI types to monitor the quality and shelf life of various food products such as refrigerated dairy products (Fu *et al.*, 1991), fresh tomatoes and naked wrapped lettuce (Wells & Singh, 1988), chilled Russian and eggplant salads (Taoukis *et al.*, 1998), frozen green peas and white mushrooms (Giannakourou & Taoukis, 2002), MAP fresh pork cuts (Taoukis, 2006), chilled Mediterranean fish boque (*Boops boops*) (Taoukis *et al.*, 1999) and fresh farmed turbot (*Psetta maxima*) packed in PVC film (Nuin *et al.*, 2008).

Kinetic models of various TTI types have been developed to correlate with the quality changes and the remaining shelf life (RSL) of a product, which has undergone the same temperature history (Giannakourou & Taoukis, 2002; Nuin *et al.*, 2008; Shimoni *et al.*, 2001; Taoukis *et al.*, 1998; Taoukis *et al.*, 1999; Taoukis & Labuza, 1989a, 1989b; Tsironi *et al.*, 2008; Yan *et al.*, 2008).

Recently, Kreyenschmidt *et al.* (2010) studied the kinetic behaviour of a novel photochromic OnVu™ TTI at isothermal conditions from 2 to 15 °C. They developed a contour diagram used for defining the right charging level of the TTI labels to suit the shelf life of a product under the same temperature conditions. The new TTI was found to produce reproducible responses under the studied conditions and, therefore, constitute a reliable tool to monitor the cold chains of food products (Kreyenschmidt *et al.*, 2010).

1.3.3 OnVu™ time temperature indicator

The newly introduced printable OnVu™ 197 TTI - Patent EP 1049930 B1 (Ciba Specialty Chemicals & Freshpoint, SW) is a solid state reaction TTI, based on the inherent reproducibility of reactions in a crystal phase. Photosensitive compounds are excited and coloured into dark blue by exposure to low wavelength (such as UV) light. This coloured state will reverse to the initial colourless state at a temperature depended rate (Galagan &

Su, 2008; Kreyenschmidt *et al.*, 2010) (Figure 3). The visual end point can be set by comparison to a light blue printed reference. By controlling the type of the photochromic compound and the length of UV light exposure during activation, the length and the temperature sensitivity of the TTI can be set. To prevent the re-activation of a charged label, an UV-Vis filter is applied on the surface of the label (Figure 4).

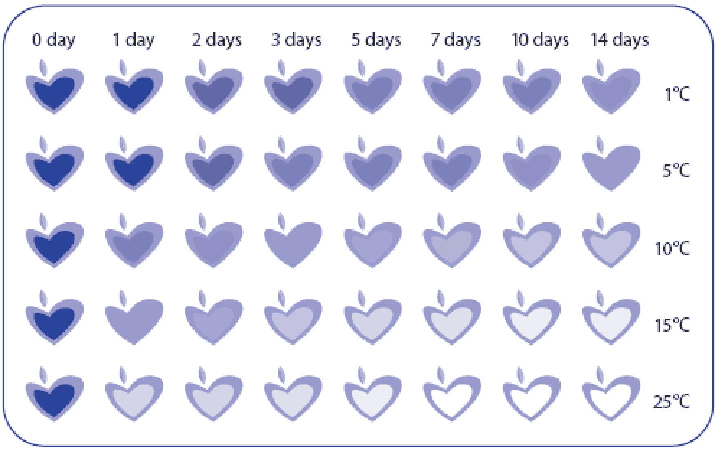

Figure 3. Discolouration process of OnVu™ labels at different temperatures (http://www.onvu.compictureshow_works_large.gif).

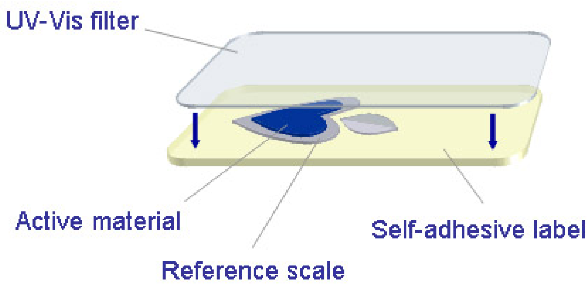

Figure 4. Structure of an OnVu™ label (http://www.onvu.com/pictures/Processes/TheStrucktureOfAnOnvuLabel.jpg).

2 AIM OF THE PROJECT

Though traceability has been practised for several years in response to legislative and market requirements, its effectiveness has not been observed for all companies in the food industry (Levinson, 2009). A framework for self assessment of traceability system effectiveness is therefore important for companies in a food/seafood supply chain so as to enable them to take necessary actions to ensure traceability. Furthermore, little knowledge on the seafood industrial benefits of traceability and lack of systematic approach for decision making on implementing traceability may restrict actors in a seafood supply chain from adopting a more advanced traceability system or solution. Detailed information of traceability benefits in the seafood sector and cost-benefit analyses are necessary to bridge the gap here. Compliance and efficiency of quality control and full traceability at plants can only be achieved by fully integrating laboratory data with the movements of materials, production, final products, shipping and customer information (Deasy, 2002). However, available data on quality, process control and process parameters are normally not efficiently exploited by companies. Therefore, it is desirable to explore a more efficient use of recorded data to improve quality and supply chain management.

Despite the availability of scientific and practical knowledge on the effect of different factors in cold chains on the temperature distribution and quality of food products, detailed information of temperature evolution, as the main factor affecting fish freshness, during the logistics of fresh fish with regard to different modes of transport (air vs. sea), precooling practice and product location is not sufficiently researched and reported and thus requires further study. This is to find out hazardous steps in the chain to improve logistics management and quality management of fresh fish products. Automatic and continuous monitoring of the temperature history of fresh food throughout the distribution chain by time-temperature indicators is a promising alternative in freshness control (Olafsdottir, 2005; Olafsdóttir *et al.*, 1997). The applicability of a newly introduced photochromic TTI for chilled fish products under dynamic conditions of real supply chains requires further research.

The aim of the project was to:

- Investigate the qualitative and quantitative benefits of traceability and the net benefits of adopting a new traceability system for the seafood industry through cost-benefit analysis which can be used as a decision support tool;
- Develop a framework to evaluate the effectiveness of traceability systems of food/seafood producers;
- Explore the temperature evolution of fresh fish products during logistics processes as affected by modes of transport (air vs. sea freighting), precooling (with/without), and product location in relation to the product shelf life so as to improve logistics management;
- Explore the applicability of a novel photochromic time-temperature indicator to continuously monitor the temperature history, quality and shelf life of fresh fish products under dynamic temperature conditions in a supply chain context, in comparison with other methods of quality control.

The focus of the studies described in this dissertation will be on fresh fish export chains from Iceland (cod loins and haddock fillets) and Vietnam (*Pangasius* fillets) to the European market. These chains are among the most important ones in the seafood sectors in the two countries. The findings can potentially be extended to other fresh fish chains.

Specific research questions of the project were as follows:

- What are the benefits of traceability? What are the net benefits of adopting new traceability system(s) for the seafood industry? How are the costs/benefits of implementing new traceability system(s) distributed among the actors in a chain? (Paper I)
- What are the main components to ensure traceability? How is traceability practised at a seafood processing company? What kinds of data are recorded and how? Does such traceability system meet the TraceFish standard? How can the effectiveness of traceability systems at food/seafood producers be evaluated? How can recorded data be used more efficiently? (Paper II)
- How does the temperature of fresh fish evolve during the logistics from processing to market as affected by modes of transport (air vs. sea freighting), presence/absence of precooling and locations of products? What are the pros and

cons of each mode of transport? How is the shelf life of fresh fish affected by logistics? What can be done to improve the logistics? (Papers III and IV)

- How does the novel photochromic OnVu^{TM} time-temperature indicator perform under dynamic temperature conditions in a fresh supply chain context? Is it applicable to continuously monitor the temperature of fresh fish products? Can the kinetic model, developed for isothermal conditions at 2-15 °C, be applied for lower temperatures? How should the charging level(s) be chosen to suit the shelf life of the fresh fish products concerned? (Paper V)
- Where should TTI labels be placed on retail packs of fresh fish? Is it possible to use the novel OnVu^{TM} TTI to continuously monitor the temperature history, freshness and shelf life of fresh fish (cod loins in retail packs) as an alternative to other conventional methods of quality control such as sensory, chemical and microbiological analyses or to replace direct temperature recordings? (Paper VI)

The results will provide insights into seafood companies' perspectives on the benefits of adopting new traceability system(s) or solution(s) and knowledge on the net benefits of the project(s) and on the distribution of costs and benefits among the actors, which support decision making. A framework to assess traceability system effectiveness will help food/seafood companies to locate problems and take necessary actions to ensure an effective traceability. Further, the results on temperature profiling will identify hazardous steps, allowing business operators in fresh fish supply chains to improve their logistics as well as to make decision on transport alternatives so as to improve quality management. Additionally, the results will allow choosing suitable activation levels and correctly placing the TTI to monitor the quality and shelf life of the fresh fish products concerned.

Altogether the outcomes of this study will provide a necessary basis to enhance quality management at a firm level in terms of improved logistics management and ensured traceability effectiveness. The information gained is not only of academic interest, but also of great practical importance for the fish industry in general and fresh fish supply chains in particular.

3 MATERIALS AND METHODS

In this chapter an overview of the materials and methods used in the thesis is given. The samples and experimental procedures are described in more detail in the original papers I-VI.

3.1 Study design

The thesis is based on the studies described in papers I-VI. An overview of the study design is illustrated in Figure 5. The study focused on the two main pillars of a fresh fish supply chain – *traceability* and *logistics*, among others (e.g. initial quality of raw materials and ingredients and their handling process and processing technology), which affect the *quality* of a product delivered to the customer(s).

Initially, a literature review and surveys were carried out to estimate the qualitative and quantitative benefits of traceability. The inputs from the surveys were then used to perform cost-benefit analyses of adopting new traceability systems to estimate the net benefits and cost/benefit distribution among actors in the chain (I). Furthermore, a literature study and process mapping were conducted on the necessary components to ensure traceability and recorded information at a firm. The outcomes were used to develop a framework for evaluating traceability system effectiveness as well as suggestions for more efficient use of recorded data (II). In paper III, temperature mappings were done for several fresh fish supply chains transported by air and sea. Hazardous steps were pinpointed, the pros and cons of each transport mean were analysed, and improved practices were proposed (III, IV). Papers V and VI focused on investigating the performance and applicability of the novel OnVu™ time-temperature indicator to continuously monitor temperature conditions, quality and shelf life of fresh fish in a supply chain context. This was to find out the reliability (V), and the right placement and charging level(s) of the TTI for monitoring purposes (V, VI).

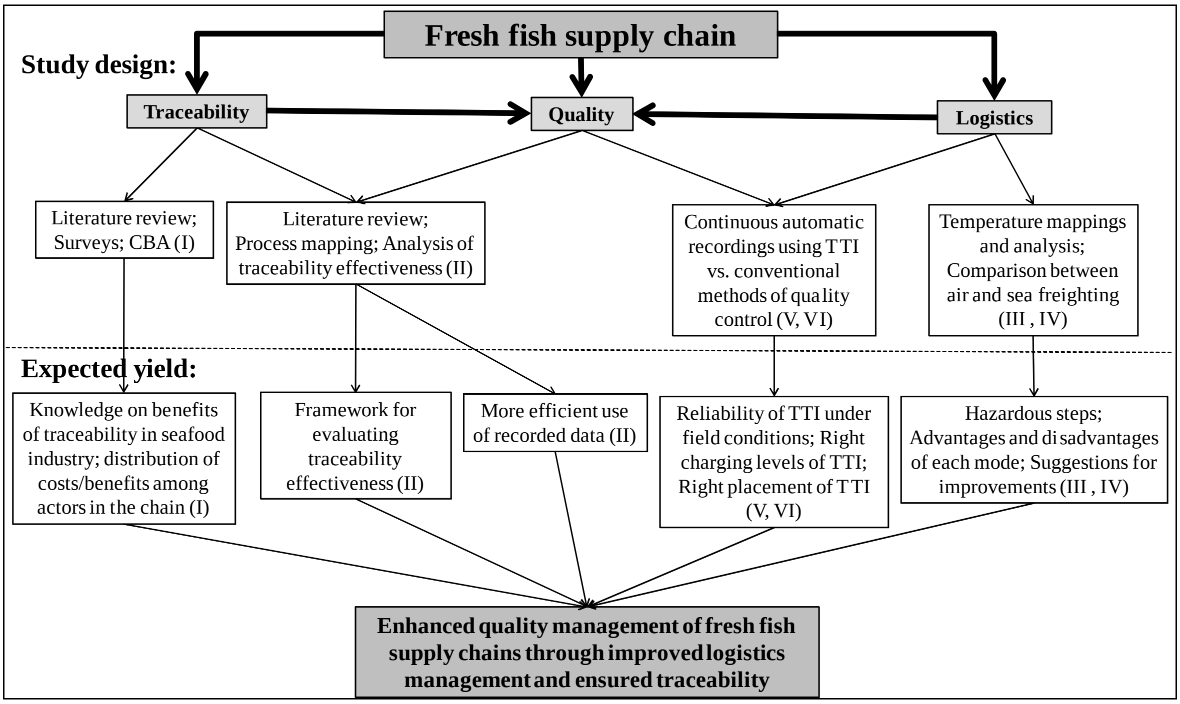

Figure 5. Overview of the study design. Paper numbers are shown in parentheses.

3.2 Surveys

To investigate the seafood companies on their attitudes toward traceability implementation and benefits, an on-line questionnaire using a 5-point Likert scale (from 1 = "very unlikely" to 5 = "very likely") was used. The questionnaire was adopted and modified from the one used for the Chinese seafood industry (Wang *et al.*, 2009a). In one part of the questionnaire, the companies were asked how they qualitatively perceived benefits of the implementation of traceability systems by rating their answers. The studied groups were seafood companies, located in European Economic Area (EEA), Vietnam and Chile, involved in one or more steps of seafood supply chains, namely, traders, processors, suppliers, importers and exporters (I).

To obtain quantitatively perceived benefits of implementing traceability and adopting new traceability system(s) or solution(s), a questionnaire with 7 sections and 21 questions was used for interviewing seafood companies. The first section of the questionnaire asked for general information about the companies and their attitude toward a new traceability system or solution. In the second to the sixth sections, the interviewees were asked to quantitatively estimate their perceived benefits of a specific new traceability system or solution with regard to market, recall, liability, process improvements and labour cost savings. The last section asked about company size and yearly turnover. The interviewees were either chairmen or managerial staff of the companies who know their production and business well. The questionnaire was emailed about one month in advance to the companies for preparation. Each interview took about 45-60 minutes (I).

The costs of implementing a traceability system or solution were obtained from another type of questionnaire to technology developers where they asked to itemise and monetise all the opportunity costs together with the lifespan, if applicable, of each item needed (I).

All the questionnaires were developed or adopted based on the results from the literature review and expert suggestions and tested with some volunteer companies for improvements/modifications before their actual use.

3.3 Cost-benefit analysis

Ex ante cost-benefit analyses (CBAs) of adopting new traceability system(s) were based on the calculation of net present value (NPV) (Eq. 4, I) as described by Boardman *et al.* (2006).

$$NPV = \sum_{t=0}^{n} \frac{NB_t}{(1+r)^t} \tag{4}$$

where t is the time of the cash flow; n the lifetime of the project; r the discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk); NB_t the net benefits at time t, $NB_t = B_t - C_t$, B_t the benefits arise at time t; and C_t the costs arise at time t (I).

Costs associated with permanent structures were not included in the calculation. Furthermore, before-tax real Euro and real discount rates were used as the analyses were assumed to reflect the gross benefits accruing to the processor and trader. In addition, it was assumed that implementation of the project would not affect the market price of inputs used due to its small size (Bell and Devarajan, 1983; Dreze and Stern, 2001).

The calculations were based on the following assumptions:

- A real discount rate of 4.5% was used for base-case scenario; sensitivity analysis was performed with discount rates currently used in EU countries between 2.4 and 7.0% (Evans and Sezer, 2005);
- The time frame of the system was five years, based on the survey responses of the technology developers;
- The first cash flow occurred at the end of each year from the first year;
- As the system was composed of relatively short lifetime items, depreciation was assumedly ignored;
- The scrap value of system items equalled zero.

In the conducted cost-benefit analyses, three scenarios were considered: base-case, worst-case and best-case. In the base-case scenario, discount rate was 4.5%; costs were the average estimated; and benefits were assigned with two values "Low" or lower bound of estimated benefits and "High" or upper bound of estimated benefits. In the worst-case scenario, discount rate was 7.0%; costs were the maximum estimated; benefits were the lower-bound estimated. For the best-case scenario, discount rate was 2.4%; costs were the minimum estimated; and benefits were the upper-bound estimated.

3.4 Process mapping

Process mapping was based on a method and structured tables of questionnaires described by Olsen & Karlsen (2005) and Olsen & Aschan (2010). The questions aimed to find out the flow of materials and information within and through the studied company, the traceable units, unit identifications (identifiers), transformation points of the processes, the presence or absence of the links/recorded relationships between the identified units and the ability to track and trace through a company. The mapping included a backward factory walk through; in-depth interviews (1-2 hours each) with the quality control (QC) manager, production manager and laboratories' staff; and a document analysis on traceability, quality, process control and other recorded files (II).

3.5 Temperature mapping

Temperature mappings were performed with the help of temperature data loggers, which were configured in the way that temperature changes at different positions inside a box and on box surface, and at different positions of boxes on a pallet could be sufficiently monitored. For each studied box, loggers were placed at the bottom, middle and top height levels inside the box, and another logger was placed outside on the (top or side) surface (II, III, IV). On each studied pallet, temperatures of three (sometimes four) boxes positioned at bottom corner, middle side, top corner, and sometimes top middle of the pallet were mapped. In each study set, one or two pallets were investigated (III, IV).

DS1922L temperature loggers iButton® (Maxim Integrated Products Inc., CA, USA) were used for mapping the temperature inside the boxes, with temperature range -40 °C to 85 °C, resolution 0.0625 °C, accuracy ± 0.5 °C and ± 1 min/wk. Recording intervals were set at 2-10 min. TBI32-20+50 Temp Data Loggers Onset® (Onset Computer Corporation, Southern MA, USA) were used for the measurement of ambient temperature on the box surfaces, with temperature range -20 °C to +50 °C, resolution 0.3 °C, accuracy ± 0.4 °C and ± 1 min/wk. Recording intervals were set at 1-5 min. All loggers were calibrated in thick mixture of freshly crushed ice and water before use (II, III, IV).

3.6 Laboratory reference methods

3.6.1 Sensory evaluation

The Quantitative Descriptive Analysis (QDA) introduced by Stone and Sidel (1985) and a freshness score sheet modified from the Torry scale originally described by Shewan *et al.* (1953) were used to assess the cooked samples of cod loins (VI).

3.6.2 Chemical measurements

Total volatile basic nitrogen (TVB-N) and thrimethylamine (TMA) was performed by the methods described by Malle & Tao (1987) (VI).

3.6.3 Microbiological analysis

Total viable psychrotrophic counts (TVC) and counts of H_2S-producing bacteria (black colonies) were done on iron agar (IA), modified from Gram *et al.* (1987) by using 1% NaCl and no overlay. Plates were spread-plated and incubated at 17°C for 5 days. Enumeration of presumptive pseudomonads was performed using modified Cephaloridine Fucidin Cetrimide (mCFC) agar as described by Stanbridge & Board (1994). *Pseudomonas* Agar Base (Oxoid) with CFC selective Agar Supplement (Oxoid) was used and the plates were incubated at 22°C for 3 days.Counts are reported as logarithmic average values ($\log_{10}$ colony-forming units (CFU)/g) (VI).

3.7 TTI experimental set up

3.7.1 TTI activation

The OnVu™ TTI B1+090807 (Ciba Specialty Chemicals & Freshpoint, Basel, Switzerland) were activated in an automated UV light charger GT 240 Bizerba (Bizerba GmbH & Co. KG, Balingen, Germany) with a speed of 10 labels/min and covered after charging with an UV-filter Thermal Transfer Ribbon TTR 70QC 53141 to prevent any further light-induced reactions. The charging was done under stable ambient (temperature and relative humidity) conditions (V, VI).

3.7.2 TTI discolouration measurements

TTI colour changes were measured with Gretag Macbeth OneEye spectrophotometer (X-Rite, Regensdorf, Switzerland) at D65 illumination and 2° observation angle conditions. The measurements were done in the laboratory at an ambient temperature of 6-7 °C. The square value (SV) in CIE-Lab space (Eq. 5) was used to characterise the TTI-charging and discolouration process:

$$SV = \sqrt{L^2 + a^2 + b^2} \tag{5}$$

where L represents the lightness of the labels; a represents their redness and greenness; and b represents their yellowness and blueness. The reference scale corresponds to a measured SV value of 71, which is regarded as the end of a charged OnVu label's shelf life (Kreyenschmidt et al., 2010) (V, VI).

3.7.3 TTI kinetic model fitting

The square values (SV) of the non-abused labels were fitted with a sigmoidal function (Eq. 6) (Kreyenschmidt et al., 2010):

$$SV(t) = \frac{d}{1 + e^{-k(t-c)}} \tag{6}$$

where d is the amplitude of the colour change; c is the reversal point; k is the rate constant of the colour change, which is temperature-dependent; and t is the storage time (V, VI).

3.8 Data analysis

Microsoft Excel 2003 or 2007 (Microsoft, Redmont, WA, USA) was used to calculate means, standard deviations and ranges for all measurements and to generate graphs (I-VI).

Analysis of variance (ANOVA) was used to test whether groups were significantly different with regard to temperatures at different locations on a pallet or inside a box and at different steps of a fresh fish supply chain (III), or at plate/tray surfaces and within the product (V, VI) with post hoc Tukey and Bonferroni correction; TTI response (V, VI); and sensory attributes with Duncan's multiple comparison test (VI). T-test was applied if there were only 2 groups (V, VI). For variables on ordinal scales and/or in cases when sample numbers in each group were ≤ 6, a non-parametric Wilcoxon W test was used (I, V, VI). All tests except on QDA data were performed using the software SPSS version 16.0 (SPSS, Chicago, Il, USA) (I, III, V, VI). QDA data were corrected for level effects, caused by level differences between assessors and replicates, by the method of Thybo & Martens (2000) and ANOVA was carried out on QDA corrected data using the statistical program NCSS 2000 (NCSS, Utah, USA) (VI). All tests were performed with a significance level of 0.05 (I, III, V, VI).

Multivariate analysis was performed using the Unscrambler version 9.0 (CAMO Process AS, Norway). The main variance in the data set was studied using principal component analysis (PCA) with full cross validation. Data were autoscaled prior to the PCA, that is, first centred by subtracting the column average of elements from every element in the column; and then each element was scaled by multiplying with the inverse standard deviation (1/STDEV) of the corresponding variable, to handle the model offsets and to let the variance of each variable be identical initially (Bro and Smilde 2003) (III).

The Seafood Spoilage and Safety Predictor (SSSP) software version 3.0 (DTU Aqua, Denmark) was used to predict the effect of time-temperature combinations on the RSL based on the recorded temperature profile. Recorded product temperature data were fitted into a square-root model for relative rate of spoilage (RRS) of fresh seafood from tropical (II) or temperate waters (III, VI). In SSSP, RRS is defined by the ratio of sensory shelf life at a reference temperature, normally 0 °C, to the sensory shelf life of the product under evaluation at T °C (Dalgaard, 2002) (II, III, VI).

Origin 7.5 (OriginLab, Northampton, MA, USA) was used to fit the TTI data and to build graphs (V, VI).

4 RESULTS AND DISCUSSION

4.1 Benefits of traceability

Benefits of traceability in the food industry can be categorised into qualitative (intangible) and quantitative (tangible) groups (Table 2, I). *Qualitative* benefits here are those that are infeasible or difficult to be quantified and assigned monetary values; *quantitative* ones, in the other hand, can be monetised (Boardman *et al*., 2006). Quantitative benefits in turn are classified into five subgroups: market benefits, savings on recall costs, savings on liability costs, savings on process improvements and labour cost savings (various sources, e.g. Can-Trace, 2007; Chryssochoidis *et al.*, 2009; Golan *et al.*, 2004; Hobbs, 2004; McEntire *et al.*, 2010). A survey conducted in Beijing, China showed that 60.1% of the consumers were willing to pay a price premium, about 6% in average and up to 10%, for traceable fish products to increase safety (Wang *et al.*, 2009b). Navobi calf-milk replacer manufacturer through its traceability information system was able to save over $100,000 in recalls and recovery costs from a *Salmonella* outbreak (Buhr, 2003). Gilde Norge, a Norwegian slaughtering plant, has incorporated an electronic traceability system with a visual grading system and obtained an increase of 5-7% in the final meat yields (Buhr, 2003). Margeirsson (2007) indicated that traceability led to transparency in the cod value chain and that sharing of traceability information (such as origin) along with other relevant information (such as catching method, grading, fillet yield, gaping and parasite) could help managing the catch (fishing ground and volume) and organising the processing. More examples on the benefits of traceability are given in the following subsections.

Table 2. Summary of traceability benefits based on a literature survey (I).

	Benefit categories					
	Qualitative (intangible)	*Quantitative (tangible)*				
		Market	*Recall*	*Liability*	*Process*	*Labour*
Market recovery improvement		x				
Market and revenue growth		x				
Product price premium		x				
Less frequent recalls			x			
Less severe recalls			x			
Better management of recalls			x			
Less frequent claims & lawsuits				x		
Less severe claims & lawsuits				x		
Liability insurance cost reduction				x		
Inventory turnover improvement					x	
Spoilage/out of date cost reduction					x	
Yield improvements					x	
Labour cost savings						x
Regulatory & legislative compliance	x					
National security	x					
Enhanced customer confidence/trust	x					
Litigation risks mitigation or elimination, e.g. ability to shift the responsibility to other(s)	x					
Resolution of track trace data gaps	x					
Company reputation - customers	x					
Company reputation - consumers	x					
Company reputation - government & public	x					
Improved customer service	x					
Company reputation - suppliers	x					
Being technological proficient and an industry leader in new technologies and processes	x					

Variuos sources (among others): Buhr, 2003; Karkkainen, 2003; Can-Trace, 2004; Poghosyan *et al.*, 2004; Sparling *et al.*, 2006; Pouliot and Sumner, 2008; Chryssochoidis *et al.*, 2009; Wang *et al.*, 2009a.

4.1.1 Qualitative benefits of traceability

Seafood companies in the studied groups consider improving supply chain management as the most important benefit of traceability (Figure 6, I). Other perceived benefits are the increase of the ability to retain existing customers, product quality improvement, product differentiation and reduction of customer complaints. The results here are similar to the findings of Wang *et al.* (2009a) on the perceived benefits of traceability by Chinese seafood enterprises, which are, in general, the improvement of product quality and improvement of management style. Overall, the Vietnamese and EEA companies perceive that traceability can reduce liability claims and lawsuits, while the Chilean firm does not have the same perception. The EEA companies' group and the Chilean firm also see traceability benefits in the reduction of product spoilage. These benefits have also been considered and/or reported in other food sectors, e.g. improvement of supply management (Golan *et al.*, 2004), increase of product quality (Chryssochoidis *et al.*, 2009; Poghosyan *et al.*, 2004), retaining of existing beef markets in those countries which require traceability (Souza-Monteiro & Caswell, 2004) and product differentiation in the fresh fruit and vegetable industry (Golan *et al.*, 2004) and the dairy-processing sector (Sparling *et al.*, 2006).

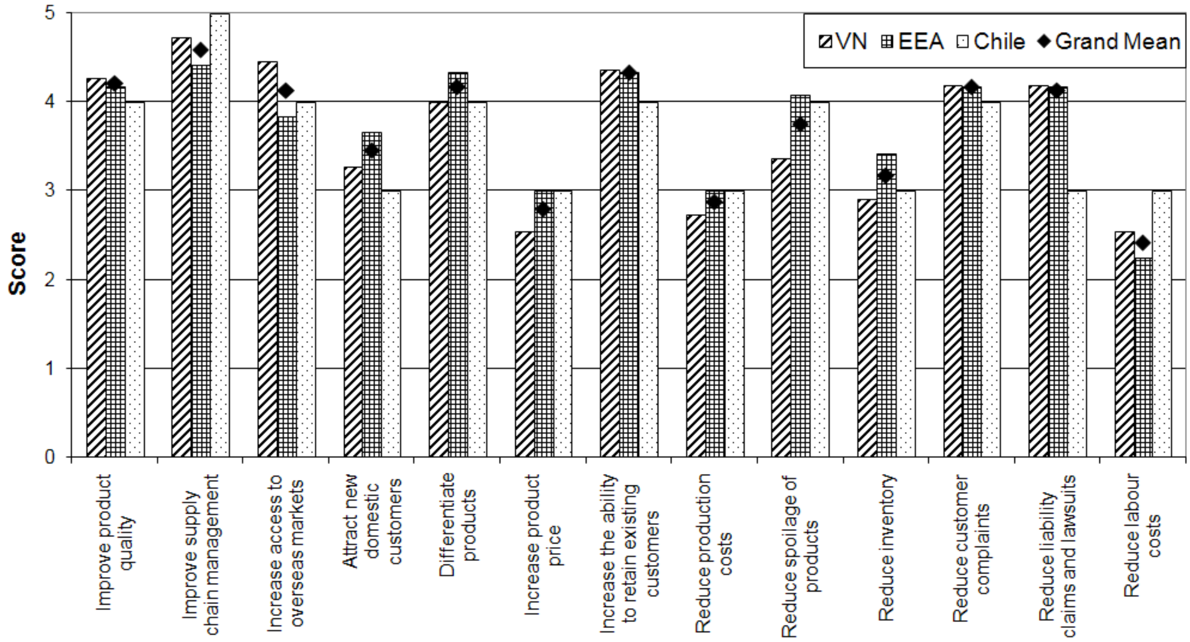

Figure 6. Qualitative peceived benefits of traceability from the industrial perspectives. The mean scores across the companies of the same region are given for 11 Vietnamese (VN) and 12 European Economic Area (EEA) firms; single values of scores are shown for the Chilean (Chile) company. The average score across 24 companies is also shown as grand mean (I).

Surprisingly, other benefits of traceability highlighted in the literature, such as reduction of inventory costs (Can-Trace, 2004), reduction of production costs, increase of product price (e.g. positive consumer willingness-to-pay) (Hobbs, 2003; Hobbs *et al.*, 2005) and saving of labour costs (Buhr, 2003; Chryssochoidis *et al.*, 2009) are considered of minor importance by the companies-respondents. No significant difference ($p > 0.05$) of perceived benefits was found between the Vietnamese and EEA companies' groups.

4.1.2 Cost-benefit analyses of adopting advanced traceability systems

Present and net present values of benefits of 5-year lifetime of two RFID-based traceability systems were calculated and are presented in Table 3 (I). The three scenarios included the effects of uncertainty related to the discount rate (2.4, 4.5% and 7.0%) and future benefits (lower bound and upper bound). As shown in Table 3, in the seafood processing company case, aiming to use passive RFID tags Rf-TTI (coupled radio frequency and time temperature indicator) on all master boxes, the net present value (NPV) of the lower-bound base-case scenario, where the benefits of recall reduction have not been perceived, is negative. Contrastingly, when the recall is expected to be reduced from 0.25 ("unlikely") level with the current traceability to 0.1 ("very unlikely") with the new system (see Paper I), the NPV becomes positive. The NPV in the trading company case, aiming to use one active RFID tag on each pallet, is always positive; and the benefits by far outweigh the costs (16-252 times). Although not all the scenarios of the seafood processing company case appear to be beneficial in monetary terms, it is worth noting that the new traceability solution in this case is aimed at a more detailed level (master boxes) than in the trading company case (pallets).

Table 3. Present values of benefits and net benefits of implementing new traceability solutions (€ thousand) (I).

Benefit components	*Processing company case*				*Trading company case*			
	Worst	*Best*	*Base*		*Worst*	*Best*	*Base*	
			Low	*High*			*Low*	*High*
Market growth benefits [a]	0.0	0.0	0.0	0.0	18,691.6	39,062.5	19,138.8	38,277.5
Recall reduction [b]	0.0	1,164.8	0.0	1,097.5	0.0	0.0	0.0	0.0
Savings from clams & lawsuits	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Labor cost savings [a]	93.5	195.3	95.7	191.4	37,383.2	58,593.8	38,277.5	57,416.3
Savings from process improvements [a]	0.0	48.8	0.0	47.8	0.0	0.0	0.0	0.0
Total benefits	*93.5*	*1,408.9*	*95.7*	*1,336.7*	*56,074.8*	*97,656.3*	*57,416.3*	*95,693.8*
NPV	*-6,952.6*	*1,191.1*	*-749.4*	*491.7*	*52,648.8*	*97,270.2*	*56,615.4*	*94,892.9*

[a] Assume that benefits occur once at the end of the first year. [b] Assuming yearly benefits, from the end of the first year. NPV is net present value.

Because the two case studies are not of the same supply chain and aimed at different traceability solutions (rf-TTI vs. active RFID tags) and precisions (boxes vs. pallets), the CBA results are not comparable. However, they have strengthened the argument on costs shifting among the stakeholders in a supply chain. It was shown that the seafood processing company paid much for what was needed, resulting in some negative NPVs, while the trading company could expect steady benefits. In order to implement new traceability solution(s), e.g. RFID-based, at the supply chain level, it is suggested that the price of intermediate products would go up, which is a way that trading companies could entice or persuade food producers to put new traceability system(s) in place. The findings support the need for an open discussion between different actors in a food supply chain on the distribution/redistribution of costs and benefits of implementing traceability (Can-Trace, 2004).

4.2 Traceability effectiveness in the fresh fish supply chain and more efficient use of recorded data

4.2.1 Effective traceability framework

Main components to ensure traceability at a food/seafood processing firm can be summarised as follows: registration of unique IDs for all resources' batches, registration of unique IDs for all newly formed batches, recording of all relevant product and process information and linking it to the batches' IDs, and transferring all traceability relevant information of the inputs (e.g. relevant batches IDs and associated information) with the product to the next step (e.g. next production step or next link of the chain) (Can-Trace, 2010; CEN, 2003; Derrick & Dillon, 2004; Donnelly *et al.*, 2009; EAN, 2002; Kelepouris *et al.*, 2007; Lindh *et al.*, 2008; McEntire *et al.*, 2010; Senneset *et al.*, 2007; Storøy *et al.*, 2007; Thompson *et al.*, 2005). Based on these, a framework to assess the effectiveness of a company traceability system was developed and is presented in Table 4 (II). A traceability system is effective if all the assessed questions can be answered in the affirmative (YES), if not required actions (RA) need to be taken to ensure traceability effectiveness. Detailed required actions or modifications to a seafood firm traceability system to ensure traceability should be consulted elsewhere, e.g. the traceability guide of Derrick & Dillon (2004).

Table 4. Framework for evaluating the effectiveness of a food processing company's traceability system and necessary modification to ensure traceability (II).

Question No.	Category of traceability information	Question	Possible answer and next action	Required Action (RA)
Ia	**Resource ID registration**	**Ia.** Are all batches of resources (e.g. raw materials and ingredients, etc.) registered with unique IDs?	- YES → Go to **Ib** - NO → Go to **RA-Ia**	**RA-Ia.** Register all batches of resources with unique IDs. Go to **Ib**.
Ib	**Resources' information**: associated/ relevant resources' information other than IDs	**Ib.** Is all traceability relevant information of resources' batches (e.g. suppliers' IDs, date of reception, quantity, grade, quality, etc.) provided and/or recorded, kept, and linked to batches' IDs?	- YES → Go to **II** - NO → Go to **RA-Ib**	**RA-Ib.** Develop procedure(s)/method(s) to obtain, keep, and link all traceability relevant information of resources' batches to their IDs. Go back to **Ib**.
II	**Transformation information**	**II.** Are all relevant resource, product, and process information (e.g. bill of lots) recorded and linked to resources' IDs or product IDs?	- YES → Go to **III** - NO → Go to **RA-II**	**RA-II.** Record all relevant resource, product, and process information and link to batches' IDs. Go to **III**.
III	**Product ID registration**	**III.** Are unique IDs assigned to all newly formed batches (e.g. product) and are these records kept?	- YES → Go to **IV** - NO → Go to **RA-III**	**RA-III.** Assign unique IDs to all newly formed batches and keep records. Go to **IV**.
IV	**Transferred information**	**IV.** Is all traceability relevant information of the input(s) (e.g. relevant IDs of the input(s) and associated information) transferred with the output (e.g. product) to the next step (e.g. next production step or next link of the chain)?	- YES → Go to **Conclusion** - NO → Go to **RA-IV**	**RA-IV.** Develop procedure(s)/method(s) to transfer all relevant IDs of input(s) and associated information with the output to the next step. Go back to **IV**.
		Conclusion: Traceability system is effective		

4.2.2 Traceability practice at a seafood processing company-a case study

Results from analyzing the traceability system at a Vietnamese *Pangasius* processing company using the proposed framework (Table 4, II) show that all the answers are YES which indicate a sufficient traceability system. Details on the IDs' configuration, product and process information inputs, and how the associated IDs are linked are presented in Paper II. Figure 7 shows traceability information flow at the company, indicating the link between associated IDs as well as between unit IDs and their associated product and/or process information.

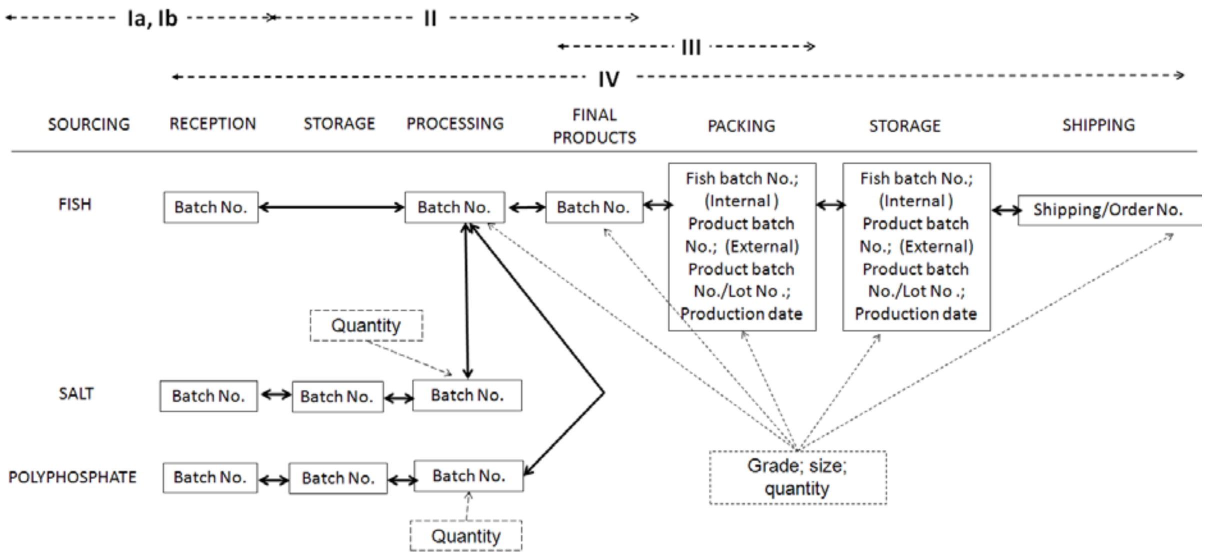

Figure 7. Traceability information flow at the processing plant. Frame boxes = IDs of the units; Two-way arrows = links between the units; Dash boxes = associated information; Dash one-way arrows = link of associated information to unit IDs. The dash two-way arrows with Roman numerals show the mapped areas with respective assessed questions for evaluating the effectiveness of the traceability system (II).

At the studied company, for each of all incoming batches of raw materials and ingredients, the IDs of suppliers and transporters are recorded in the reception form (II). For every dispatched batch of product, the IDs of buyers and transporters are recorded in the shipping form (II). This is in accordance with good traceability practice concerning information transfer for chain traceability (Storøy *et al., 2007*).

The current traceability system is effective because the codes of incoming resources (i.e. fish and ingredients' batch numbers) are associated uniquely to the final product (i.e. internal product batch number) and the codes of final product are also linked to the lot numbers (i.e. external product batch number) which are used for logistics and distribution (Bertolini *et al.*, 2006). All the data of the current system conform to mandatory data list of food traceability as described by Folinas *et al.* (2006). The studied system also meets the fundamental structure of a traceability system proposed by Moe (1998).

4.2.2.1. Ability to trace

Tracing back from the distributor through the company can be practised using the information on the box labels about the *production date* and the *external product batch number* which is uniquely assigned to each *product batch* defined as a certain type of product (e.g. fresh *Pangasisus* fillets) produced from the same fish raw material batch in the same production shift, date and workshop (II). Batch number of fish raw material (or *fish batch No.* for short) is uniquely assigned a three-digit ordinal number for each production year to the raw material from the same pond received at the processing plant during the same day. The company is then able to trace the origin of their products up to aquaculture pond level using an internal code system. Each product batch is uniquely assigned an *internal product batch number*, indicating the processing workshop; the shift; production date and the farming pond code uniquely given by the company (II).

Other ingredients can be traced back through the company to a delivery batch of a supplier. This is because a delivery of the resource from a certain supplier is uniquely assigned an *ingredient batch number* which is indirectly linked to the product batch number through the fish batch number. However, sometimes a product batch is produced from one fish batch and more than one batch of an ingredient, meaning that sometimes the traceability level is at a group of two continuously received ingredient batches (II).

4.2.2.2. Ability to track

Tracking forward through the company is possible using the same set of identifiers-numbers as when tracing back. Tracking of fish raw material is rather simple as there is no mixing of the resource from a pond throughout the production and to the customer. Concerning the other ingredients, e.g. a delivery of polyphosphate is normally used for 15 days of production. Therefore, if a recall (although very unlikely) of a delivery batch is issued by its supplier, a half month production of fish would have to be recalled (II). Frederiksen *et al.* (2007) have indicated that material identity with the longest time in production, e.g. polyphosphate in this case, has to be very well controlled, as it affects many product lot identities. The willingness to improve the precision of ingredients' traceability depends on the recall risks of each resource and the final product, detail level of information required by the customers and associated costs (Donnelly *et al.*, 2009; Kelepouris *et al.*, 2007; Moe, 1998; Randrup *et al.*, 2008). This is an area for future research.

4.2.2.3. Compliance with regulation and standard

The company meets with 178/2002 European Common Food Law requirements (EC, 2002b) for traceability which consider one step forward - one step backward traceability. However, the traceability system does not meet with TraceFish requirements (CEN, 2003) because globally unique identifiers, identified by Global Trade Item Numbers (GTIN), are not used (II).

4.2.3 More efficient use of recorded data

Connecting traceability with the whole documentation and control system represents an effective mean to improve the consumers' perception on food safety and quality (Moe, 1998). Along with traceability information, lot of information on process parameters and on quality is recorded and kept at the company, mainly in paper form and most of them for internal use only (II). These facts restrict the company from using the available data in an efficient manner. These data could be entered into computer system for faster access. Data on ambient temperature during logistics steps can be used to calculate the product warm up time (Margeirsson, 2009) (II). Furthermore, with the correlation between ambient and product temperatures, the remaining shelf life of a product can be estimated, using available software such as SSSP (DTU Aqua, Denmark) (II). These thus help to improve the management of product quality as well as improve the supply chain management (II).

4.3 Logistics of fresh fish: air versus sea transport. Measures for improvements

4.3.1 Air transport

Results from temperature mappings of air cargo and passenger freights for fresh cod loins and haddock fillets in expanded polystyrene (EPS) boxes from producers in Iceland to customers in the UK are shown in Figures 8 and 9. There are several critical steps found in air freighting, especially in the passenger flight, including the flight itself, loading/unloading operations, land transport and holding storage at un-chilled conditions (III, IV). Similar hazardous operation steps of air transport have been reported by Brecht *et al.* (2003); James *et al.* (2006); and Nunes *et al.* (2003). These cause fluctuation and/or rise of product temperature inside boxes, especially in those with more free sides such as at top corners of the pallets (III, IV). Position of the product on a pallet influences the product temperature evolution: middle boxes are the most resistant while top and bottom corner boxes are more sensitive to environmental temperature changes (III, IV). Other authors (Moureh & Derens, 2000; Moureh *et al.*, 2002; Raab *et al.*, 2008; Rediers *et al.*, 2009) have also found that products in the middle of a pallet are less affected by the ambience than those on top level, which is explained by better insulation of the middle part. All these authors have, however, found that the top corner boxes are the most influenced by the environment while it is not always the case in this study where bottom corner boxes are sometimes the most sensitive. This difference might be caused by different positioning of the pallets in relation to the cooling units and/or door.

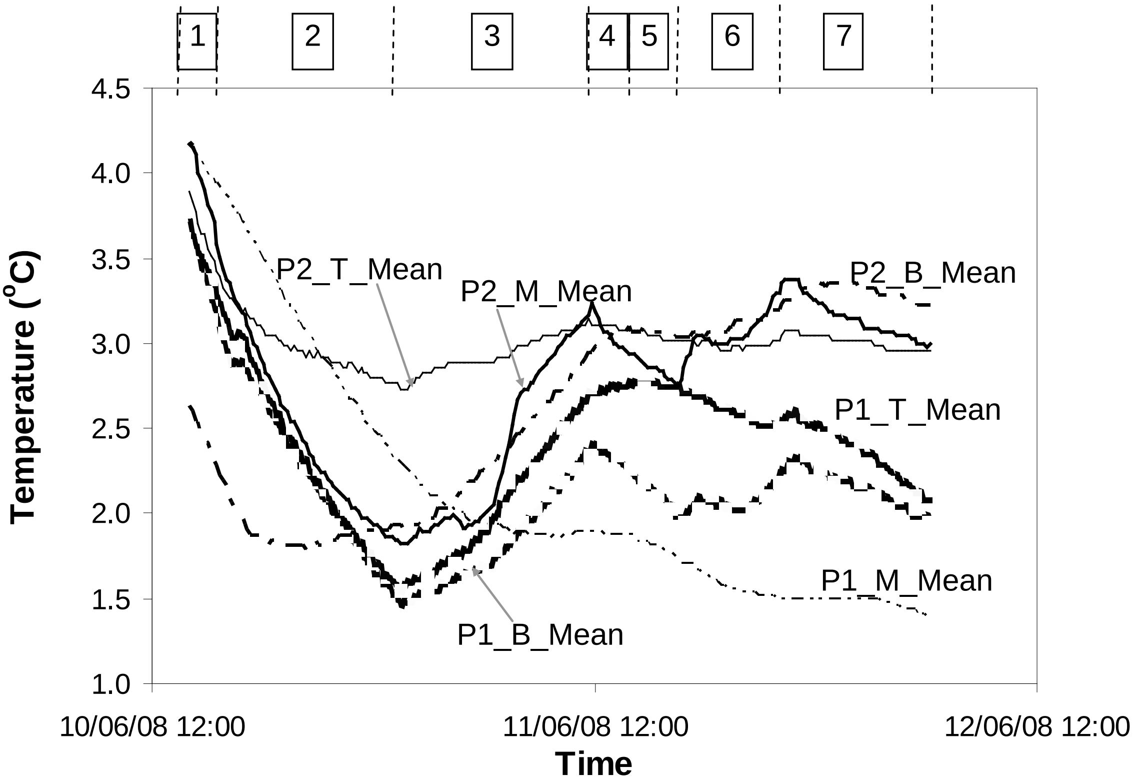

Figure 8. Average product (cod loins in 3-kg EPS boxes) temperature (_Mean) on two pallets during a cargo air freight study. P stands for pallet. T, M and B indicate top corner, middle side and bottom corner boxes on a pallet. Numbers in squared boxes indicate steps in the supply chain: 1 = Cold storage after packing at the producer (Dalvik); 2 = Loading truck and transportation to Reykjavik (RVK), 3 = Un-chilled storage over night in RVK, 4 = Transportation in refrigerated truck to Keflavik (KEF), 5 = Chilled storage at KEF airport, 6 = Loading at KEF and flight from KEF to Nottingham (UK), 7 = Transportation from processor storage (III).

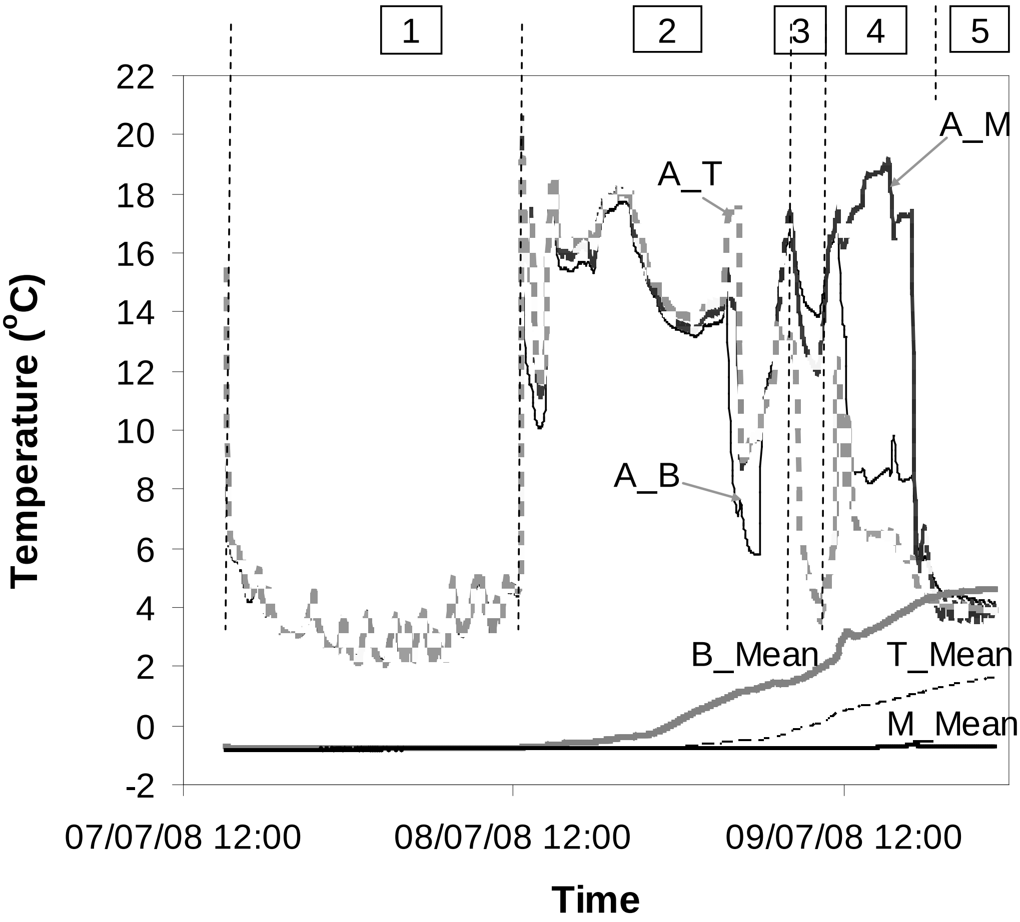

Figure 9. Box surface (A_) and average product (haddock fillets in 12-kg EPS boxes) (_Mean) temperatures during a passenger air freight study. T, M and B indicate top corner, middle side and bottom corner boxes on a pallet. Numbers in squared boxes indicate steps in the supply chain: 1 = Chilled storage at the producer in Hafnarfjordur (IS) after packaging; 2 = Transport from Hafnarfjordur to some storage at KEF, 3 = Flight duration, from taking off to landing, 4 = Storage at London Heathrow airport (LHR, UK), 5 = Land transport in refrigerated truck to the secondary producer in Plymouth (UK) (III).

The greater the temperature fluctuation around the boxes, the larger the temperature range inside the packaged product becomes (III). Temperature on top of the product inside the EPS boxes is more sensitive to ambient changes than those deeper in the box (III). Giannakourou *et al.* (2005) have also shown that there is a difference in temperatures between top and middle levels inside transported Styrofoam ice boxes of chilled gilt-head seabream during most abused/fluctuated periods.

Furthermore, precooling reveals an important operation before loading for transportation. Those products which were precooled resulted in lower temperature at the end of the logistics compared to those without precooling (III, IV). This is in accordance with the recommendation to precool product before transportation (James *et al.*, 2006).

4.3.2 Sea transport

In contrast to air transport, temperature mapping for sea freighting (Figure 10, III, IV) shows very stable temperatures of both the ambience and product since in the sea freight chain the boxes were kept in a refrigerated container for the whole trip from the processor to the final destination. Furthermore, the product temperature difference between locations inside a box is small (≤ 0.2 °C most of the time) thanked to the pre -cooling (by liquid and combined blast and contact (CBC) cooling) before skinning and adding of ice on top of the fillets when packing into the EPS boxes. Product temperature was maintained well below 0 °C as normally stated in contracts (III, IV).

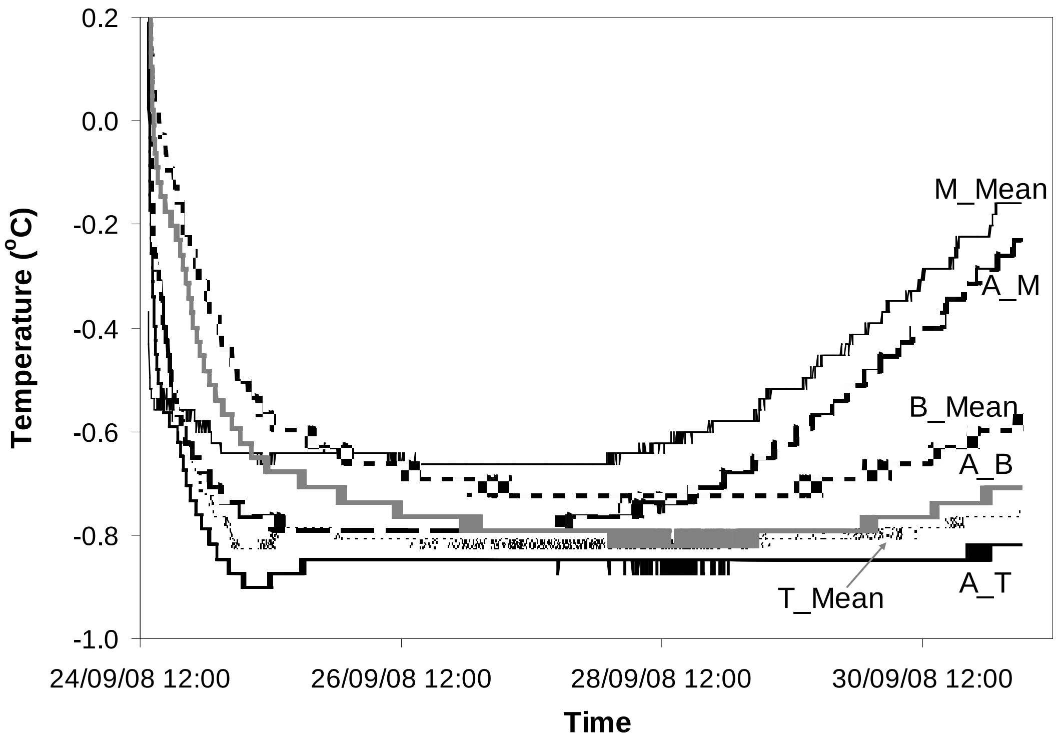

Figure 10. Box surface (A_) and average product (cod loins in 5-kg EPS boxes) (_Mean) temperatures of the top corner (T), bottom corner (B) and middle side (M) boxes on a pallet during a sea transport study (III, IV).

4.3.3 Influence of logistics on the product shelf life

Figure 11 gives an overview on three air and one sea trips regarding total used time (length of the logistics plus three days from catch), predicted remaining shelf life (RSL), and (average) temperatures of product and box surface. The product RSL is affected by the length of the logistics, presence/absence of precooling, mode of transport as well as product location (III, IV).

Length of the logistics (time from packaging to delivery at customers, e.g. retailers, including handling, storage and transport processes): Longer logistics result in shorter remaining shelf life as seen in the cases of the air freight in September 2007 and sea freight in September 2008 compared to other cases despite the fact that the temperature was well controlled in sea transport (III). This verifies an earlier observation that even under optimal conditions the quality of a perishable product apparently decreases with time (Pawsey, 1995).

Presence/Absence of precooling: Precooling helps to lower the initial temperature of the product, reduce the temperature heterogeneity between different height levels inside a box, and increase the RSL as in the case of air passenger transport in July 2008 even though the pallet was split up (III). This reveals the importance of precooling the product before packing as stated by others (James *et al.*, 2006).

Mode of transport affects the logistics length and ambient temperatures (Figure 11, III), meaning that transport mode affects the product time-temperature history, and consequently influences on the product shelf life (III). It is understandable as temperature and time are the key factors affecting the product degradation process (Jol *et al.*, 2005; Olafsdottir, 2005; Pawsey, 1995; Raab *et al.*, 2008; Rediers *et al.*, 2009), thus its RSL.

Product location: Products at different locations on a pallet and inside a box experience different degrees of environmental temperature changes and their temperatures evolve differently (Figures 8-10, III, IV), which in turn affects the RSL (III).

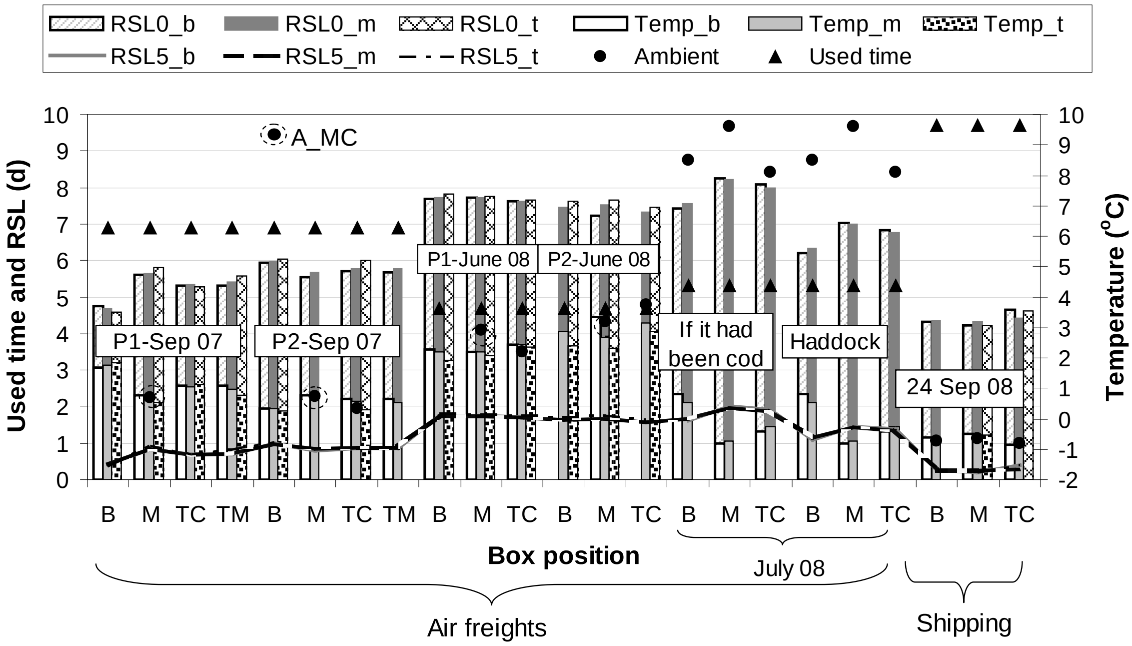

Figure 11. Total used time from catch and predicted remaining shelf life (RSL) of product at 0 °C (RSL 0) and 5 °C (RSL 5). The average ambient (Ambient) and product (Temp_) temperatures over the whole logistics from different pallets (P1, P2), box positions on a pallet (B = bottom, M = middle side, TC = top corner and TM = top middle) and locations inside a box (b = bottom, m = middle height and t = top) are also shown. A_MC means the temperature on the side of a pallet. The 3 lines of predicted RSL at 5 °C (RSL 5_b, _m and _t) are almost identical on the graph (III).

4.3.4 Improvement of logistics management in fresh fish supply chains

Air freight transportation has several critical steps, including pre and post transportation and the flight itself (*transportation*), loading/unloading operations (*handling*), and holding storage at un-chilled conditions (*storage*). The single process contributing to the highest rise in product temperature in the current study turned out to be the storage process. This indicates that most potential for improvements is during this process, which would in most cases require access to a cool storage within the airport area, where products can then be moved fast to the airplanes for loading and further transportation to distributors or retailers (IV).

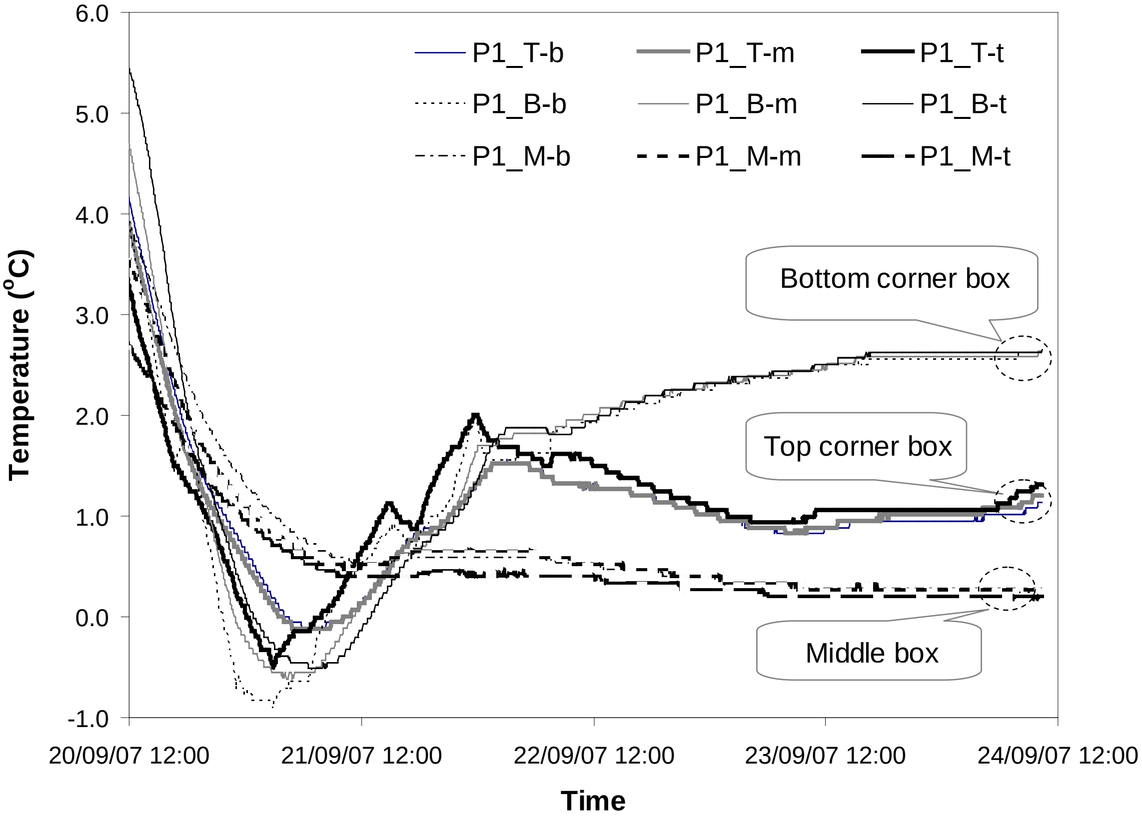

Figure 12. Product temperature at different locations on a pallet and inside the boxes during the air cargo study in September 2007. P stands for pallet; T indicates top corner box; B is bottom corner box; and M is middle side box of a pallet; t is top; m is middle height; and b is bottom product inside a box (III, IV).

Heterogeneity in temperature of product at different locations on a pallet indicates that it is possible to group the boxes according to their positions on pallets and collect boxes with similar temperature evolution during the pallet unloading (Figure 12, III, IV). This would potentially increase the market duration and possible shelf life of the products which have been exposed to lower ambient temperatures (III, IV). Jedermann *et al.* (2009) have also mentioned about grouping product items with equal temperature behaviour in batches.

Furthermore, precooling is recommended to lower the product initial temperature and reduce the temperature gradient between product levels inside a box so as to withstand the temperature fluctuations and/or abuse as well as long duration of the logistics (III, IV). This is in accordance with suggestions of precooling the product stated elsewhere (James *et al.* 2006).

Overall, the temperature mapping and predicted RSL results (Figures 8-12) support the need to continuously monitor time and temperature history of products (Giannakourou *et al.*, 2005). Long exposure to high temperature also facilitates pathogen to growth (Raab *et al.*, 2008) which causes food safety problems. To better manage fish quality including safety, it is useful to apply some technology such as temperature data loggers, time temperature indicator (TTI) labels, radio frequency identification (RFID) tags with the temperature sensor and time recorder or other similar equipment on or inside the packaged product. Heat transfer modelling of individual and palletised EPS boxes containing fresh fish, similar to the modelling of frozen fish pallets by Moureh and Derens (2000) and Moureh *et al.* (2002), would be useful to predict product temperatures under dynamic ambient conditions as described in the current study.

4.4 Continuous monitoring of quality and shelf life of fresh fish in comparison with conventional methods

The newly introduced printable photochromic OnVu™ TTI has been tested for its reliability under the fresh fish supply chain temperature conditions (V) as well as its applicability for quality and shelf life monitoring of fresh cod loins in retail packs compared to conventional methods of quality control (VI).

4.4.1 Performance of the new photochromic OnVu™ TTI under nonisothermal conditions of fresh fish supply chains

The reliability of a TTI is an important issue to enable the application of the TTI in cold chain management (Shimoni *et al.*, 2001; Kreyenschmidt *et al.*, 2010). Reproducible charging process and responses of the TTI under the conditions concerned are therefore of great importance.

4.4.1.1. Reliability of the new TTI

The investigation results show that the new TTI has produced reproducible responses right after charging and during the whole discolouration process both under isothermal temperatures below 2 °C and nonisothermal conditions simulating real fresh fish supply chains. The discolouration of the TTI reflected well its undergone temperature conditions. Some activation levels of the TTI were found to give similar lifespan of the TTI as that of air packed fresh fish products (cod fillets) under the same temperature conditions. All these indicate the potential to use the new TTI for continuous monitoring of the temperature history, quality and shelf life of fresh fish products (V).

4.4.1.2. Model validation and correlation between charging levels and the lifespan of the TTI

The kinetic model developed for the new TTI under isothermal conditions at temperature range 2-15 °C (Kreyenschmidt *et al.*, 2010) works well for non-abused temperature conditions below 2 °C (V). This indicates the possibility to extend the contour diagram of Kreyenschmidt *et al.* (2010), which presents the TTI lifespan as a function of charging levels and storage temperatures, to temperature regions below 2 °C to define suitable charging levels of the TTI to suit the shelf life of the fresh fish/food products concerned under the same low temperature conditions.

Alternatively, the choice of the right charging level(s) to suit the shelf life (lives) of fish product(s) of the same storage conditions can be done using the correlation of TTI lifespan and charging level (SVo) at specific temperature conditions as shown in Figure 13 (V).

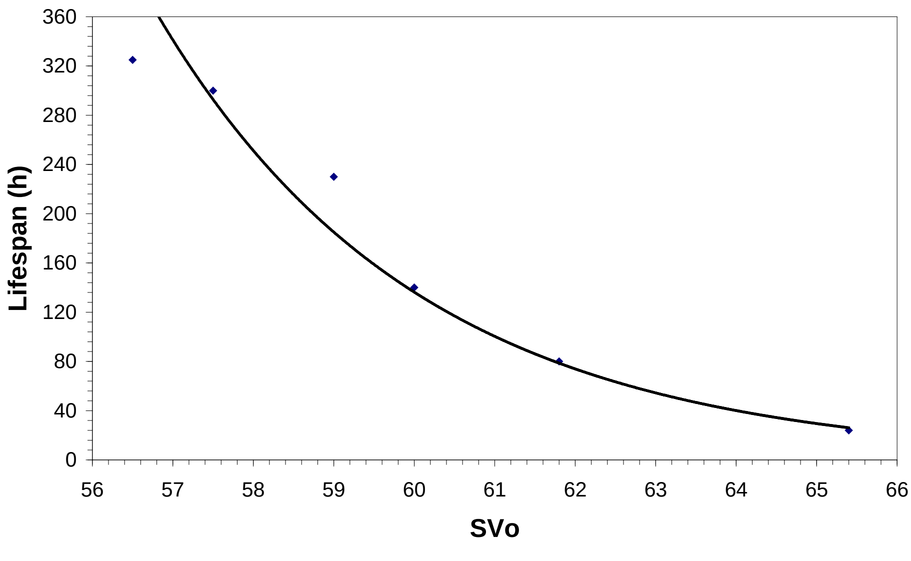

Figure 13. Lifespan of the TTI with different charging levels/initial square values (SVo) at a storage temperature of 0.5 °C. Experimental data and fitted curve by an exponential decay function (V).

4.4.2 Applicability of TTI to monitor the quality and shelf life of fresh fish in comparison with conventional methods

Product shelf life given and predicted by TTI placed on the bottom surfaces of retail trays agrees well with the one derived from TVB-N level and predicted based on product temperature history by the relative rate of spoilage (RRS) model, for both chilled and superchilled storage cases (Table 5, VI). It is also in accordance with the product shelf life declared by sensory evaluation in the case of chilled storage. However, the TTI indicates a much longer shelf life than sensory shelf life in the case of severely superchilled storage, which causes negative effects on the sensory attributes of the product (Table 5, VI). The ST group, stored at undesirable conditions (product temperature -2.8 ± 1.2 °C), was described with more dark colour, precipitation and discolouration, more rubbery texture and less tender, flaky, soft and mushy texture than the TT group (product temperature -0.2 ± 0.4 °C from day 6) (VI). Superchilled storage delayed the growth of specific spoilage organisms (SSO), H_2S-producing bacteria and Pseudomonads, in supechilled (ST) group compared to chilled (TT) samples (Table 5, VI). This explains the lower concentration of TVB-N and TMA in ST samples (VI) as H_2S-producers along with some other psychrotrophic species, such as *Photobacterium phosphoreum,* contribute to the formation of these volatile compounds (Koutsoumanis & Nychas, 2000; Olafsdottir et al., 2006). The results are in a good agreement with other studies that the proliferation rate of these bacterial species is lower at superchilled storage conditions compared to chilled storage for aerobically packed cod fillets (Olafsdottir *et al.*, 2006) or loins (Wang *et al.*, 2008). Lower TVC and SSO counts in the superchilled samples agree with the slower colour changes of the TTI in the ST group compared to the TT group (VI).

Table 5. Product (cod loins in airtight retail packs) shelf life (days from processing) given by sensory evaluation, TVB-N level, TTI discolouration, and square-root spoilage model in SSSP; and values of TMA, TVC and specific spoilage organisms, initial and at sensory rejection (VI).

		Initial values	ST		TT	
			Non-abused	Abused	Non-abused	Abused
Sensory shelf life (d)			11		10-11	
TVB-N based shelf life (d)			> 15		10-11	
Shelf life based on TTI_top (d) [a]	Measured		> 15.9	9.8	12.7	8.7
	Simulated		15.9 [b]		12.7 [b]	
Shelf life based on TTI_bottom (d) [a]	Measured		> 15.9	10.1	10.7	8.5
	Simulated		> 15.9 [b]		10.7 [b]	
SSSP, RRS model (SL) (d)			> 15.3	10.8	10.2	8.8
TMA (mg N/100 g)			< 1.1 ± 1.2		1.6 ± 0.2	
TVC (log CFU/g)		5.3 ± 0.2	< 6.6 ± 0.1		7.2 ± 0.1	
H_2S-producer counts (log CFU/g)		2.3 ± 1.0	< 4.6 ± 0.9		5.5 ± 0.5	
Pseudomonad counts (log CFU/g)		3.5 ± 0.1	< 5.4 ± 0.6		6.6 ± 0.1	

[a] Charging time of TTI labels at 7 °C were 650 ms (SVo 59) on day 0 (packaging day, i.e. 3 days from catch) for ST samples and 450 ms (SVo 61) on day 6 for TT samples; [b] Simulated using Eq. (6). ST = superchilled retail trays of cod loins stored at set -1 °C without abuse (ST, Non-abused) or with abused on day 8 (ST, Abused); TT= chilled retail trays of cod loins stored at set 0.5 °C without abuse (TT, Non-abused) or with abused on day 8 (TT, Abused); TTI_top = TTI placed on top surfaces of retail packs; TTI_bottom = TTI placed on bottom surfaces of retail packs; SL = shelf life; RRS model = relative rate of spoilage model.

Temperature recordings on the top and bottom pack surfaces as well as in the product show that the temperature on the bottom surface is not significantly different ($p > 0.05$) from the product temperature; while this is not always the case between temperatures on the top surface and in the product (VI). TTI placed on the bottom of the packs can therefore be used to monitor temperature conditions of fresh fish products. The findings strengthen the aim to use TTI to replace direct temperature recordings in the fresh food supply chains of Riva et al. (2001). Further, with a suitable activation level, TTI placed on the bottom of retail packs, can potentially be used to monitor the quality and shelf life of chilled fish products.

5 CONCLUSIONS

The studies carried out provide better understanding on the benefits, both qualitative and quantitative, of traceability in the seafood industry. The findings offer practical evidence in support of the traceability drivers mentioned in the literature which are market benefits, savings related to product recalls, savings associated with liability issues, savings from process improvements and savings from labour costs with electronic based systems. *Ex ante* cost-benefits analyses of adopting new and more advanced traceability systems provide initial knowledge on the net benefits of such projects and the distribution of costs and benefits among actors in seafood supply chains. The financial burden of implementing traceability systems may be borne by the processing firms, while gains are reaped by firms in the distribution business closer to the end consumer. This could provide a partial explanation why traceability has been slow to gain ground as a visible value adding marketing tool, and is mainly being driven by food safety regulations. The findings highlight the need for an open discussion between different actors along the chain on the distribution/redistribution of costs and benefits of implementing traceability and support the argument for cost shifting among stakeholders. In order to implement more advanced traceability system(s) or solution(s) at the supply chain level, it is suggested that the price of intermediate products would go up, which is a way that trading companies could entice or persuade food producers to put new traceability system(s) in place.

The framework developed in this study for evaluating the effectiveness of traceability at seafood companies might also potentially be useful for food producers to evaluate the effectiveness of their existing traceability systems based on process mapping information. The case study performed at a *Pangasisus* fish processing company in Vietnam supports the validity of the framework. Further, the framework could be used to locate problems of traceability systems so that the actors can take timely necessary actions to ensure traceability.

A more efficient way of using available quality and process parameters' information, routinely recorded at companies, helps to improve the management of product quality as well as improve the supply chain management (e.g. optimise shipping destination and stock rotation). It is suggested to key these data into computer system for faster access. Data on ambient temperatures during logistics steps can be used to calculate the product warm up time. Furthermore, with the correlation between ambient and product temperatures, the remaining shelf life of a product can be estimated from the ambient temperature history.

Temperature mapping studies provide insights into how fresh fish kept cool throughout logistics processes, from packaging to markets. Several critical steps were pinpointed in air transport, especially in a passenger flight, including ground transportation and the flight itself (*transportation*), loading/unloading operations (*handling*), and holding storage (*storage*) at un-chilled conditions. Abusive temperature during air freighting causes fluctuation and/or rise of product temperature inside boxes, especially in those with more free sides such as at the top corners of the pallets. The greater the temperature fluctuation around the boxes, the larger the temperature range inside the packaged product becomes. Temperature on top of the product inside the EPS boxes is more sensitive to environment changes than those deeper in the box. Thus, grouping products according to their positions during transportation is useful for further management of the resource. Temperature during sea transportation in refrigerated containers is well maintained at low temperature. However, long shipment time causes a relatively short remaining shelf life of a product in sea freighting. Precooling product before transportation reveals an important step to help withstanding the temperature fluctuations, abuse and duration of the whole logistics. Further, the studies indicate that most potential for improvements in airfreight is during *storage* process, which would in most cases require access to a cool storage within the airport area, where products can then be moved fast to the airplanes for loading and further transportation to distributors or retailers. The results also show a need for continuous monitoring of the product temperature history throughout the supply chain, from the point of packaging to retailers, and further down to end consumers with the implementation of some technology, such as time-temperature indicators (TTIs).

The study on the behaviour of the new OnVu^{TM} TTI under simulated field conditions of chilled fish products has showed that the TTI presented a good reliability under different temperature conditions as it gave reproducible responses right after charging as well as during the discolouration process. The TTI reflected well the temperature conditions of the simulated field scenarios, which indicates its potential use to monitor the cold chains of fresh fish. The existing kinetic model worked well with data from non-abuse storage at temperatures below 2 °C, which indicates the potential to extend the quality contour diagram to low temperatures so that a charging level can be defined to suit the shelf life of a product stored under the same conditions. The charging levels can also be chosen based on the correlation between the charging levels and lifespan of the TTI found in this study.

The TTI placed on the bottom of the packs were found to effectively reflect the temperature conditions of the product and could therefore be used to monitor the abuse and fluctuations in temperatures during storage of fresh cod loins in retail packs. In general, the TTI of a suitable charging level can potentially be used to continuously monitor the quality and shelf life of chilled product(s). However, severely superchilled conditions, which cause negative effects on the sensory attributes of the product, other than those induced by microbial spoilage, might influence the precision of shelf life estimation by the TTI. The findings support the idea to use TTI to replace direct temperature recordings in the fresh food supply chains.

6 FUTURE PERSPECTIVES

Market drivers for traceability in relation to environment, sustainability, carbon footprint/Food miles and similar issues needs to be further explored. Furthermore, though *ex ante* cost-benefit analysis of adopting new traceability solution(s) is useful for decision making, *in medias res* and/or *ex poste* CBA(s) is desirable to re-evaluate the net benefits of implementing new traceability solution(s) and learn about the efficiency of the *ex ante* CBA.

Precision of traceability of a product is highly affected by the traceability of ingredients involved in the bill of lots to make the product. It is very common in practice that a lot of an ingredient relates to more than one lots of dispatched product. Improvement of the precision of ingredients' traceability depends on the recall risks of each ingredient and the final product, detail level of information required by the customers and associated costs. This is an area for future research.

Study on improvement of fresh fish quality concerning improved packaging (e.g. packaging material, size and thickness, and pallet cover), optimising cooling and/or precooling techniques to reduce the effect of ambient changes on the product temperature during the logistics is another interesting research area.

Heat transfer modelling is desirable to correlate ambient temperature and fresh fish product temperature under specific conditions, which enables shelf life prediction of the product concerned and/or calculation of product warm up time based on the ambient temperature history. The knowledge of the product shelf life and/or warm up time would be helpful for producers and other downstream actors in product distribution planning.

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PAPERS I-VI

PAPER I

I

Benefits of traceability in fish supply chains - case studies

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Benefits of traceability in fish supply chains - case studies

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Benefits of traceability in fish supply chains - case studies

Paper type: Case Study

Abstract

Purpose

This study aims to investigate how the seafood industry perceives benefits of traceability implementation. Furthermore, *ex ante* cost-benefit analyses (CBAs) of adopting new traceability systems are conducted for two firms, operating at different steps of the seafood supply chains, to obtain preliminary knowledge on the net benefits of the project and on how costs and benefits are distributed among the actors.

Design/methodology/approach

This is a case based study.

Findings

The surveyed companies perceive improving supply chain management as the most important benefit of traceability. Other benefits are increase of the ability to retain existing customers; product quality improvement; product differentiation; and reduction of customer complaints. However, the quantifiable benefits are perceived differently by the actors at different steps in the supply chains, e.g. implementing RFID tags on pallets in the seafood trading company case study shows tangibly quantifiable benefits.

Research limitations/implications

The perceived benefits of traceability presented reflect only the views of the companies-respondents in the study. Further investigation with larger sample size needs to be carried out to be able to generalise the findings.

The CBA case studies are *ex ante* analyses, done in a precautionary way, with estimated costs and expected benefits as stated from the companies' perspectives, therefore the results are limited to the specified cases and conditions. Possible increase in consumer surplus due to the new traceability solutions is ignored. Extended *ex ante* and/or *ex poste* CBA(s) needs to be conducted to re-evaluate the net benefits of implementing new traceability solution(s).

Practical implications

It is suggested that the companies adopt a new traceability solution in so far as it is proved beneficial by a more extensive and targeted CBA. Implementing new traceability solution(s) at supply chain level should consider the appropriateness of cost and benefit distribution between actors in the chain. The analysis also suggests that it might be beneficial for traders to pay a higher price-premium for traceable fish-products.

Originality/value

The paper is useful for both practitioners and academics regarding perceived benefits of traceability in fish supply chains. The research provides initial insight into seafood companies' perspectives on the benefits of adopting RFID-based traceability solutions. The paper suggests that the financial burden of implementing traceability may be borne by the processing firms, while gains are reaped by firms in the distribution business closer to the end consumer. This could provide a partial explanation why traceability has been slow to gain ground as a visible value adding marketing tool, and is mainly being driven by food safety regulations.

Keywords: Traceability, Benefits, Cost-benefit Analysis, RFID, Fish Supply Chain

Benefits of traceability in fish supply chains - case studies

1. Introduction

Traceability has been applied in food supply chains for several years in compliance with legislative and market requirements, such as EC Regulation No. 178/2002 (EU, 2002) and US Bioterrorism Act PL107-188 (PL107-188, 2002).

Good traceability in food supply chains has the potential to reduce risks and costs associated with food borne disease outbreaks (Hobbs, 2003), e.g. reduce their magnitude and possible health impact; reduce or avoid medical costs; reduce labour productivity losses; reduce safety costs arising from a widespread food borne illness (Can-Trace, 2007). Reduction of costs associated with product recalls, e.g. reduced recall scope and time, is considered as another main economic incentive for implementing traceability (Golan *et al.*, 2004; Can-Trace, 2007). Traceability is also found beneficial in terms of reducing costs associated with maintaining consumer or market confidence in product (Can-Trace, 2007). In addition, traceability, especially electronic-based, is the potential to increase production efficiency, e.g. reduce cost of procurement, movement and storage; implement just-in-time (JIT) management of manufacturing (Moschini, 2007); improve planning, lower cost of distribution systems, expand sales of high-value products or of products with credence attributes (Golan *et al.*, 2004).

The provenance of the sustainable origin of the food products could more easily be tracked and traced in the supply chain, which gives an added economic benefit due to marketing possibilities otherwise not accessible at demanding clients. The more environmentally concerned consumers are willing to pay a premium for e.g. fish products sourced from fisheries that are managed in a sustainable manner. Recently another important value concept in the market has increasingly gained importance that is linked to the sustainability issues. This is the carbon footprint (Food miles) associated with a product (Intrafish, 2009), and a good traceability system is necessary to prove the more positive “green nature” (Tyedmers *et al.*, 2008) of the product in the marketplace, which again is a decision element for consumers for selecting a product with a proven more favourable green image (CarbonTrust, 2008), and usually willing to pay a premium for the assurance of a product by a recognizable standard needing a reliable traceability system for its verification. Furthermore, Fair Trade issues need tracking and traceability for proving origin and provenance of the claims. By implementing traceability, actors of supply chains are able to comply with laws and regulations of the markets and to meet demand of customers, which in turn will help to remain as well as extend their markets (Souza-Monteiro and Caswell, 2004).

Another economic reason for adopting traceability systems is to eliminate liability risks associated with unsafe food problems (Hobbs, 2003) which may result in financial damages such as penalties, loss of trade, damage to reputation, or loss of brand name capital (Can-Trace, 2007). Good traceability systems decrease the probability of a supplier being found wrongly liable for a certain food safety problem, and would give the opportunity to improve the overall level of food safety. Firms may benefit from traceability systems associating with quality and safety assurance mechanisms, because they may have the possibility of proving with well documented manufacturing system and practices that they do not present a risk when safety issues do arise. Those firms will be less vulnerable to liability than others who cannot prove that they do not have a given public health problem (Souza-Monteiro and Caswell, 2004).

Improving traceability at supply chain level can potentially reduce the costs to downstream actors (e.g. retailers or processors) of monitoring the activities of upstream steps (e.g. raw material supply) (Hobbs, 2003; Can-Trace, 2007).

Readily verifiable traceability information can lead to a reduction in information costs aimed towards consumers associated with quality verification (Hobbs, 2003; Hobbs, 2004). For example, enhancing labelling by identifying credence attributes related to food safety, environmentally-friendly production practices, assurances about feed, animal welfare, product differentiation can result in reduced costs of acquiring information for the consumer.

The benefits of implementing traceability for the companies can be grouped into the following categories: market benefits, recall cost reduction, reduction of liability claims and lawsuits, and process improvements (Can-Trace, 2004; Poghosyan *et al.*, 2004; Sparling *et al.*, 2006; Chryssochoidis *et al.*, 2009; Wang *et al.*, 2009a). In addition, applying electronic-based traceability systems can also save in labour costs compared to paper-based systems (Buhr, 2003; Alfaro and Rábade, 2009; Chryssochoidis *et al.*, 2009).

However, so far there have not been many scientific publications on the benefits of traceability from the seafood companies' views, and neither are any empirical cost-benefit analyses (CBAs) in this area. The purpose of this study is to bridge the above gaps by investigating the perceived benefits of traceability (both qualitatively and quantitatively) from the seafood companies' perspectives.

Implementing traceability at supply chain level is restricted by the uneven distribution of costs and benefits among the actors of a chain (Can-Trace, 2004). Therefore, this study also investigates the cost and benefit elements of traceability solution(s) in different chain steps. Two separate *ex ante* CBAs of adopting new RFID-based traceability solutions have been conducted for two firms at different steps of the fish supply chains. The aim is to obtain some preliminary knowledge on the net benefits of the project and on how costs and benefits are distributed among the actors; and to come up with some suggestion to improve the cost/benefit distribution.

This paper is organised as follows. Section 2 is the literature review on attitude of food companies towards traceability implementation and benefits, which is ended up with a summary table (Table 1) serving as a conceptual framework for the methodology of this study. Section 3 provides the background information of the companies-participants in the study. Section 4 presents the data collecting and analysing methods. Section 5 presents the findings of this research on the perceived benefits of traceability implementation from the seafood companies' perspectives, as well as detailed *ex ante* CBA results of the two case studies. Finally, Section 6 summarised the main findings, indicates the limitations of the study, and avenues for future work.

2. Literature review

From the firms' perspectives, benefits of traceability can come from trade effects (higher product price, extending current and new markets); from reducing recall impact; from reducing costs of liability (clams and lawsuits); from process improvements (reduction of inventory, spoilage reduction, process improvements, quality improvement, and others) (Can-Trace, 2004; Moschini, 2007).

Pouliot and Sumner (2008) have indicated that increased traceability is seen as a tool to improve food safety, which in turn increases consumers' willingness to pay for a safer product. Downstream firms may use traceability to shift liability upstream and reduce the chance of food safety incidents.

According to Olsson (2008), the driving forces to implement traceability in the entire chain actors can be recall minimization, retaining market shares, protection of the trademarks and strengthening reputation. He also noted that in a food supply chain, producers were the most often blamed when something upset consumers.

Hobbs (2004) has indicated that the role of traceability is to trace food back to the source in case of a food safety problem to identify and withdraw the affected products; to locate the source of a problem and assign liability. Traceability also reduces quality verification costs for consumers.

Frederiksen *et al.* (2002) have stated that business reasons for traceability are efficiencies, damage control, recall rate, brand name protection, and others. The authors also gave an example of loss of consumer confidence in the product of Perrier-bottlers of mineral water, which led to a loss of its market share from 60 to 15% worldwide.

In a study by Poghosyan *et al.* (2004) on motivations of traceability implementation and its benefits, focus interviews with the representatives of 17 international agribusiness corporations from Argentina, Australia, Germany, the Netherlands, South Africa, Switzerland, Zambia, the U.K., and the U.S. were used. It was found that the drivers for adopting traceability were: to improve supply chain management efficiency, to meet food quality target, to reduce risk and liability by improving their operations, to comply with regulatory requirement, to gain competitive advantages and better market access, to ensure consumer confidence and protect their brand reputation. Furthermore, the interviewees indicated that the main benefits of traceability were product and process improvements; decrease of production costs, diminishing risk of food recalls and incidents, protection of brand name.

Wang *et al.* (2009a) studied the incentives and benefits of Chinese fishery processing company in adopting traceability system. The companies-respondents were asked to use a five-point Likert scale, from “very unconsentient” to “very consentient”, in answering the survey questions. It was found that product quality improvement, need for healthy consumption, and management improvement were the most common incentives for traceability implementation. Furthermore, for private and joint-venture firms, to meet the customers’ requirements, to extent international and domestic markets and to differentiate products were also important drivers.

Sparling *et al*. (2006) studied the drivers behind the traceability implementation of Canadian dairy-processing plants. The authors used in-depth, semi-structured interviews with quality assurance managers in the first stage to form the input designed for the mail survey in the second stage. In one part of the questionnaire, the companies were asked to score 19 potential motivators of implementing traceability on a five-point Likert scale from 1 = “very unimportant” to 5 = “very important”. These authors found that three principle factors related to product problems (e.g. to reduce the risk of a product problem accruing, to reduce recall impact and risk of recalls); market drivers (e.g. to meet customer requirement, to reposition products and/or increase share of the current market, to access new market, to obtain higher product price); and legal/regulatory drivers (e.g. to reduce product liability, to meet regulatory requirements) were the most important. It was also found that 60% of 130 companies-respondents considered that benefits of implementing traceability exceeded costs and 27.8% considered that the benefits exceeded expectations. Interestingly, after implementation of traceability, these companies-respondents perceived that improved perception by customers, regulators, and consumers were the most important; while repositioning in current market, obtaining higher prices, and gaining access to new markets were somewhat unimportant.

A survey on economic implications of voluntary traceability was conducted within the meat processing, fruit and vegetable, dairy, wine, olive oil, baking and feed sectors in Italy (Banterle and Stranieri, 2008). A multiple choice, rating scale format was used. The results shows that the firms benefit from traceability through product differentiation, reduction of product recalls, precision identification of liability among the actors of the supply chain, and supply chain improvement.

A review on traceability from a US perspective in the livestock, poultry and meat industries by Smith *et al.* (2005) has shown that traceability is used to assure the food origin, to control and eradicate foreign animal diseases, to protect their national livestock population, to comply with international customer requirements and country-of-origin labelling requirements, to improve supply chain management, to facilitate value-based and value-added marketing, to effectively locate and correct the source of food problems, and to minimise product recalls and improve crisis management.

Ward *et al.* (2005) shows that traceability has made Canadian beef more acceptable than if it is nontraceable after the American bovine spongiform encephalopathy (BSE) crisis in December of 2003.

According to Leat *et al.* (1998), traceability in the Scottish agri-food industry was seen as a competitive advantage. The reasons for adopting traceability system were consumer assurance about the food origin and safety; ability to identify the source of infected or substandard product; disease control and residue monitoring; supporting measure verification; compliance with the labelling regulations; and for the beef market, lifting of the export ban on British beef and beef products.

Alfaro and Rábade (2009) investigated the traceability benefits of a Spanish vegetable firm where computerised traceability system was used. In-depth interviews with multiple employees of the firm were conducted using semi-structured questionnaire. In the production, warehousing, and distribution areas, it was found that the traceability system helped to increase production twice with the same number of employees; reduce the disruption in productive process: 90%; reduce indirect costs: 20%; increase warehousing capacity: 10-15%; reduce safety stock: 20-30%; and reduce devolution of lots (i.e. less compensation fees): 80%. In addition several qualitative benefits also listed, such as improve in operational procedure, increase the customers trust, etc. The company saw their traceability system as a tool for continuing improvement.

Chryssochoidis *et al.* (2009) have developed a cost-benefit evaluation framework of an electronic-based traceability system, using WaterCo natural mineral water company as a case study. Questionnaire to the company's executives composed of questions with 1-7-value scale to choose/answer. Benefits of the electronic-based traceability system can be seen as labour cost savings; asset and operating cost savings; inventory improvement; savings from better recall and risk management; supply-side management improvement; and compliance with regulations.

Buhr (2003) studied the role of electronic supply chain traceability in European meat and poultry processing firms. The study included site-visits and interviews of key personnel at each stage of the process, from feed manufacturing through retail. He found that the likely reason for adopting electronic traceability was to reduce information asymmetry within the supply chain. Several incentives for traceability were reported, such as reducing labour, improving accuracy and avoiding error of human input. In addition, electronic traceability helped to reduce food safety and recall costs, for example, Navobi calf-milk replacer manufacturer through their traceability information systems was able to save over $100,000 in recalls and recovery costs from a *Salmonella* outbreak. The electronic traceability system also helped to improve the processing process, for instance, a Norwegian slaughtering plant called Gilde Norge using traceability incorporating with a visual grading system made them able to add 5-7% to the final meat yields.

The total benefits for Sainsbury's (retailer store) with a full-scale implementation of RFID tagging on chilled products (without supplier participation) were estimated to be £8.5 million a year, of which savings from depot inventory control was £130,000; from store receiving was £294,000; from stock/code check was £2,556,000; from replenishment productivity was £1,425,000 (primarily in store); and from stock loss was £4,117,000 (primarily in store) (Karkkainen, 2003).

It was shown that implementing RFID logistics system(s) could reduce the loss rate of products from 0.05% (as in conventional logistics systems) to 0.01%; reduce misrecognition rate of products from 0.1% to 0.01%; and improve logistics processing rate from 0% to 10-30% (Kim and Sohn, 2009).

The benefits of traceability can also be reflected through the willingness to pay (WTP) for traceable food products.

Experimental auction method was used to determine Chicago and Denver consumers' preferences for steaks (Umberger *et al.*, 2003). The consumers were asked for visually evaluating and bidding on two steaks, which differed only in package labels. Most of the respondents were willing to pay average premiums of about 19% for the US-labelled steak. One of the reasons that caused the studied consumers to prefer US guaranteed beef over imported beef was a fear of meat from specific countries that had BSE outbreaks.

Premiums for "U.S. Certified" label obtained from the regional Colorado study (Loureiro and Umberger, 2003) were 38% for steak and 58% for hamburger, which is much higher than those above studies.

It was also reported that US consumers were willing to pay a premium $1.899/lb. of steak for traceability information in the label (traceable to the farm where the animal was produced) (Loureiro and Umberger, 2007).

Results from a laboratory auction market study at the Utah State University (Dickinson and Bailey, 2002) show that U.S. consumers may be willing to pay for meat traceability, transparency (e.g., assurances on animal treatment), and extra safety assurances (e.g., extra tests conducted for *E. coli* or *Salmonella* for beef or pork, respectively). Average premium for the roast beef sandwich with basic meat traceability is $0.23, with assurances on animal treatment is $0.50, with extra assurances of food safety is $0.63, and with all those three attributes is $1. For pork (ham sandwich), the WTP was $0.50 for basic meat traceability, $0.53 for assurances on animal treatment, $0.59 for extra food safety assurances, and $1.14 for all three attributes.

Experimental auction study in Saskatchewan and Ontario showed that Canadians would will to pay a premium of less than 10% for traceability on a Cnd$2.50 beef sandwich (Hobbs, 2003). Another study in Canada using experimental auctions (Hobbs *et al.*, 2005) showed that customers were willing to pay Cnd$0.27 on average for traceable ham/pork sandwich, accounting for 4.9% premium over the base sandwich value of Cnd$2.85. Both of the studies pointed out that traceability alone (without quality verification) has limited value to individual consumers. Combining traceability with quality assurances is proved to have potentially higher value.

Table 1. Summary of traceability benefits

	Benefit categories					
	Qualitative (intangible)	*Quantitative (tangible)*				
		Market	*Recall*	*Liability*	*Process*	*Labour*
Market recovery improvement		x				
Market and revenue growth		x				
Product price premium		x				
Less frequent recalls			x			
Less severe recalls			x			
Better management of recalls			x			
Less frequent claims & lawsuits				x		
Less severe claims & lawsuits				x		
Liability insurance cost reduction				x		
Inventory turnover improvement					x	
Spoilage/out of date cost reduction					x	
Yield improvements					x	
Labour cost savings						x
Regulatory & legislative compliance	x					
National security	x					
Enhanced customer confidence/trust	x					
Litigation risks mitigation or elimination, e.g. ability to shift the responsibility to other(s)	x					
Resolution of track trace data gaps	x					
Company reputation - customers	x					
Company reputation - consumers	x					
Company reputation - government & public	x					
Improved customer service	x					
Company reputation - suppliers	x					
Being technological proficient and an industry leader in new technologies and processes	x					

Variuos sources (among others): Smyth and Phillips, 2002; Buhr, 2003; Karkkainen, 2003; Can-Trace, 2004; Poghosyan *et al.*, 2004; Sparling *et al.*, 2006; Pouliot and Sumner, 2008; Chryssochoidis *et al.*, 2009; Wang *et al.*, 2009a.

Interviews were conducted on 169 Italian consumers after their purchase of extra-virgin olive oil in a supermarket and they suggested that the lack of traceability produced a welfare loss approximately €1 per litre of Italian oil purchased (Cicia *et al.*, 2005).

An on-site questionnaire survey conducted in Beijing, China regarding consumers' attitude toward traceability (Wang *et al.*, 2009b) showed that about 60% of the consumers were willing to pay a positive amount (up to 10%) for traceable fish products to increase safety. In average, the price premium was about 6%.

Diverse consumers' WTP for traceable products in different European countries (Germany, France, Italy, and Spain) (van Rijswijk *et al.*, 2008) may indicate that traceability contributes to improving consumer confidence, but primarily in an indirect manner through the general benefits perceived such as quality labels.

From the literature review, the benefits of traceability from the companies' perspectives can be summed up and considered as qualitative (intangible) or quantitative (tangible). Qualitative benefits here are those that are infeasible or difficult to be quantified and assigned monetary values; quantitative ones, in the other hand, can be monetised (Boardman *et al.*, 2006). Quantitative benefits in turn can be classified into five categories: market benefits (Market), savings from recall costs (Recall), savings from liability costs (Liability), savings from process improvements (Process), and labour cost savings (Labour) (Table 1).

3. Background

A survey on the qualitative benefits of traceability was carried out with different fisheries companies in the European Economic Area (EEA), Vietnam and Chile. They are operating at one or more different steps of supply chains, namely raw material supply, processing, transportation, trading, and wholesaling.

Interviews on the quantitative benefits of changing to new traceability solution(s) (e.g. RFID-based) were conducted with 8 fisheries companies. Two of them are processing companies (one Icelandic, and another Chilean); the third one is an Icelandic trading company; and the other five are Spanish wholesalers, four of which have business only in domestic markets, and the fifth one has 80% domestic business versus 20% in the EU markets.

Two CBAs were performed with seafood processing and seafood trading companies. The processing company is a small enterprise with two branches, one in Iceland and another in France. Its yearly turnover is about €10,000,000; number of employees is 50. It produces finished seafood delicatessen in fresh, frozen, smoked and/or salted form. This company has been practicing paper-based traceability for many years, and is interested in implementing the Rf-TTI label, which is a coupled time temperature indicator (TTI) and Radio Frequency technology (Rf), on each master box. The box size varies from 1kg to 17.7 kg. Annual trade volume of products intended for the new traceability solution is 450 ton in average. In the CBA, box size of 1 kg is used for the calculation.

Regarding the trading company, its' headquarter is located in Iceland; other branches are in several EU countries (such as Germany, France, Spain, Greece), in the US, and also in Asia. It deals with sales and marketing of seafood products (frozen, fresh, salted, dried, etc.) from producers to worldwide customers (for value-adding processors, wholesalers, distributors, retailers, restaurants, etc.). This company has a yearly turnover of about €400,000,000; and 70 employees. Its current traceability is paper-based, electronically stored, and also using bar code for some products. The company is willing to apply a RFID tag on each pallet. As the production volume, box and pallet size vary, the cost-benefit analysis was assumedly calculated for an average annual trade volume of 10,000 product ton; box size of 3 kg; and pallet of 100 boxes.

4. Methodology

4.1. Surveys

Three different types of questionnaires were used during the study. Firstly, a short questionnaire (about 1 page, see Appendix) was sent out in December 2008 to 7 technology developing partners to get the costs of traceability systems/solutions, 2 answers were received.

Secondly, another questionnaire with 7 sections and 21 questions (see Appendix) were used to interview at one seafood processing and one seafood trading companies in Iceland to get the quantitative benefits of implementing traceability systems/solutions. The first section of the questionnaire asks for general information about the companies and their attitude toward a new traceability system/solution. From the second to the sixth sections, the interviewees were asked to quantitatively estimate their perceived benefits of the new traceability system/solution by five above listed quantitative benefit categories (Table 1). In the last section, some more sensitive questions were asked, such as the company size and yearly turnover. The same questionnaire was sent to Chile and Spain for interviewing the fisheries companies there, 1 response from Chile and 5 from Spain were obtained. The interviewees were either chairmen, or managerial staff of the companies who know their production and business well. The interviews took place in December 2008, January and February 2009. The questionnaire was emailed about one month in advance to the companies for preparation. Each interview took about 45-60 minutes.

Information gathered from the first and second survey was to be used in the CBA analysis.

Finally, to investigate a broader range of companies on their attitude toward traceability implementation and benefits, an on-line questionnaire was launched in January and February 2009 using a 5-point Likert scale (from 1 = "very unlikely" to 5 = "very likely", see Appendix). The questionnaire is adopted and modified from the one used in our project for Chinese seafood industry (Wang *et al.*, 2009). In one part of the questionnaire, the companies were asked how they qualitatively perceived benefits of the implementation of traceability systems/solutions by rating their answers. Therefore, it is worth noting that "qualitatively" here is the way the companies perceived the benefits. It does not mean that all the benefits listed in the questionnaire cannot be monetised. The studied group was seafood companies (traders, processors, suppliers, importers, and exporters). One hundred and twenty invitations to the on-line survey were sent out, and 24 answers were received (12 from EEA located companies, 1 from Chile, and 11 from Vietnam).

All the questionnaires were developed or adopted based on the results from the literature review, expert suggestions, and tested with some volunteer companies for incorporating improvement modifications before the actual survey dispatch.

4.2. Case studies of the selected actors

Ex ante CBAs of implementing traceability systems were conducted for the two previously mentioned companies (one is seafood processor, and another is trader). The costs of the system were based on analysis of the short questionnaire results from the technology developers, whereas the benefits were obtained from the interviews with the selected companies.

4.3. Methods of cost benefit analysis

Net present value (NPV), which is used as a main criterion in the CBAs of the two case studies, is calculated by the following formula: (Boardman *et al.*, 2006)

$$NPV = \sum_{t=0}^{n} \frac{NB_t}{(1+r)^t}$$

Where t is the time of the cash flow; n - the lifetime of the project; r - the discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk); NB_t - the net benefits at time t, $NB_t = B_t - C_t$, B_t - the benefits arise at time t; and C_t - the costs arise at time t.

Costs associated with permanent structure were not included in the calculation. Furthermore, before-tax real Euro and real discount rate were used, as the analysis was assumed to reflect the gross benefits accruing to the processor and trader. In addition, it was assumed that implementation of the project will not affect the market price of inputs used due to its small size (Bell and Devarajan, 1983; Dreze and Stern, 2001).

The following assumptions are used in the calculations of the two case studies:

- ✓ A real discount rate of 4.5% is used for base-case scenario; sensitivity analysis is performed with the discount rates between 2.4 and 7.0% (those are currently used in EU countries) (Evans and Sezer, 2005);
- ✓ Time frame of the system is five years (based on the survey responses of the technology developers);
- ✓ The first cash flow occurs at the end of each year (from the first year);
- ✓ As the system is composed of relatively short lifetime items, depreciation is assumedly ignored in the calculation;
- ✓ The scrap values of the system items equal zero (meaning that costs are overestimated).

In both the case studies, three scenarios are considered: base-case, worst-case, and best-case. In the base-case scenario, discount rate is 4.5%; costs are the average estimated; benefits are assigned with two values: “Low” means lower bound of estimated benefits, and “High” means upper bound of estimated benefits. In the worst-case scenario, discount rate is 7.0%; costs are the maximum estimated; benefits are the lower-bound estimated. For the best-case scenario, discount rate is 2.4%; costs are the minimum estimated; and benefits are the upper-bound estimated.

4.4. Data analysis

Wilcoxon W test for 2 independent samples at significant level 0.05 is performed, using statistical software SPSS version 16, to see if there is any difference between the score means of perceived benefits between the Vietnamese and EEA companies’ groups.

Microsoft Excel 2007 is used to calculate mean of scores, present values of costs and benefits, NPV, to do the sensitivity analysis; and to build the graphs.

5. Results and Discussions

5.1. Qualitatively Perceived Benefits of Traceability

The results from the survey on qualitatively perceived benefits of traceability are illustrated in Figure 1. The mean scores across the companies of the same region are given for 11 Vietnamese (VN) and 12 EEA firms, while single values of scores are shown for the Chilean company. The average score (grand mean) across 24 companies is also shown.

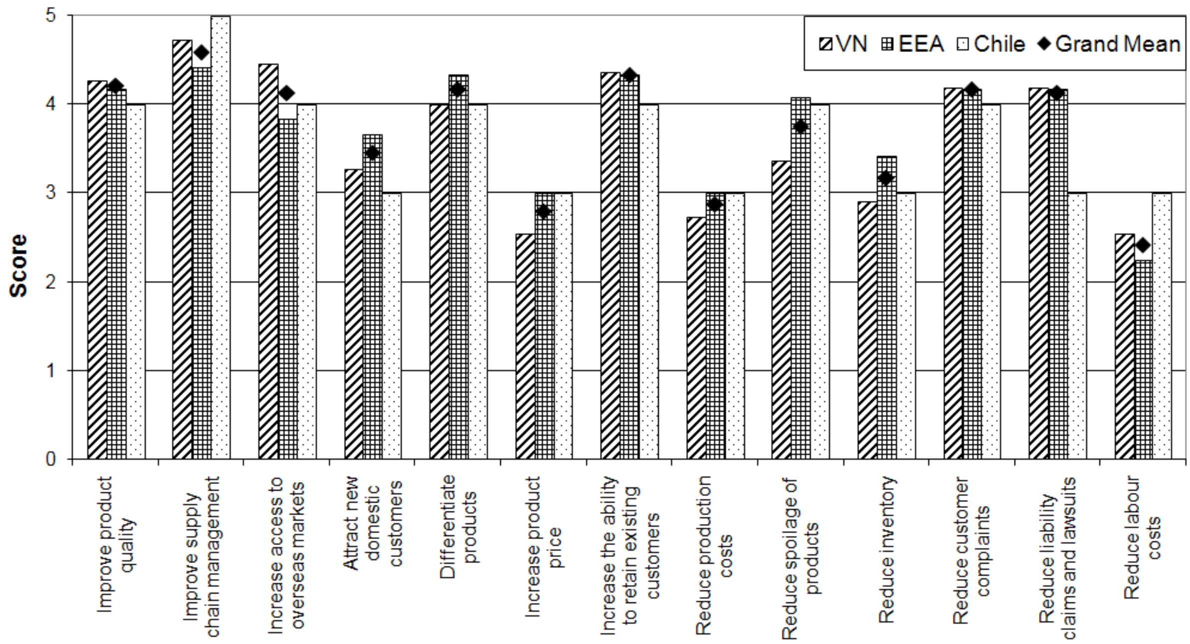

Figure 1. Qualitatively perceived benefits of traceability. Score 1 means “very unlikely”; 2 = “somewhat unlikely”; 3 = “Neither unlikely nor likely”; 4 = “somewhat likely”; 5 = “very likely”

It can be seen from Figure 1 that the companies consider improving supply chain management as the most important benefit of traceability. Other perceived benefits are increase of the ability to retain existing customers; product quality improvement; product differentiation; and reduction of customer complaints. Overall, the Vietnamese and EEA companies have perceived that traceability can reduce liability claims and lawsuits, while the Chilean firm has not had the same perception. The EEA companies’ group and the Chilean firm also see traceability benefits in the reduction of product spoilage. These benefits have also been considered and/or reported in other food sectors, e.g. improvement of supply management (Golan *et al.*, 2004); increase of product quality (Poghosyan *et al.*, 2004; Chryssochoidis *et al.*, 2009); retaining of existing beef markets in those countries which require traceability

(Souza-Monteiro and Caswell, 2004); product differentiation in the fresh fruit and vegetable industry (Golan *et al.*, 2004) and the dairy-processing sector (Sparling *et al.*, 2006).

Surprisingly, other literature-based benefits of traceability, such as reduction of inventory costs (Can-Trace, 2004), reduction of production costs, increase of product price (e.g. positive consumer willingness-to-pay (Hobbs, 2003; Hobbs *et al.*, 2005), and saving of labour costs (Chryssochoidis *et al.*, 2009), are considered of minor importance by the companies-respondents. No significant difference of perceived benefits was found between the Vietnamese and EEA companies' groups.

5.2. Quantitatively Perceived Benefits of Traceability

Survey results from the 24 seafood companies show that they are currently practicing paper-based traceability with or without typed-in (electronically stored) data. Many of them (14 out of 24 cases) also use bar code. Interestingly, 75% of the companies (18 cases) have expressed their willingness to change to a more advanced traceability system.

Quantitative benefits of adopting new traceability solution(s) (e.g. RFID, coupled Rf-TTI, etc.) were obtained from the interviews with eight seafood companies. A summary of perceived benefits is shown in Table 2. Regarding the market benefits' category, the companies have expressed that they cannot "sell traceability" twice (i.e. not both with current and new traceability), therefore they do not expect to gain higher price just with simple marketing as "traceable products". Sparling *et al.* (2006) also found that the dairy processing companies perceived obtaining higher prices as an unimportant benefit from traceability. However, most of the seafood companies in our study have expected to be able to get their markets to grow with new traceability solutions. It may be because new solutions can bring opportunities to market those credence values such as organic(s), sustainability, reduced food miles, etc. (TESCO, 2007; TESCO, 2008).

Regarding the benefits from recall reduction, the companies have expected to reduce the recall frequency as well as recall scope which result in the savings of the new system compared to the current one. This is in a good accordance with the recall model described by Resende-Filho and Buhr (2007), where the recall costs are proportional to the quantity of products recalled. This is also in line with the finding of Sparling *et al.* (2006) that factor related to these product problems are considered between important and very important level (i.e. qualitatively scored above 4).

Table 2. Expected benefits of implementing new traceability solution(s), companies' perspectives

Benefit category	*Benefits expected by the companies* (number of companies shown in parentheses)		
	Processors (2)	*Trader* (1)	*Wholesalers* (5)
1.Market growth (% increase of the current turnover)	From 0 to ≤ 10	≤ 10	From ≤ 10 to >20
*2a.Recall reducing (number of case per year)**	From 0.1-0.25* with current system to 0-0.1* with new system	0	From 0-0.25* with current system to 0 with new system
2b.Reducing the impact of recall (% of the yearly turnover)	From ≤ 2.5% with current system to 0% with new system	From ≤ 5% with current system to ≤ 2.5% with new system	From 0-2.5% with current system to 0% with new system
3a.Reducing impact of claims (% of the yearly turnover)	0	0	From 0-5% with current system to 0% with new system
3b.Reducing impact of lawsuits (% of the yearly turnover)	0	0	From 0-1% with current system to 0% with new system
4.Savings from labour costs (% of the yearly turnover)	From ≤ 2 to ≤ 5	≤ 15	From ≤ 10 to > 20
5a.Reduction of Inventory (% of the yearly turnover)	0-0.2	0	From > 5 to > 10
5b.Spoilage Reduction (% of the yearly turnover)	0-10	0	From > 5 to > 10
5c.Process Improvements (% of the yearly turnover)	0.3-10	0	From > 5 to > 20
*5d.Quality improvement** (% of the yearly turnover)*	0-10	0	0
5e.Others	10,000 €/year; 10% of the yearly turnover	0	0

* 0.1 means "very unlikely"; 0.25 = "unlikely".
** Fish with a higher quality reflects on a higher price of the product (comment from one interviewee).

The companies perceive the savings from reduction of liability claims and lawsuits very differently. Those who have not expected any liability savings explained that it is because they have never experienced that kind of problem with their current traceability system. Others are more conservative in the issue, although they have not got any liability claims or lawsuits recently; they still expect the new solutions can save them if any problems arise. For example, time-temperature records from using RFID tags coupled with temperature sensor can be used as evidence about the compliance or incompliance of product handling conditions.

RFID-based traceability systems are considered as fast systems compared to the paper-based ones. Therefore, all the companies expect to gain from labour savings. It has been shown that an electronic-based traceability system can avoid doubled time for both paper and electronic data recording procedures (Chryssochoidis *et al.*, 2009).

Regarding the benefits from the process improvements, it is expected to save from inventory tied-up and operation costs, from product spoilage reduction, from yield improvement, and from quality improvement. The results are in good agreement with the findings of Chryssochoidis *et al.* (2009) and Kim and Sohn (2009) that electronic-based traceability solution can improve inventory in terms of reducing misplacements and mistaken shipments; reduce the loss rate of products; reduce misrecognition; improving tracking of product movement; and increasing visibility of assets. Chryssochoidis *et al.* (2009) also noticed the revenues from the product quality improvement. Some interviewees in our study also expect to save costs of routine analytical (e.g. microbiological) tests if they couple their traceability system with fast testing methods such as q-PCR (quantitative polymerase chain reaction).

It is worth noting from Table 2 that companies operating at different steps of the supply chains perceive potential benefits of new traceability solution(s) differently. For example, the trading company and the wholesalers expect to save more on labour costs compared to the processing firms. The trading company does not expect to have any benefits from the process improvements (such as reduction of inventory, spoilage reduction, and yield improvement) because it does neither produce nor store the products itself.

5.3 Cost-Benefits Analysis of Implementing New Traceability Solutions – Case Studies

The costs of traceability systems can be divided into start-up phase (initial investment) costs and operational phase (on-going) costs (Chryssochoidis *et al.*, 2009). In general, RFID-based traceability system costs can be listed by spending categories, namely, RFID tags, data accumulator (laptop/desktop), software, RFID readers (including antennas), training and change management, outside consultants, tag loss replacement, implementation service costs (internet, power), labours and administration costs (Can-Trace, 2007; Montanari, 2008; Chryssochoidis *et al.*, 2009).

The costs of the new traceability solutions obtained from the technology developers in the current study are presented in Table 3. The cost components for the processing company case are items numbered 1-2 and 5-14, while for the trading case are numbers 3-14. It is assumed that computer is used 50% for traceability purpose and the rest 50% for others. Therefore, when calculating the costs of computer, just half of the price is used. The same assumption is applied for internet connecting devices and office software. It is also assumed that the outside consultant cost is evenly distributed over the 5 years of the system lifetime.

Table 3. Costs of implementing new traceability solution(s)

No.	*Item*	*Costs per unit (€)*			*Lifetime (Years)*	*Quantity (units)*
		Average	*Min*	*Max*		
1.	Passive RFID tags Rf-TTI	0.40	0.10	3.00	One- time	
2.	RFID readers for passive tags Rf-TTI	3,000.00	200.00	5,000.00	7	15
3.	Active RFID tags	20.00	10.00	70.00	5	
4.	RFID Readers active Portal	1,500.00	700.00	4,000.00	7	15
5.	Computer (laptop/desktop)	1,000.00	700.00	1,500.00	3	50%
6.	Internet connecting devices	30.00	20.00	100.00		50%
7.	Software (MS. Office, SQL server,…)	1,000.00	400.00	10,000.00		50%
8.	Software RFID	10,000.00	2,000.00	40,000.00		
9.	Training & Change Management	5,000.00	1,000.00	20,000.00; 10,000.00*		
10.	Policy Development, Compliance and Audit	0.00	0.00	0.00		
11.	Labour	0.00	0.00	0.00		
12.	Outside Consultants per hour	100.00	N/A**	N/A**		60
13.	Implementation services per year (Internet; power)	300.00	250.00	2,000.00		
14.	Tag loss replacement (only for active tags) (% of the tag quantity)	3.0%	2.0%	10.0%		

* The maximum costs for item No.9 are €20,000.00 in the processing company case; and €10,000.00 in the trading company case.
** N/A means that input data are not available.

It can be noticed from Table 3 that the computer costs will occur at the start-up phase as well as after three years of the system operation; the same occurrence points are applied for the costs of internet connecting devices and office software. The costs for passive RFID tags Rf-TTI occur assumingly at the beginning of each year, as they are non-reusable. It is reported by the technology developers that the price of active tags strongly depends on the volume purchased; buying 100 units at a time can save 20%. Active tag costs, therefore, are reduced by 20% in the base-case and the best-case scenarios' calculation, assuming that the processing company purchases more than 100 tags each time. No extra labour is reported with the new RFID-based traceability solutions compared to the current paper-based ones, even labour cost savings are expected (see Table 4). This is in good agreement with the results of Chryssochoidis *et al.* (2009) that electronic-based traceability solutions can save labour from double data recording processes. Generally, Table 3 shows that there is a large variability in the range of the items' costs, contributing to the wide range of overall costs of adopting new traceability solutions between worst, based-case, and best scenarios (see Table 4).

Regarding the benefits of the new systems, the seafood processing company expects that they can benefit 0-2.5% of the annual turnover from recall reduction; 1-2% from labour cost savings, and 0-0.5% from process improvements. The trading firm expects to gain 5-10%

yearly turnover from market growth and 10-15% from labour cost savings. The minimum values of those ranges are regarded as lower-bound estimated, and their maximum values are as upper-bound estimated for further calculations.

Present values of costs and benefits of 5-year lifetime of the traceability systems were calculated and presented in Tables 4 and 5, respectively. The three scenarios included the effects of uncertainty related to the discount rate (2.4, 4.5%, and 7.0%), estimated costs (average, min, and max), and future benefits (lower bound and upper bound).

Table 4. Present values of costs of implementing new traceability solution (€ thousand)

Costs components	*Processing company case*			*Trading company case*		
	Worst	*Best*	*Base*	*Worst*	*Best*	*Base*
RFID tags(1)	6,885.3	203.7	776.2	2,333.4	333.3	666.7
RFID readers(2)	75.0	3.0	45.0	60.0	10.5	22.5
Computer (laptop/desktop)	1.4	0.7	0.9	1.4	0.7	0.9
Internet connecting devices	0.1	0.0	0.0	0.1	0.0	0.0
Software (MS. Office)	9.1	0.4	0.9	9.1	0.4	0.9
Software RFID	40.0	2.0	10.0	40.0	2.0	10.0
Training & Change Management	20.0	1.0	5.0	10.0	1.0	5.0
Policy development, Compliance and Audit	0.0	0.0	0.0	0.0	0.0	0.0
Labour	0.0	0.0	0.0	0.0	0.0	0.0
Outside consultants	5.1	5.7	5.4	5.1	5.7	5.4
Implementation services (internet; power)	10.2	1.4	1.6	10.2	1.4	1.6
Tag loss replacement	0.0	0.0	0.0	956.7	31.1	87.8
Total costs	*7,046.1*	*217.9*	*845.1*	*3,425.9*	*386.1*	*800.9*

(1) RFID tags are passive Rf-TTI for the processing company case; and RFID tags active for the trading company case.
(2) RFID readers are readers for passive tags Rf-TTI in the processing company case; and RFID readers active portal in the trading company case.

Table 4 shows that the present values (PVs) of costs for outside consultants were found the highest for the best-case scenarios and the lowest for the worst cases. It is because the same hourly consultant costs (€100) were assumed for all the scenarios due to unavailability of the input data (see Table 3) while discount rate of 2.4%, 4.5%, and 7.0% were used for the best, base-case, and worst scenarios, respectively. However, these PVs do not affect much the total costs' PVs which are mainly influenced by the costs of RFID tags. Furthermore, the cost of external consultant accounts only for a small proportion (0.1-2.6%) of the total costs; this is in a good accordance with the study of Sparling *et al*. (Sparling *et al.*, 2006) where outside consultant cost is considered unimportant.

Overall, Table 4 indicates that the main expense goes for the investment of RFID tags, accounting for 91.8-97.7% of the total cost in the seafood processing company case, and 94.2-96.0% (including tag loss replacement) in the seafood trading company case.

From Table 5, it can be seen that in the seafood processing company case, the NPV of the lower-bound base-case scenario, where the benefits of recall reduction have not been perceived, is negative. Contrastingly, when the recall is expected to be reduced from 0.25 ("unlikely") level with the current traceability to 0.1 ("very unlikely") with the new system, the NPV becomes positive. The NPV in the trading company case is always positive; and the benefits by far outweigh the costs (16-252 times).

Table 5. Present values of benefits and net benefits of implementing new traceability solution(s) (€ thousand)

Benefit components	*Processing company case*				*Trading company case*			
	Worst	*Best*	*Base*		*Worst*	*Best*	*Base*	
			Low	*High*			*Low*	*High*
Market growth benefits[(1)]	0.0	0.0	0.0	0.0	18,691.6	39,062.5	19,138.8	38,277.5
Recall reduction[(2)]	0.0	1,164.8	0.0	1,097.5	0.0	0.0	0.0	0.0
Savings from clams & lawsuits	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Labor cost savings[(1)]	93.5	195.3	95.7	191.4	37,383.2	58,593.8	38,277.5	57,416.3
Savings from process improvement[(1)]	0.0	48.8	0.0	47.8	0.0	0.0	0.0	0.0
Total benefits	*93.5*	*1,408.9*	*95.7*	*1,336.7*	*56,074.8*	*97,656.3*	*57,416.3*	*95,693.8*
NPV	*-6,952.6*	*1,191.1*	*-749.4*	*491.7*	*52,648.8*	*97,270.2*	*56,615.4*	*94,892.9*

(1) Assume that benefits occur once at the end of the first year.
(2) Assuming yearly benefits, from the end of the first year.

To test the uncertainty of the discount rate, a sensitivity analysis of the rate range 2.4-7.0% was performed for the base-case scenario of the processing company. For the lower bound, the NPV is negative (minus €786,591) even at the discount rate of 2.4%. The result for the upper bound is shown in Figure 2. It can be seen that this upper-bound base-case scenario has passed the discount rate test as the NPV is always positive.

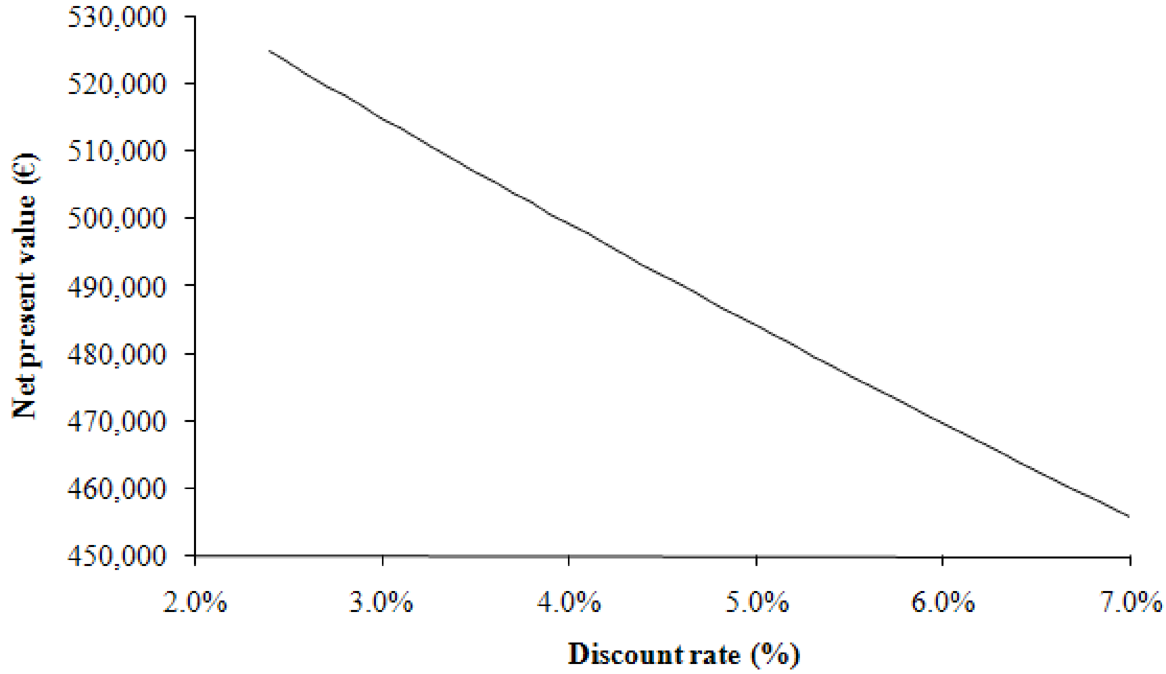

Figure 2. Sensitivity analysis of the upper bound base-case scenario in the seafood processing company case

It is unnecessary to do the sensitivity analysis on the discount rate for the trading company case because its worst-scenario NPV is already positive. Overall, it can be recommended that the trading company should implement RFID tags on pallets for traceability purpose.

Although not all the scenarios of the seafood processing company case appear to be beneficial in monetary terms, it is worth noting that the new traceability solution in this case is aimed at a more detailed level (i.e. master boxes) than in the trading company case (i.e. pallets).

6. Conclusions and avenues of future research

This paper illustrates the qualitatively perceived benefits of traceability from the companies' perspectives. Improvement of supply chain management is expected as the most important benefit of traceability. Other benefits are increase of the ability to retain existing customers; product quality improvement; product differentiation; and reduction of customer complaints. The findings offer practical evidence in support of the traceability drivers mentioned in previous studies, such as in Smyth and Phillips, 2002; Buhr, 2003; Karkkainen, 2003; Golan *et al.*, 2004; Poghosyan *et al.*, 2004; Sparling *et al.*, 2006; Can-trace, 2007; Pouliot and Sumner, 2008; Chryssochoidis *et al.*, 2009; Wang *et al.*, 2009a; etc. However, due to a small sample size of the study (24 companies), the results cannot be generalised. Further research with larger number of samples is desirable.

The paper also describes the quantitatively estimated benefits of adopting new traceability solution(s) in response to the willingness of the industry to change for a more advanced traceability system. The companies at different steps of the fish supply chains have perceived benefits differently. Overall, benefits are expected to come from market growth; recall reduction; liability claim and lawsuits reduction; labour savings; and process improvements. The findings support the benefit templates developed by Can-trace (2004) and Chryssochoidis *et al.* (2009).

The *ex ante* CBA for the seafood processing case shows that implementing Rf-TTI tags on master boxes can bring monetary benefits if there are recall reductions and labour cost savings. The NPV is negative when the savings from recall reduction are not perceived. The CBA for the seafood trading company case proves tangibly quantifiable benefits of applying active RFID tags on pallets. Once again, the findings provide additional empirical support of traceability benefits from implementing RFID-based traceability solutions, which have been stated elsewhere (Karkkainen, 2003; Vasvik, 2006; Chryssochoidis *et al.*, 2009).

However, the CBA case studies are just *ex ante* analyses with estimated costs and expected benefits from the companies' perspectives, therefore the results are limited to the specified cases and conditions. Extended *ex ante* and/or more extensive *ex poste* CBA may need to be conducted to re-evaluate the net benefits (Boardman *et al.*, 2006) of implementing new traceability solution(s).

Because the two case studies are not of the same supply chain and aimed at different traceability solutions (rf-TTI versus active RFID tags) and precisions (boxes versus pallets), the CBA results are not comparable. However, they have strengthened the argument on costs shifting among the stakeholders in a supply chain. It was shown that the seafood processing company pays much for what is needed, resulting in some negative NPVs, while the trading company can expect steady benefits. In order to implement new traceability solution(s), e.g. RFID-based, at the supply chain level, it is suggested that the price of intermediate products would go up, which is a way that trading companies could entice or persuade food producers to put new traceability system(s) in place. The findings support the need for an open discussion between different actors in a food supply chain on the distribution/redistribution of costs and benefits of implementing traceability (Can-Trace, 2004).

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Appendices

(A) Questionnaire regarding the qualitatively perceived benefits

(Adopted and modified from a questionnaire of Dr. Weisong Mu from the China Agricultural University)

1. Please give the scores for the potential benefits of implementing traceability system/solution at your company.

	Very unlikely 1	Somewhat unlikely 2	Neither unlikely nor likely 3	Somewhat likely 4	Very likely 5
Improve product quality					
Improve supply chain management					
Increase access to overseas markets					
Attract new domestic customers					
Differentiate your products from others					
Increase product price					
Increase the ability to retain existing customers					
Reduce production costs					
Reduce spoilage of products					
Reduce inventory					
Reduce customer complaints					
Reduce liability claims and lawsuits					
Reduce labour costs					

2. Please rate also other benefits and specify (if any). *Please choose option N/A if you think there is no other benefit from those listed in the question 1 above.*

N/A	Very unlikely 1	Somewhat unlikely 2	Neither unlikely nor likely 3	Somewhat likely 4	Very likely 5

Other benefits (**Please specify**)

3. Please give the scores for the facing difficulties in implementing traceability system/solution at your company.

	Very unlikely 1	Somewhat unlikely 2	Neither unlikely nor likely 3	Somewhat likely 4	Very likely 5
Lack of technical staff					
High costs of application of the traceability system					
Less flexibility to introduce new products					
Uncertainty about the future benefits					
No unified standards in the markets					
Lack of support from government					
Lack of managerial staff					
Less flexibility of					

	Very unlikely 1	Somewhat unlikely 2	Neither unlikely nor likely 3	Somewhat likely 4	Very likely 5
production process					
Less staff time availability for other tasks					

4. Please rate also other difficulties and specify (if any). *Please choose option N/A if you think there is no other difficulty from those listed in the question 3 above.*

N/A	Very unlikely 1	Somewhat unlikely 2	Neither unlikely nor likely 3	Somewhat likely 4	Very likely 5

Other difficulties (please specify)

5. Please specify your current traceability status. *More than one answer is possible.*

☐ No traceability
☐ Paper based
☐ Typed-in data
☐ Use bar code
☐ E-exchange

6. Are there any changes you would like to make to the existing traceability system/solution?

☐ Yes ☐ No

7. Would you like to change your current traceability status to a more advanced system/solution in the near future?

☐ Yes ☐ No

8. In which step of the supply chain does your company work? *More than one answer is possible.*

☐ Raw material supply
☐ Processing
☐ Transportation
☐ Distribution
☐ Import
☐ Export

9. Please provide an approximation of your company yearly turnover.

☐ Below 10,000,000 €
☐ 10,000,000 - 100,000,000 €
☐ 100,000,000 - 200,000,000 €
☐ 200,000,000 - 400,000,000 €
☐ Above 400,000,000 €

10. How many employees are there in your company? ....

11. Please provide an approximation of your total production (tons/year). *This is an optional question/answer; you do not need to answer it if you are not willing to.*

(B) Questionnaire for company interviews

Name of your company: ....

We would like to know about the positive impacts of traceability on your business. Please take some times to go through 7 sections with 21 questions in total.

A. GENERAL INFORMATION: Questions 1-3

1. ***Please specify your current traceability status by crossing the most appropriate answer(s)?***

a.	No traceability	
b.	Paper based	x
c.	Typed-in data	
d.	Use bar code	
e.	E-exchange	

2. ***How would you like to change your traceability status in the near future?*** *Cross the most appropriate answer(s)*

a.	No change	
b.	Use bar code	X
c.	Use RFID*	
d.	Use Rf-TTI**	x
e.	Other (please specify)	

* RFID is the abbreviation of Radio Frequency Identification
** Rf-TTI is coupled Time Temperature Indicators (TTI) and Radio Frequency technology

3. ***How would you like to use RFID or Rf-TTI?*** *Please cross the most likely option and give additional information on the right columns of this row when needed.*

	Use of RFID or Rf-TTI	Cross (x)	Number of tags/unit	Number of packs per box			Number of boxes per pallet		
				Min	Max	Average	Min	Max	Average
a.	For retail packs		1						
b.	For boxes	X	1	-	-	-	35	108	-
c.	For pallets			-	-	-	-	-	-
d.	For containers			-	-	-	-	-	-

- Please specify the ***size of retail packs*** *(grams)*:

Min: 100……………........; Max: 1500………………..; Average: ……………………….
(e.g. 35 units of 50 g → 1750 g; 10 units of 100 g → 1000 g)

- Please specify the ***size of boxes*** *(kg)*:

Min: 1……………........; Max: 17.5………….; Average: ……………………….
(e.g. 35 units of 50 g → 1750 g; 10 units of 100 g → 1000 g)

- Additional information (optional): ***Annual trade in volume of product(s) intended for NEW* traceability system/solution*** *(tons/year) (based on your recent trade figures)****:***

Min: ………........; Max: ……………..; Average: 450………………

* NEW traceability system/solution here means the one you would like to use in the future instead of your current traceability system/solution.

4. ***How would you like to use traceability to market your products?*** *Cross appropriate option(s)*

Nothing	
Products with "visible traceability" (provided a code that customers can use to consult the full traceability, e.g. via interenet)	**X**
Sustainable products	**X**
Products from specified origin	**X**
Organic products	
Reducing carbon footprint products	**X**
Others	

B. MARKET BENEFITS: Questions 5-7

5. ***Please answer question (5a) if your company has already been using traceability for more than five years before 2005; otherwise please answer question (5b), i.e. if your company just implemented traceability not long/right before or after the 2005 regulation.***

5a. How did the 2005 EU traceability regulation change/affect your traceability system and business?

	Traceability system	Business
No change	x	x
Adjusted to make it compliant with the regulation		-
Better off	-	
Worse off	-	
Other comments		

5b. How have you experienced the benefits of your CURRENT traceability versus NON-traceability from having been able to sell products with higher price? *(% estimated contribution of the TRACEABLE products to your yearly turnover)*

0%	≤2%	≤5%	≤10%	≤15%	≤20%	>20%
☐	☐	☐	☐	☐	☐	☐

6. ***How do you expect NEW traceability system to make your market(s) GROW?*** (% increase of the current turnover). Cross the most likely option.

0%	≤2%	≤5%	≤10%	≤15%	≤20%	>20%
☒	☐	☐	☐	☐	☐	☐

7. ***Do you expect NEW traceability system to DEFEND your CURRENT MARKET share?***

Yes	No	Don't know
☒	☐	☐

C. BENEFITS FROM RECALL REDUCTION: Questions 8-11

8. How many recalls did you experience per year before implementing traceability?

0 (nil)	0.1 (very unlikely)	0.25 (unlikely)	0.5 (even)	0.75 (likely)	0.9 (very likely)	1	2	3	4	≥5
X										

9. How did the recall(s) affect your yearly turnover?

0% (Not significant)	≤2%	≤5%	≤10%	≤15%	≤20%	>20%
☒	☐	☐	☐	☐	☐	☐

10. How many recalls per year do you expect in the future?

	0 (nil)	0.1 (very unlikely)	0.25 (unlikely)	0.5 (even)	0.75 (likely)	0.9 (very likely)	1	2	3	4	≥5
With Current Ability			X								
With NEW Traceability		x									

11. Please provide an estimate of the total financial impact of recall(s) on your FUTURE yearly turnover? (% of yearly turnover) *(It may include: Lost/recalled material costs; Lost time - employee time, plant time, production time, etc.; Customer reaction/lost sales margin; Additional marketing/public relations expense; Charge backs per recall; ...)*

	0 (not significant)	≤2.5%	≤5%	≤7.5%	≤10%	>10%
With Current Ability		X				
With NEW Traceability	X					

D. SAVINGS FROM LIABILITY CLAMS OR LAWSUITS: Questions 12-16

12. How often have you experienced liability claims or lawsuits in the last three years?

Regular clam

	None	1	2	3	≥4
Clams	X				
Lawsuits	X				

13. How do CLAM(s) affect your yearly turnover? *(% of yearly turnover)*

	None	1	2	≤5	≤10	>10
Before implementing traceability	X					
With Current Ability	X					
With NEW Traceability (expected)	X					

14. How do LAWSUIT(s) affect your yearly turnover? *(% of yearly turnover)*

	None	1	2	≤5	≤10	≤20	>20
Before implementing traceability	X						
With Current Ability	X						
With NEW Traceability (expected)	X						

15. ***How much do you CURRENTLY pay for liability insurance per year?*** *(% of yearly turnover)*

Insurance for food safety	0.003%
Insurance for food damage during shipping	Not applicable

16. What do you expect to pay for liability insurance per year in the FUTURE? *(% of yearly turnover)*

	Insurance for food safety	Insurance for food damage during shipping
With Current Ability	Same	
With NEW Traceability	Same	

E. SAVINGS FROM LABOR COSTS: Questions 17

17. Please estimate the average expected benefits from labor cost savings of NEW traceability system compared to the current one *(% of yearly turnover)*

0% (Not significant)	≤2%	≤5%	≤10%	≤15%	≤20%	>20%
☐	☒	☐	☐	☐	☐	☐

F. BENEFITS FROM PROCESS IMPROVEMENTS: Questions 18

18. ***Please estimate the average expected benefits of traceability from process improvements*** *(% of yearly turnover)*

		With Current Ability	With NEW traceability	Comment
a	**Reduction of Inventory**	0%	0.2%	
b	**Spoilage Reduction**	0%	0%	
c	**Process Improvements (**Yield Improvement)	0%	0.3%	
d	**Quality Improvements**			
	One-Time Benefit with Traceability			
	Annual Benefit with Traceability			Difficult/subjective
e	**Other Benefits**			
	One-Time Benefit with Traceability			
	Annual Benefit with Traceability			

G. BUSINESS SIZE: Questions 19-21

19. Please provide an approximation of your market share in the main market(s)

	Domestic	EU	US	Japan	Others
0%					
< 2%		x			
2-5%					
5-10%					
> 10%					

20. Please provide an approximation of your company yearly turnover

≤ 10,000,000 €	
≤ 100,000,000 €	
≤ 200,000,000 €	
≤ 400,000,000 €	
> 400,000,000 €	

or specify your yearly turnover	10,000,000€

21. ***How many employees are there in your company?*** 50...

OTHER COMMENTS:
....
....
....
....

THANK YOU VERY MUCH FOR YOUR CONTRIBUTION!

C. Questionnaire to technology developing partners

Your Name (optional): *Name of your organization*:

We would like to know about the costs of traceability system(s) using the technology such as RFID or smart labels. Please take some time to fill in the information needed. Please put before-tax costs, indicating the currency of your system (e.g. in US$ or €) and keep it consistently throughout the survey

Cost Category (*Note: below are just suggested categories, please change as needed to more suitable ones*)		**Life cycle (years)**	**Initial cost per unit (€)**			**Annual cost per unit (€)**		
			Min	**Max**	**Average**	**Min**	**Max**	**Average**
1.	Paper system							
2.	RFID tags passive HF							
3.	RFID tags passive UHF							
4.	RFID tags active							
5.	RFID tags passive + temperature sensor							
6.	RFID readers HF Portal							
7.	RFID readers HF PDA							
8.	RFID readers active Portal							
9.	Computers							
10.	Internet connecting devices							
11.	Software (MS. Office, SQL server,…)							
12.	Software RFID							
13.	Changes to current processes							
14.	Training & Change Management							
15.	Outside Consultants							
16.	Policy Development, Compliance and Audit							
17.	Labour for RFID reading HF							
18.	Labour for RFID reading UHF							
19.	Implementation Services (Internet; power)							
20.	Tag loss replacement (%) RFID Labels UHF							

PAPER II

Evaluation of a seafood firm traceability system based on process mapping information - More efficient use of recorded data

II

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Evaluation of a seafood firm traceability system based on process mapping information: More efficient use of recorded data

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Abstract

The purpose of this work was to develop a conceptual framework that can be used to evaluate the effectiveness of traceability systems at food producers based on information from process mapping. The framework was based on a broad literature review from the food processing industry. The proposed framework was then applied to evaluate the traceability system at a Vietnamese fresh farmed *Pangasius* catfish producer and validated by evaluating the ability to track and trace through the company. In addition, the studied traceability system was analyzed on its compliance with regulation on traceability of importing countries such as EU regulation No. 178/2002, as well as with the TraceFish standard. The paper also aimed to propose how to use recorded data more efficiently to improve quality management and supply chain management. The results show that the framework works well in the specified case, but further investigation for other cases is desirable. The company traceability system meets with EU regulation No. 178/2002, but not with the TraceFish standard as global trade item numbers (GTIN) are not used for dispatched products. It is suggested that the company also stores recorded data in electronic form in parallel with paper form to facilitate data access. It is proposed that the temperature data during storage and transportation are used to estimate the warm up time and the remaining shelf life (RSL) of the products.

Key words: Traceability, effectiveness, fresh fish supply chain, process mapping, traceable resource unit, batch, identification, transformation, *Pangasius*, warm up time, shelf life.

Introduction

Traceability is defined as "the ability to trace the history, application or location of that which is under consideration" (ISO 9000:2000 [1] - Part 3.4.2); or ''the ability to trace and follow a 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 regulation No. 178/2002 [2], Article 3).

EU regulation No. 178/2002 [2] of the European Parliament and Council on food safety stipulates one step up - one step down traceability for each food/feed business operator. This implies the responsibility of every entity in the production chain for ensuring traceability.

There are two types of product traceability which are tracing and tracking [3]. Tracing (backward or upstream) is the ability to find the product origin from given criteria, through records, upstream in the supply chain; used to find the source of a problem or give other origin dependent information [3-7]. Tracking (forward or downstream) is the ability, at every point of the chain, to find the product location from given criteria; used in case of product recall and to find the cause of the problem [3, 4, 6, 7].

Kim *et al.* [8] have proposed the concept of traceable resource unit (TRU) as a homogeneous collection of one resource class that is used/produced/released by a primitive activity (basic operation) in a finite, non-zero quantity of that resource class. The TRU is a unique unit and no other unit can have the same (or comparable) characteristic from the traceability point of view.

Kelepouris *et al.* [9] have, however, used the "TRU" term for only those traceable entities traded between supply chain partners; otherwise the term "batch" is used to refer to traceable entities in internal traceability system of a partner. Information about batches is not exposed to the whole supply chain, but made available upon request.

In a recommended guide to good traceability practices (GTP) in the food industry [10], it is stated that traceable units can be trade units (TUs); logistic units (LUs); or production batches (raw materials' or ingredients' batches; and product batches). The production batches are considered an internal matter and do not need to have globally unique identifiers; while TUs and LUs are recommended to be assigned GS1 (Global Solution) numbers [11]. Information related to history (e.g. temperature records, information related to production process), application (e.g. information related to property: weight, species, fat content, etc.) and location (e.g. distribution route) should be recorded and linked to a traceable unit. From the chain traceability perspective, it is required to record identifications (IDs) of supplier and transporter of received TUs (raw materials and/or ingredients) and ID's of buyer and transporter of dispatched TUs.

Transformations, such as mixing (adding, joining), splitting, and transfer, are considered as the most critical points in traceability [12]. Addition of resources is the mixing of a main resource with other resources in lesser quantities, i.e. many to one relationship between the resources. Joining of resources is the gathering together of different units of a main resource, that is also many to one resources' relationship. Splitting of resources is the splitting up of a resource into multiple units, forming one to many resources' relationship. Transfer of a resource is the transferring to another step without any splitting or mixing of that resource, giving one to one relationship of the resources. Donnelly *et al.* [12] have pointed out that resources' transformations can happen both within and between food business operators and thus are of importance to both internal and chain traceability.

Similarly, Dupuy *et al.* [3] have defined the concept of downward dispersion (as splitting); upward dispersion (as joining and/or adding); and batch dispersion (as sum of the two first types) and have regarded minimization of batch dispersion as a tool to optimize traceability. It is worth noting that internal traceability requires all transformations during the production to be recorded[13]. For instance, a complete bill of lots of resources contributing to the composition of a product batch has to be registered [9].

Derrick and Dillon [14] indicate that components such as product IDs; transferring of IDs with the product to the next process step; and record keeping of IDs, product and process data are necessary to ensure traceability at a seafood processing factory.

According to Senneset *et al.* [13], three basic operation types to obtain internal traceability are: recording the unique IDs of TRU (e.g. IDs of resources); assigning unique IDs to new TRU (e.g. IDs for products); and linking a set of input unique IDs to one or more sets of output unique IDs (e.g. recording transformations of raw materials and ingredients to final products). Recording of process and transformation information is considered as routine procedures of an internal traceability system. Thompson *et al.* [15] have also indicated that each seafood processing firm must assign new TRUs during processing and the initial TRU must follow the fish lot through all processing steps.

Similarly, Lindh *et al.* [16] have stated that traceability is based on the control of identity which allows separating a certain quantity (commonly, a batch) of product. Unique batch number must follow the batch throughout the production line and be connected to the identity of the final product.

A traceability system can be evaluated by its effectiveness and efficiency. The system's effectiveness is defined as the ability to collect the necessary information; meanwhile efficiency is regarded as the ability to rapidly recover and reuse the information [17].

There are guidelines on how to establish a traceability system in the fish industry [14, 18, 19]; articles and reports on the analyses of traceability systems in the food industry [12, 20-22], which are done by outside bodies or researchers rather than the industry/company itself and normally by evaluating the ability to trace and track through a company in case of a problem. Derrick and Dillon [14] have developed a decision tree for assessing traceability and identifying necessary modification to ensure traceability based on process step analysis at seafood factories. A framework for a food processing company to validate its own traceability system effectiveness is not fully available. Therefore, this study has aimed to bridge the gap. The purpose of this work was to develop a conceptual framework that could be used to evaluate the effectiveness of traceability systems based on information from process mapping. The framework was based on a broad literature review from the food processing industry. The proposed framework was then applied to evaluate the traceability system at a Vietnamese fresh *Pangasius* fillet producer and validated by evaluating the ability to track and trace through the company in case of problem occurrence [12, 22]. The studied traceability system was also analyzed on its compliance with regulation on traceability of importing countries such as EU regulation No. 178/2002 [2], as well as with TraceFish standard [19].

Compliance and efficiency of quality control and full traceability at plants can only be achieved by fully integrating laboratory data with the movements of materials, production, final products, shipping, and customer information [7]. However, available data on quality, process control and process parameters, which are numerous, are normally not efficiently exploited at the companies. The study, therefore, has also aimed to demonstrate some possible uses of recorded data to improve quality and supply chain management.

Methodology

The conceptual framework was developed based on a broad literature review concerning important components to ensure traceability at a food processing company.

The model was applied to a seafood processing company and validated by evaluating the ability to trace and track through the company in case of problem occurrence [12, 20-22].

To obtain necessary input data for the case study, a process mapping was done in the third week of July 2009 at a *Pangasius* producer in My Tho industrial zone, Vietnam, using a suitable set of structured tables of questionnaires which were described in detail by Olsen and Karlsen [22]. It was to find out the movement of materials and information within and through the studied company; the traceable units; unit identifications (identifiers); transformation points of the processes; the presence or absence of the links/recorded relationships between the identified units; the ability to track and trace through the company. This included a backward factory walk through; in-depth interviews (1-2 hours each) with quality control (QC) manager, production manager, and laboratories' staff; and document analysis on traceability, quality, process control, and other recorded files [12, 22].

During the process mapping, a temperature investigation was also carried out with the final product from the packaging point to the transportation step. The obtained data were used to demonstrate how recorded information could be used more efficiently to improve quality management or/and supply chain management. The measurements were done with 2 boxes with 3 loggers inside (top, middle, and bottom of product) and 1 on the surface of each box. DS1922L temperature loggers iButton® (Maxim Integrated Products, Inc., CA) were used for mapping the temperature, with temperature range -40°C to 85°C; resolution 0.0625°C; accuracy ± 0.5°C and ± 1 min/wk. Recording intervals were set at 5 minutes.

The temperature mapping data were then used for the calculation of warm up time and estimation of the remaining shelf life of product. The product warm up time t (hours), i.e. the time length that caused an increase of average product temperature from an initial value T_{init} (°C) to a maximally allowed final one T_{final} (°C), was estimated using Equation 1 (modified from Margeirsson [23] based on Singh *et al.* [24]):

$$t = m_p C_p \frac{1/h + R_s}{3.6A} \, ln \frac{T_{amb.mean} - T_{init}}{T_{amb.mean} - T_{final}} \quad (1)$$

where A is internal surface area of packaging (m^2), A = 2 x (L x W + L x H + W x H) = 0.2782 m^2 in this study; C_p is specific heat capacity of product (kJ/kg/K), e.g. C_p = 3.85 kJ/kg/K in this study (C_p = 3.683-4.144 for white fish with temperature between 10-0°C [23, 25]); h is global heat convection coefficient outside the box (W/m^2/K), depending on the difference between the ambient temperature and the box surface temperature (the larger temperature difference, the higher value of h), and on the outer dimension of the box, h = 2-10 W/m^2/K [23]; L is inner box length (m), L = 0.38 m in this study; W is inner box width (m), W = 0.25 m in this study; H is inner box height (m), H = 0.07 m in this study; m_p is net weight of product (kg), m_p = 3 kg in this study; R_s is system thermal resistance (m^{2}K/W), accounting for the type, shape and size of insulating material (expanded polystyrene EPS), its wall thickness; gel pack type, shape and size (gel pack latent heat and melting rate); and to some extent the effect of product [24]; $T_{amb.mean}$ is mean ambient temperature (°C); T_{init} is initial product temperature (°C).

The SSSP software version 3.0 (DTU Aqua, Denmark) was used to predict the effect of time-temperature combination on the RSL based on the recorded temperature profile. Recorded temperature data of *Pangasius* fillets from different positions inside boxes were separately fitted into a square-root model for relative rate of spoilage (RRS) of fresh seafood from tropical water. In SSSP, RRS at T°C has been defined as the shelf life at a reference temperature T_{ref}, which has normally been 0°C, divided by the shelf life at T°C [26], where shelf life was determined by sensory evaluation. The SSSP used the concept of accumulative effects of time and temperature. The SSSP was based on growth kinetics of specific spoilage organisms and empirical RRS secondary models [27]. A reference shelf life of 15 days stored at 0.5°C for fresh *Pangasius* fillets in EPS boxes (own study) was used.

Background information of the studied company, product and production process: The studied company is a *Pangasius* processing plant with two workshops. Main products are frozen and fresh fillets of *Pangasius* for export. The capacity is 250 tons of fish raw materials per day. The mapping was done for the fresh fillet product in 3 kg EPS boxes (430 mm x 300 mm x 120 mm) which is exported to EU markets.

Tra catfish (*Pangasius hypophthalmus*) is one of the most popular fish species currently raised in Mekong Delta of Vietnam, South of Vietnam. Its total value of export in 2008 was $ 1.48 billion [28].

Fish has been farmed in ponds and fed with commercial floating pellets. The studied company owns over 250 hectares of ponds located in 5 different provinces of Mekong Delta. Fish is also sourced from outside suppliers.

Live fish is transported from the farm to the processing plant by well boats. *Pangasius* from one farm is normally processed for several days and the fish is transported only on the day of production. Transporters are contractors.

The fish undergoes the following steps: Transporting (≤ 16 hours) → Receiving → Slaughtering → Bleeding (15 minutes) → Filleting → Washing → De-skinning → Trimming (≤ 2 minutes, fillet temperature kept at ≤ 15°C by flake ice) → Washing (water temperature 5-10°C) → Lighting/Parasite checking → Washing (water temperature 5-10°C) → Grading and sizing → Rotating in salt and phosphate solution → Washing (water temperature ≤ 5°C) → Weighing → Packing into PE bags (3 kg of product per bag) → Cooling in alternating layers of flake ice (about 3 hours to product temperature of 2-3°C) → Packing into EPS boxes (3 kg of product, with a gel pack of 500 g on top) → Storage (at -10°C, 0.5-2 days) → Shipping by truck (at temperature -10°C) to Hochiminh City → Holding storage (at -18°C, duration: 0-3 hours) → Transport to Tan Son Nhat Airport (SGN) by truck → Air freighting to Luxembourg (including loading, unloading operation, and possible holding).

The processing time from slaughtering to packing into PE bags is 30-45 minutes at ambient temperature ≤ 18°C. The processing company is responsible for transporting the product to Hochiminh City, and then the customer (distributor) is taking care of the rest.

Results and Discussion

Framework for evaluating the effectiveness of traceability system at the factory: From the literature review in the introduction part it can be seen that the main components to ensure traceability at a food processing firm are: registration of unique IDs for all resources' batches; registration of unique IDs for all newly formed batches; recording of all relevant product and process information and linking to the batches' IDs; and transferring all traceability relevant information of the inputs (e.g. relevant batches IDs and associated information) with the product to the next step (e.g. next production step or next link of the chain). Based on these, a conceptual framework to evaluate the effectiveness of a traceability system has been developed and presented in Table 1. If all the questions turn in answers YES (Y), i.e. all needed information are recorded and provided; all needed identifications are registered; and all relevant relationships are linked together, a conclusion of an effective traceability system can be drawn. If one of the answers returns NO (N), indicating an ineffective traceability system, modification needs to be done until all the answers become YES. The needed modifications/improvements to obtain YES answers in traceability system of a seafood factory are proposed by Derrick and Dillon [14] through investigating each production step. In this study, the required actions to obtain YES answers are presented in the last column of Table 1.

Traceability at the studied company: To apply the proposed framework for evaluating the traceability system effectiveness at the studied company, a process mapping was carried out to gather necessary information. Mapping results are shown in Figs 1-3 and in Table 2.

Fig. 1 shows the material flow and transformations of the resources through the company. It can be seen that a batch of fish raw material is not mixed with other fish batches throughout the processing stages until shipping. The ingredients, e.g. salt and polyphosphate, on the other hand, can sometimes be mixed to form a final product batch. The main transformation types of the resources are transfer, addition, splitting, and possible joining.

As all the transformation information such as original batches' identification number (or batch No., Fig. 2), quantity, and associated attributes such as grade and size are recorded and transferred to the next operation step inside the company and to the next actor of the chain (i.e. importer/distributor), the tracking

Table 1. Framework for evaluating the effectiveness of a food processing company's traceability system and necessary modification to ensure traceability.

Question No.	Category of traceability information	Question	Possible answer and next action	Required action (RA)
Ia	Resource ID registration	Ia. Are all batches of resources (e.g. raw materials and ingredients, etc.) registered with unique IDs?	- YES → Go to Ib - NO → Go to RA-Ia	RA-Ia. Register all batches of resources with unique IDs. Go to Ib.
Ib	Resources' information: associated / relevant resources' information other than IDs	Ib. Is all traceability relevant information of resources' batches (e.g. suppliers' IDs, date of reception, quantity, grade, quality, etc.) provided and/or recorded, kept, and linked to batches' IDs?	- YES → Go to II - NO → Go to RA-Ib	RA-Ib. Develop procedure(s)/method(s) to obtain, keep, and link all traceability relevant information of resources' batches to their IDs. Go back to Ib.
II	Transformation information	II. Are all relevant resource, product, and process information (e.g. bill of lots) recorded and linked to resources' IDs or product IDs?	- YES → Go to III - NO → Go to RA-II	RA-II. Record all relevant resource, product, and process information and link to batches' IDs. Go to III.
III	Product ID registration	III. Are unique IDs assigned to all newly formed batches (e.g. product) and are these records kept?	- YES → Go to IV - NO → Go to RA-III	RA-III. Assign unique IDs to all newly formed batches and keep records. Go to IV.
IV	Transferred information	IV. Is all traceability relevant information of the input(s) (e.g. relevant IDs of the input(s) and associated information) transferred with the output (e.g. product) to the next step (e.g. next production step or next link of the chain)?	- YES → Go to Conclusion - NO → Go to RA-IV	RA-IV. Develop procedure(s)/method(s) to transfer all relevant IDs of input(s) and associated information with the output to the next step. Go back to IV.
Conclusion: Traceability system is effective				

and tracing through the company is enabled. This is supported by a study result of van Dorp [29] that all the mixing and splitting of batches within an organisation can be tracked by using the bill of compositions (bill of lots) which gives the information on the composition of a uniquely identified product out of identified component batches and on all uniquely identified products having consumed an identified component batch. Donnelly *et al.* [12] has also indicated that documentation on the relationship between uniquely identified units enables the tracing of the resources and the final product through a company.

Table 3 shows the results from analyzing the traceability system at the studied company using the above proposed framework (Table 1). It can be seen that all the answers are YES which indicate a sufficient traceability system if all traceability information related to packaging materials, which are not investigated in this study, are well documented. Details on the IDs' configuration, product and process information inputs, and how the associated IDs are linked are shown in Figs 2 and 3. The validation of the framework is discussed in the sections below.

Ability to trace: Assuming a contamination of the product in some invisible way, tracing back from the distributor through the company can be practiced by using the information on the box labels about the *production date* and the *external product batch number* (or Lot No., Fig. 3). The latter is uniquely assigned to each *product batch* which is considered as a certain type of product (e.g. fresh *Pangasius* fillets) produced from the same fish raw material batch in the same production shift, date and workshop (see Fig. 1). Batch number of fish raw material (or *fish batch No.* for short) is uniquely assigned three-digit ordinal number (starting from 001, e.g. 190, Fig. 3) for each production year to the raw material from the same pond received at the processing plant in the same day. The configuration of an *external product batch number* (Lot No.) is as follows: "VN" = product of Vietnam; "aaa" = exported code (three digits) of the workshop or company approved by importing market such as EU code; "IV" = the processing company is under the regional administration of The National Fisheries Quality Assurance and Veterinary Directorate-Branch 4 (NAFIQAVED IV); and three-digit ordinal number (from 001 to 999, e.g. "379") in the production year is uniquely assigned to each product batch entering certain importing market in that year.

The company is then able to trace the origin of their products up to aquaculture pond level using an internal code system (Fig. 3). Each product batch is uniquely assigned an *internal product batch number* which is a combination of a letter and seven digits, e.g. A 2 201 261. The letter indicates the processing workshop of the company (A = workshop number I; B = workshop number II); the first digit represent the shift of the production day (1 or 2); the next three digits are production date by Julian Date Coding of the year (for instance, 201 = 20th July 2009); and the last three numbers are the farming pond code uniquely given by the company. There is no mixing of fish raw material from different ponds (Fig. 1) and fish batch code follows the product throughout the production line (Fig. 2); therefore loss of information can be avoided. It is in agreement with the data model for traceability of Kelepouris *et al.*[9] that the "batch" (*internal product batch number*) is used internally and information about the batches not exposed to the

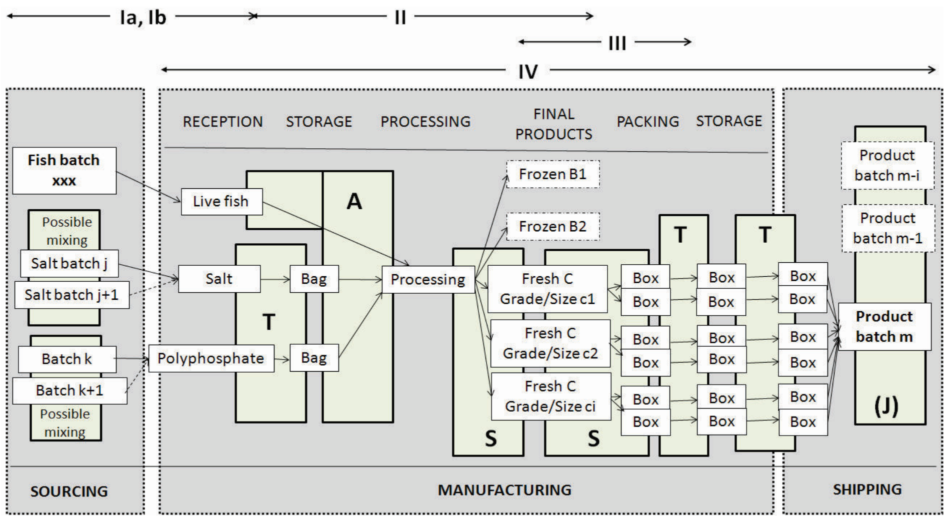

Figure 1. Material flow and transformations of resources at the studied *Pangasisus* fillet producer with focus on the processing of fresh fillets. The solid one-way arrows represent common material flow; the dash arrows represent uncommon, but possible material flow. The greyish boxes illustrate the transformation types: A = Addition; J = Joining; S = Splitting; and T = Transfer. Dash white boxes represent product batches processed from other fish raw material batches than batch xxx. The two-way arrows with Roman numbers show the mapped areas with respective assessed questions for evaluating the effectiveness of the traceability system.

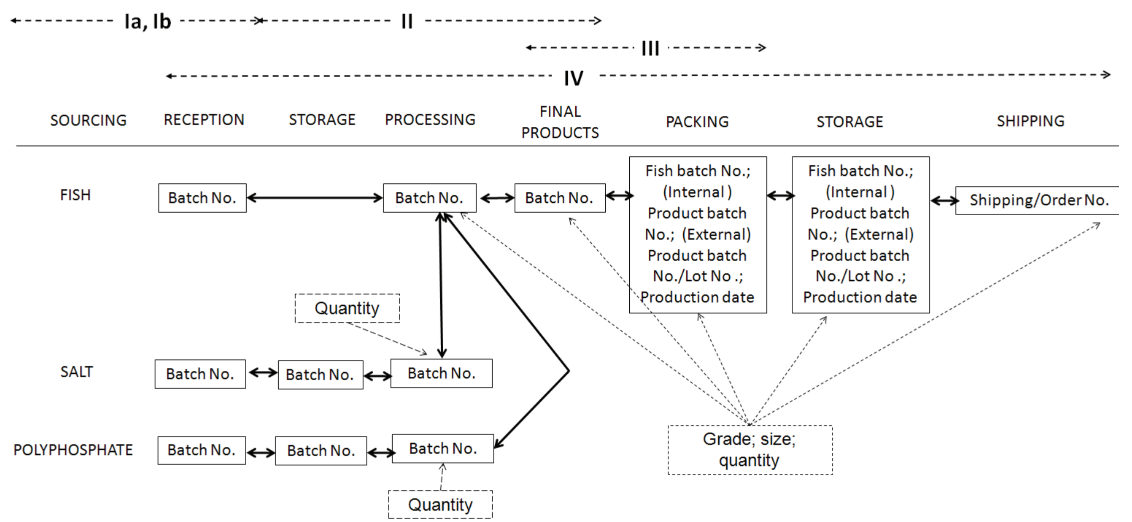

Figure 2. Traceability information flow at the processing plant. Frame boxes = IDs of the units; Two-way arrows = links between the units; Dash box = associated information. The dash two-way arrows with Roman numbers show the mapped areas with respective assessed questions for evaluating the effectiveness of the traceability system.

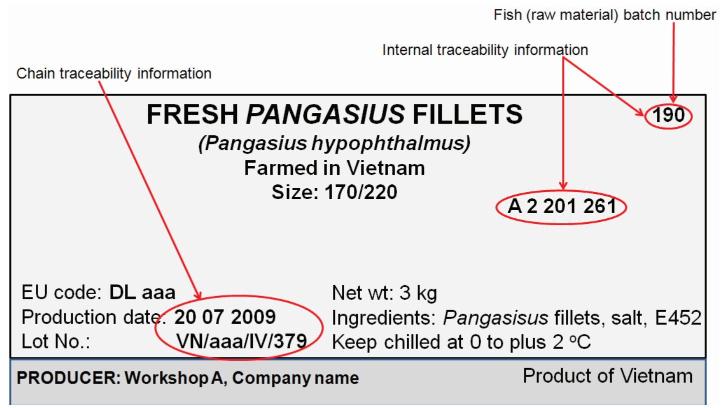

Figure 3. An illustration of the label for fresh *Pangasisus* fillets in 3kg EPS box exported to a customer in EU.

Table 2. Process parameters', quality and traceability information kept at the studied company.

	What (Type of information)	When and frequency	Where	Who	How (Record keeping method)	Related traceability question No.
1.	Absence/presence of forbidden antibiotics /chemicals	2 weeks before harvesting For all ponds	Fish samples from the pond	Internationally accredited inspection body (NAFICAVED 4)	Paper form	
2.	Extended tests' results on restrictedly allowed antibiotics /chemicals	Every 3 months	Fish samples from the pond	NAFICAVED 4	Paper form	
3.	CCP form at reception of resources (according to HACCP plan and traceability procedure with IDs of resources' batches)	All delivered batches	At reception area	Internal reception staff	Paper form	Ia, Ib, IV
4.	Control of processes (according to GMP)	Every hour Each of all processing step	At respective processing area	QC staff	Paper form	
5.	Temperature of washing water	Every hour At all washing steps	At respective processing area		Paper form	
6.	Tests on TVC, hygienic and pathogenic indicators	Routinely as indicated in the sampling schedule	Raw materials, semi-products, final products and contacted surfaces	Internal laboratory and NAFICAVED 4	Paper form	
7.	Product temperature	Every hour	At cooling step and upon refrigerated storage	QC staff	Paper form	
8.	Temperature of storage rooms	Continuously for all rooms	At the most abusive area of the rooms	Automatic recording (loggers)	Electronic and paper form	
9.	Tests on quality of final product: sensory, chemical (for forbidden antibiotics), and microbiological	Each final product batch	Product samples before shipping	Internal laboratory and NAFICAVED 4	Paper form	
10.	Temperature of refrigerated trucks	Continuously for all trucks	At the most abusive area of the trucks	Automatic recording	Electronic and paper form	
11.	NUOCA dairy			QC staff	Paper form	
12.	Invoice/Order No.	All incoming batches			Paper form	Ib
13.	Bill of lots	All production/ product batches			Paper form	II, IV
14.	Yield form (including grade and size)	All fish raw material batches			Paper form	II, IV
15.	IDs of product batches	All product batches			Paper form	III
16.	Shipping No./Order No.	All dispatched batches			Paper form	IV

CCP = Critical control point.
HACCP = Hazard analysis and critical control points.
GMP = Good manufacturing practice.
TVC = Total viable counts.
NUOCA =Notations of unusual occurrences and corrective actions.

whole supply chain, but available upon request; meanwhile information about "TRU" (*external product batch number*) is sent along the chain.

Regarding other ingredients, such as salt and polyphosphate E452, it is possible to trace back through the company to a delivery batch of a supplier. This is because a delivery of the resource from a certain supplier is uniquely assigned an *ingredient batch number* which is indirectly linked to the product batch number through the fish batch number (Fig. 2). However, due to non-proportionality between ingredients batches and fish batch, i.e. large quantity of the ingredients' batches (can be up to 20 tons) and small quantity used for each fish batch, sometimes a product batch is produced from one fish batch and more than one batch of an ingredient (Fig. 1). This means sometimes the traceability level is at a group of two continuously received ingredient batches.

Table 3. Summary table of results from the analysis of traceability system effectiveness.

Question	Fish raw material	Salt	Polyphosphate	Final product
Ia. Are all batches of resources registered with unique IDs? (Y/N)	Y	Y	Y	
Ib. Is all traceability relevant information of resources' batches provided and/or recorded, kept, and linked to batches' IDs? (Y/N)	Y	Y	Y	
II. Are all relevant resource, product, and process information recorded and linked to resources' IDs or product IDs? (Y/N)	Y	Y	Y	
III. Are unique IDs assigned to all newly formed batches and are these records kept? (Y/N)				Y
IV. Is all traceability relevant information of the input(s) transferred with the output to the next step? (Y/N)	Y	Y	Y	Y

Ability to track: Tracking forward through the company is possible with the same set of the above mentioned identifiers-numbers. Tracking of fish raw material is rather simple as there is no mixing of the resource from a pond throughout the production and to the customer. Concerning the other ingredients, e.g. a delivery of polyphosphate is normally used for 15 days of production. Therefore, if a recall (although very unlikely) of a delivery batch is issued by its supplier, a half month production of fish would have to be recalled. Frederiksen *et al.* [30] have indicated that material identity with the longest time in production, e.g. polyphosphate in our case, has to be very well controlled, as it affects many product lot identities. The willingness to improve the precision of ingredients' traceability depends on the recall risks of each resource and the final product, detail level of information required by the customers and associated costs [9, 12, 20, 31]. This is an area for future research.

At the studied company, for each of all incoming batch of raw material and ingredients, the IDs of supplier and transporter are recorded in the reception form. For every dispatched batch of product, the IDs of buyer and transporter are recorded in the shipping form. This is in accordance with good traceability practice concerning information transfer for chain traceability [10].

In general, the traceability system at the company is good, enabling both tracing and tracking. The current traceability system is effective because the codes of incoming resources (i.e. fish and ingredients' batch numbers) are associated uniquely to the final product (i.e. internal product batch number), and the codes of final product are also linked to the lot numbers (i.e. external product batch number) which are used for logistics and distribution [17]. All the data of the current system conform to mandatory data list of food traceability described by Folinas *et al.* [32]. The studied system also meets the fundamental structure of a traceability system proposed by Moe [31].

In a study on traceability system at a lamb processing company, Donnelly *et al.* [12] found that there was no link between ingredient IDs and product lot IDs. This means that some NO answers are given according to the proposed evaluation framework in Table 1. This is an example of ineffective traceability system. Donnelly *et al.* [12] have therefore suggested establishing the links needed.

Compliance with regulation and standard: The company meets with 178/2002 European Common Food Law requirements for traceability [2] which considers one step forward - one step backward traceability. However, the traceability system does not meet with TraceFish requirements [19] because globally unique identifiers, identified by Global Trade Item Numbers (GTIN), are not used. The TraceFish requires information on production parameters and raw materials to be keyed to globally unique trade units, while the company uses locally unique batch numbers. These will limit the company's ability to send information in a structured and standardized way along the chain.

All record keeping is in paper form (Table 2, items No. 3, 12-16) which may cause time-consuming traceability. Therefore, it is suggested that the company also keeps their records in electronic form, e.g. paper based data periodically transferred to computer system [30]; or/and adopts a new electronic traceability system to make the traceability more efficient [17]. Furthermore, it is advisable to use an international standard code system such as GS1 codes[11] for the dispatched trade units to facilitate the data transfer, in a structured and standardized way, among actors of the chain.

Process parameters' and quality information recorded at the studied company and possible usage: Moe [31] has stated that connecting traceability with the whole documentation and control system represents an effective mean to improve the consumers' perception on food safety and quality. Along with traceability information, huge amount of information on process parameters and on quality is recorded and kept at the company. Main types of process parameters' and quality information are presented in Table 2 (items No. 1-11).

It can be seen from Table 2 (items No. 1-11) that the information on quality and process parameters are mainly recorded and kept in paper form. Most of them (except items No. 1 and No. 9) are for internal use only. These restrict the company from using the available data in an efficient manner. Table 2 also shows that all the raw material batches and product lots have quality control measurement results in place. In addition, as above mentioned, no mixing of fish raw material is practiced, thus if there is some problem detected, the withdrawal is related to only a specified batch of raw material. This indicates the time-line approach for integration of quality management system information and traceability information [30] is very easy to be adopted at the studied company.

These data can be exploited and used more efficiently. Some of possible improvements and data usages are as follows: to type in, scan, and keep the data in electronic form, such as spreadsheets and PDF files, in parallel with paper form. The company can also use commercially available software such as Wisefish from Maritech and MPS from Marel to directly connect quality related data to production batches [30]. Electronic store of data will facilitate data access when necessary, e.g. upon a customer request on quality information of the product.

Temperature data of product and its surroundings can be used in different ways. For instance, the information can be used to estimate the maximum time that a certain product in a specified box type and size can be exposed to certain outside temperature in order to retain the product temperature below a certain limit. This can be done using Equation 1 and assumed/estimated parameters' values, e.g. in case the average initial temperature is -0.9°C (Fig. 4) and the average final temperature of product is 3.9°C (Fig. 4), average ambient temperature is 28.9°C (Fig. 4), value of $(1/h + R_s)$ is estimated equal 13.764 m^2K/W based on the experimentally measured product warm up time 27.75 hours (Fig. 4). The product warm up time then can be recalculated for other values of temperature inputs using the same set of parameters' values. The product warm up time here is much longer than the one found by Margeirsson [23], in despite of the higher input ambient temperature and the lower input final product temperature in this study, thanks to the use of cooling gel pack on top of the fish. Margeirsson [23] has reported that the error of estimation (using non-modified equation for fish in EPS box without cooling gel pack) is about 16% of the experimental value which indicates that Equation 1 and estimated values of parameters could potentially be used to roughly calculate the allowed product warm up time. This helps the company and the distributor to plan their shipping.

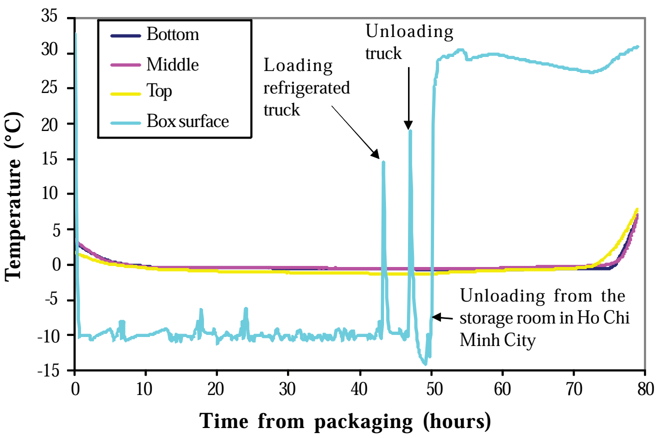

Figure 4. Box surface and product temperatures during truck and simulated air transportation after packaging of chilled *Pangasius* fillets in EPS (430 mm x 300 mm x120 mm; 3 kg of fish with a gel mat of 500 g on top) box from the processor.

Furthermore, if the company studies the correlation between the ambient temperature and product temperature, e.g. using temperature mapping to have the results as shown in Fig. 4, the product temperature in certain packaging can be predicted based on the ambient temperature. The shelf life of product then can be estimated using available software such as SSSP [33] based on a known shelf life of product at certain temperature and the temperature history. For example, using the product temperature history shown in Fig. 4, and a referenced shelf life of 15 days at 0.5°C (own study result), the product is estimated to have a remaining shelf life of 12.7 days at 0°C or 7 days at 5°C. This will help the company and other downstream actors to better manage their product and its quality, e.g. the product with shorter remaining shelf life will be sold earlier. SSSP is validated and shown to be very suitable to validate the product freshness with a temperature record [30]. The result here also supports the concept LSFO (Least Shelf-life First Out) [34-36] and the statement of Taoukis [36] that based on the RSL, one can optimize the handling, shipping destination and stock rotation.

Conclusions

The developed framework was applied, partly validated, and shown to work well in the specified case study. It is potentially useful for the food producers, in general, to evaluate the effectiveness of their existing traceability systems based on process mapping information. However, further investigation for other cases is desirable.

It is possible to track and trace through the studied company. The traceability system at the company meets with 178/2002 European Common Food Law requirements for traceability, but does not meet with TraceFish requirements.

Huge amount of quality and process parameters' information exist at the company and it is suggested to key these data into computer system for faster access. Data on ambient temperature during logistics steps can be used to calculate the product warm up time. Furthermore, with the correlation between ambient and product temperatures, the remaining shelf life of product can be estimated. These thus help to improve the management of product quality as well as improve the supply chain management.

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PAPER III

Temperature Mapping of Fresh Fish Supply Chains - Air and Sea Transport

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ABSTRACT:

Temperature history from three air and three sea freights of fresh cod loins and haddock fillets in expanded polystyrene (EPS) boxes, from Iceland to the UK and France were analyzed to find out the effect of different factors on the temperature profile and predicted remaining shelf life (RSL) of the product. It was also aimed to pinpoint hazardous steps in the supply chains. Significant difference ($p < 0.001$) was found in: the temperature at different locations inside a certain box; mean product temperature between boxes of a certain shipment; and the boxes' surface temperature at different positions on a pallet for the whole logistics period. The predicted RSL depends on the time and temperature history of the product, shortest for sea transportation, and longest for an air shipment with pre-cooled product. Several critical steps were found in air freighting: the flight itself, loading/unloading operations, and holding storage at un-chilled conditions.

PRACTICAL APPLICATION:

The paper strengthens fundamental understandings on logistics of fresh fish by air and sea in EPS boxes using ice or gel mats as coolants, with particular contribution of information related to mode of transportation, box-pallet arrangement and location, time-temperature, and pre-cooling effects. It is proposed to pre-cool products before packing to better stabilize the temperature of product during abusive period(s). It is also suggested to group the products based on the time-temperature history and/or positions on the pallets for better management in further handling of the fish.

Keywords: temperature mapping, fresh fish supply chain, air freight, sea freight, shelf life

INTRODUCTION

The consumption of fresh fish has been growing while other forms of fish products have remained the same or even declined (Vannuccini 2004; FAO 2009). This makes the supply of fresh fish increasingly important. The world production of fresh seafood has gradually grown from about 30,000,000 tons in 1994 to 50,000,000 tons in 2002 (Vannuccini 2004).

Temperature is considered as the main factor that affects the quality and safety of perishable products. Abusive and/or fluctuating temperature accelerates rapid growth of specific spoilage microorganisms as well as pathogens (Jol *et al.* 2005; Raab *et al.* 2008), thus may cause economic losses and safety problems.

It is well known that fresh fish is often stored and shipped at melting ice temperature (Pawsey 1995; ATP 2007) or even below 0 °C, at superchilled temperature (Olafsdottir *et al.* 2006b) to keep it good and safe for a certain period. However, the fresh fish supply chains may face certain hazards when the requirements are not fulfilled.

The transportation of perishable products such as fresh fish is very common by air as it is very fast. However, during loading, unloading, truck and air transportation, storage and holding the product is normally subjected to temperature abuse at un-chilled conditions (Brecht *et al.* 2003; Nunes *et al.* 2003), which means that much of its journey is un-protected (James *et al.* 2006). Even fluctuation and/or high temperature for short time was reported to cause the rejection of a whole strawberry load (Nunes *et al.* 2003). Results from a study on chilled modified atmosphere packaged (MAP) Pacific hake have shown that even a small fraction of storage time (4.3%) at abusive temperature caused a significant reduction in shelf life (25%) of the product (Simpson *et al.* 2003).

Another mean of transporting fresh fish is by sea where the product is containerized in refrigerated containers to maintain the required low temperature for the whole voyage. This mode of transportation, however, takes much longer time compared to air freighting where time is known as main factor to reduce the quality of perishables even at optimum conditions of handling (Pawsey 1995).

There are several studies about the effect of different factors in the cold chains on the temperature distribution and/or quality of food products such as fresh cut endive (Rediers *et al.* 2009), strawberry (Nunes *et al.* 2003), asparagus (Laurin 2001), chilled chicken breast (Raab *et al.* 2008), frozen fish (Moureh and Derens 2000), chilled gilt-head seabream (Giannakourou *et al.* 2005), and so forth. However, there is still no scientific publication on the temperature mapping and comparison for a real supply chain of fresh cod loins or haddock fillets from processing to market by air and sea transportation.

Shelf life models are very useful to assess the effects of temperature changes on product quality (Jedermann *et al.* 2009). The data set of time-temperature history can be fitted to predict RSL by using available models such as the square-root model for relative rate of spoilage (RRS) of fresh seafood (DTU-Aqua 2008).

The aim of this work was to investigate the temperature changes of fresh cod loins and haddock fillets packed in EPS boxes, as well as of the environment around the product during the logistics from producers in Iceland to markets in the UK and France by air and sea freights; and from that to pinpoint critical steps in the supply chains. The study was also aimed to compare the effect of different factors such as product locations inside each box, box positions on a pallet, logistics units (that is, master boxes; pallets; or containers), pre-cooling, and modes of transportation on the temperature profiles of product and box surface; and to compare the effect of these factors on the predicted RSL of product based on the time-temperature records from the shipments.

MATERIALS AND METHODS

Temperature mapping

The temperature mappings were performed for 3 air and 3 sea trips of the fresh fish supply chains from the processors in Iceland (IS) to the markets (distributors, retailers, or secondary processors) in the UK and France (FRA) in September 2007, June, July, and September 2008. Descriptions of the logistics of these chains are shown in Table 1.

TABLE 1. DESCRIPTIONS ON THE LOGISTICS OF THE STUDIED CHAINS

Freight	**Step**	**Description**	**Duration**	**Ambient temperature Mean ± STDEV (°C)**	**Ambient temperature of pallet 1 Mean ± STDEV (°C)**	**Ambient temperature of pallet 2 Mean ± STDEV (°C)**
Air_ Sep 2007 (Freighter)	1	Frozen storage at producer after packing (Dalvik, IS)	6 h	-16.2 ± 9.2	-22.5 ± 3.3	-13.0 ± 9.6
	2	Chilled storage at producer	2 h	2.5 ± 0.5	2.3 ± 0.3	2.5 ± 0.5
	3	Transportation from Dalvik to Reykjavik (RVK, IS) in a refrigerated truck	8 h 20 min	-12.3 ± 6.0	-8.1 ± 3.5	-14.4 ± 5.9
	4	Unloading and loading in a chilled truck in RVK	2 h	8.6 ± 1.3	8.4 ± 1.1	8.7 ± 1.3
	5	Transportation from RVK to Keflavik airport (KEF, IS) in a chilled truck	1 h 20 min	1.6 ± 1.1	2.2 ± 0.7	1.3 ± 1.1
	6	Un-chilled storage at KEF airport	5 h 20 min	11.3 ± 3.0	13.3 ± 2.0	10.3 ± 3.0
	7	Chilled storage at KEF airport	6 h	3.1 ± 4.9	8.1 ± 5.3	0.5 ± 1.6
	8	Flight from KEF to Humberside airport (HUY, UK) and un-chilled storage at HUY	6 h 15min	9.9 ± 4.5	6.4 ± 4.8	11.7 ± 3.1
	9	Storage at HUY and transportation to Carlisle (UK)	7 h 15 min	0.2 ± 0.8	1.0 ± 0.4	-0.2 ± 0.6
	10	Unloading/un-chilled storage at wholesaler in Carlisle	3 h	3.9 ± 2.1	4.7 ± 2.7	3.6 ± 1.7
	11	Storage in Carlisle	45 h 45 min	1.5 ± 1.1	1.3 ± 1.0	1.7 ± 1.1
	12	Distribution to retailers	2 h 12 min	3.7 ± 1.3	3.0 ± 1.2	4.0 ± 1.2
	Total	3.9 d at distributor; or 4 d at retailers		0.6 ± 7.7	0.7 ± 8.0	0.5 ± 7.6
Air_ June 2008 (Freighter)	1	Cold storage after packing at producer (Dalvik)	2h	-6.8 ± 8.2	-11.5 ± 6.0	-2.2 ± 7.4
	2	Loading truck and transportation to RVK	9 h 35 min	-0.3 ± 2.9	-2.4 ± 2.8	1.7 ± 1.1
	3	Un-chilled storage over night in RVK	10 h 10 min	8.8 ± 2.5	10.5 ± 1.7	7.1 ± 2.0
	4	Transportation in refrigerated truck to KEF	2 h 15 min	3.4 ± 2.8	4.5 ± 2.5	2.2 ± 2.7
	5	Chilled storage at KEF airport	2 h 45 min	1.2 ± 1.0	1.9 ± 0.7	0.5 ± 0.6
	6	Loading at KEF and flight from KEF to Nottingham (UK)	5 h 30 min	4.6 ± 3.0	3.6 ± 2.6	5.6 ± 3.2
	7	Transportation from processors storage	7 h 55 min	1.7 ± 2.3	1.0 ± 2.6	2.3 ± 1.8
	Total		1.7 d	3.0 ± 5.2	2.6 ± 6.3	3.5 ± 3.7
Air_ July 2008 (Passenger)	1	Chilled storage at the producer in Hafnarfjordur (IS) after packaging	21 h 30 min	3.6 ± 1.3		
	2	Transport from Hafnarfjordur to some storage at KEF	19 h 10 min	14.4 ± 2.8		
	3	From taking off to landing	3 h 5 min	12.1 ± 4.2		
	4	Storage at London Heathrow airport (LHR, UK)	7 h 15 min	10.7 ± 5.0		
	5	Land transport in refrigerated truck to secondary producer in Plymouth (UK)	5 h	4.2 ± 0.4		
	Total		2.3 d	8.7 ± 5.6		
Sea_18-23Sep 2008		Handling and transportation in refrigerated container: trucked from producer to habor Reydarfjordur (IS); shipping to Rotterdam habor (the Netherlands); and land transportation till final destination (Boulogne sur mer, FRA)	4 d 19 h 45 min (4.8 d)	-0.2 ± 0.5		
Sea_23-29Sep 2008	1	Cold storage at the producer (Dalvik)	3 h 35 min	-11.6 ± 5.5		
	2	Loading into container and transportation to RVK	8 h 30 min	-2.8 ± 2.1		
	3	Partly-chilled hold in RVK	4 h 50	3.5 ± 4.3		
	4	Transportation and handling in refrigerated container: trucked from producer to RVK; shipping to Immingham (UK); and land transportation till final destination (Grimsby, UK)	5 d 3 h 30 min	-0.4 ± 1.5		
	Total		5.9 d	-0.7 ± 2.8		
Sea_24Sep - 1Oct 2008		Handling and transportation in refrigerated container: trucked from producer (Dalvik) to RVK; shipping to Immingham (UK); and land transportation till final destination (Grimsby, UK)	6 d 16 h 35 min (6.7 d)	-0.7 ± 0.2		

Product profile for the shipments

Products of all the studied trips, except for the one in July 2008, were fresh cod loins from a processing company in Dalvik (North - Iceland). In July 2008, they were fresh haddock fillets from another company in Hafnarfjordur (South West - Iceland).

The cod was caught east of Iceland. Onboard it was bled, gutted, washed and iced in insulated tubs. The fish to ice ratio was about 3:1, and the fish was packed in 4 - 5 layers alternatively with ice above and below each fish layer. The pre-processed whole fish was stored in the tubs in the refrigerated ship's hold until landing approximately 2 – 4 days from catch. After landing it was transported in un-refrigerated trucks to the processing plant located only a few hundred meters away from the harbor. The catch was processed the following day after a chilled storage overnight.

For the products aimed to air transportation, the fish was headed, filleted, skinned, and cut into portions (approximate size: 26 x 5 x 2.3 cm, approximate weight: 0.32 kg). After processing, the cod loins were immediately packed in EPS boxes (outer dimensions: 400 x 264 x 118 mm), which contained about 3 kg of cod loins with 2 frozen gel - mats (September 2007) or 1 gel mat of 125 g (June 2008) lying on top of the loins, and with a plastic film in between. The EPS boxes were loaded on Euro-pallets (1200 x 800 mm) with 8 boxes in each row and 12 rows high (Fig. 1), and the palletized boxes wrapped in a thin plastic sheet for protection.

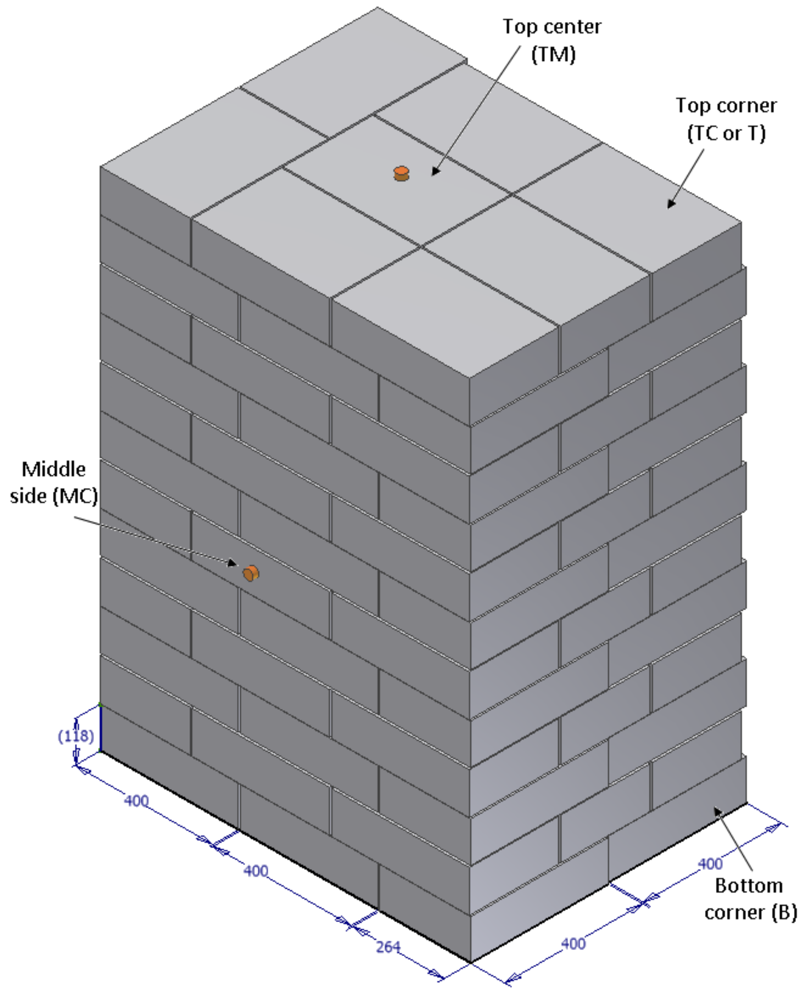


FIG. 1. COMMON LOADING PATTERN OF 3-KG EPS BOXES ON A PALLET. ROUND BUTTONS ON TOP AND SIDE OF THE PALLET ILLUSTRATE THE SURFACE LOGGERS.

For the products aimed to sea transportation, the processing steps include heading, filleting, liquid cooling, Combined Blast and Contact (CBC) cooling, skinning and trimming. After processing, the cod loins of the same size as for air shipments were immediately packed in EPS boxes (400 x 264 x 135 mm) which contained 5 kg of cod loins. The boxes were equipped with drainage holes at the bottom in order to drain melting ice which was put on top of a thin plastic sheet above the loins. The amount of ice utilized in each box was about 0.3 – 0.5 kg. The boxes were palletized on Euro pallets (1200 x 800 mm) with 9 boxes in each row and 12 rows on each pallet. A few layers of thin plastic film were wrapped around the palletized boxes before they were containerized.

The haddock was caught north of Iceland by a line vessel in July 2008. On board it was bled, washed, packed and stored with ice in insulated tubs until landing in North Iceland. Fish tubs were transported in a refrigerated truck approximately 400 km to the processing plant in Hafnarfjordur. The raw material was stored in the plant's chilled storage room (ambient temperature about 2 to 4 °C) overnight. The fish was about 1 d old from catch when the processing started the following morning. The different steps in the processing include gutting, washing, filleting, trimming, liquid cooling (10 – 15 min in ice slurry at -1 to 1 °C), CBC cooling (10 – 11 min at about -10 to -8 °C), skinning and trimming, followed immediately by packaging into EPS boxes (600 x 400 x 147mm). Each box contained 12 kg of haddock fillets, without any ice or gel packs as a cooling medium since the CBC treatment decreases the fillet temperature to around -0.5 °C. Twenty eight boxes (7 rows with 4 boxes in each row) were palletized on each Euro-pallet (1200 x 800 mm) and the pallet load wrapped with layers of thin plastic sheet.

Logger configurations

Based on previous studies (Moureh and Derens 2000; Moureh *et al.* 2002) and own preliminary studies, it was observed that the temperature at different position of product and packages is often not homogeneous during thermal load. Loggers were configured in the way that temperature changes at different positions inside a box and on box surface, and at different positions of boxes on a pallet could be sufficiently monitored.

Loggers for the temperature mapping were placed in the product during packaging and on the box surface before or during palletizing. Logger configurations are the following:

In September 2007, measurements were carried out with 2 pallets (P1, P2); 4 boxes for each pallet: at top center (TM), top corner (TC), bottom corner (B), and in the center of middle row (M) of the pallets; 3 loggers inside each box: on top (t), in the middle (m), and at the bottom (b) of product. Three outside loggers to measure box ambient temperature (A) were attached to the middle side (MC) boxes of P1 (P1_A_MC), P2 (P2_A_MC), and to the top corner box of P2 (P2_A_T). The box positions and outside loggers are shown for 1 pallet in Fig. 1. At the end, 2 inside loggers of P2, which were the top loggers inside the centre-middle row box (P2_M_t) and the top center box (P2_TM_t), got lost.

In June 2008, measurements were conducted with 2 pallets (P1, P2); 3 boxes for each pallet: at top corner (T), bottom corner (B), and middle height (M); 3 loggers inside each box (t, m, and b). Four outside loggers were placed on top (P1_A_T, P2_A_T) and side (P1_A_MC, P2_A_MC) of the 2 pallets. However, 2 inside loggers of P2, which were at the bottoms in the bottom corner box (P2_B_b) and the top corner box (P2_T_b), failed to record. Therefore, the data sets are just available for 9 inside loggers of P1, 7 inside loggers of P2, and 4 outside loggers.

For the air shipment by a commercial passenger flight in July 2008, one pallet was investigated; 3 boxes (T, B, and M) with 2 loggers inside (m and b) and 1 on the surface of each box (A_T, A_B, and A_M).

In the sea freight study September 18th – 23rd 2008, measurements were done with 1 pallet; 3 boxes (T, B, and M) with 3 loggers inside (t, m, and b) and 1 on the surface of each box (A_T, A_B, and A_M). However, all the inside loggers were lost; 2 outside loggers stopped working before the shipment started, only 1 outside logger on the middle box (A_M) worked properly.

In the sea freight September 23rd – 29th 2008, a study was carried out for 1 pallet with only 3 surface loggers on top corner, bottom corner, and middle boxes (A_T, A_B, and A_M, respectively).

Lastly, in the sea trip September 24th – October 1st 2008, the temperature mapping was done on 1 pallet; 3 boxes (T, B, and M) with 3 loggers inside (t, m, and b) and 1 on the surface of each box (A_T, A_B, and A_M). One inside logger (B_t) was lost.

It should be noticed that in all the sea trips and in the air freight July 2008, the middle boxes (M) also means middle side (MC) as they have 1 free side on a pallet side. Furthermore, the middle box in July 2008 had 2 free sides as it was located at the corner of the middle row.

In general, each mapped box was equipped with 3 loggers inside (one at the bottom, one in the middle height of product, and another on top of product) and a logger on the box surface (top or side). This gives the actual temperature history of product at different position inside a box, as well as the actual temperature changes on the box surface.

Types of loggers

The ibutton temperature loggers are small and relatively cheap devices with wide range of operation temperature, high precision, and sufficient memory for data storage (up to 4096 data points, e.g. recording continuously for 14 days at 5 minute interval or 28 days at 10 minute interval). They can function during contact with food, water or ice and can be easily set. DS1922L temperature loggers iButton® were used for mapping the temperature inside the boxes, with temperature range: -40 °C to 85 °C; resolution: 0.0625 °C; accuracy: ± 0.5 °C and ± 1 min/wk. Recording intervals were set at 2 (Air_July 2008), 4 (Air_Sep 2007), 5 (Sea-_24Sep 2008), or 10 (Air_June 2008) min.

TBI32-20+50 Temp Data Loggers were used for the measurement of ambient temperature on the box surfaces, with temperature range: -20 °C to +50 °C; resolution: 0.3 °C; accuracy: ± 0.4 °C and ± 1 min/wk. Recording intervals were set at 1 (Sea_23-29Sep 2008, Sea_24Sep 2008), 2 (Air_July 2008), 4 (Air_Sep 2007), or 5 (Air_June 2008, Sea_18-23Sep 2008) min.

All loggers were calibrated in thick mixture of freshly crushed ice and water before use.

Data analysis

Multivariate analysis was performed using the Unscrambler version 9.0 (CAMO Process AS, Norway). The main variance in the data set was studied using principal component analysis (PCA) with full cross validation. Data was preprocessed by autoscaling prior to the PCA, that is, first centered by subtracting the column average of elements from every element in the column; and then each element was scaled by multiplying with the inverse standard deviation (1/STDEV) of the corresponding variable, to handle the model offsets and to let the variance of each variable be identical initially (Bro and Smilde 2003).

One-way repeated measures analysis of variance (ANOVA) was applied to the data using the software SPSS version 16.0 (released September 2007) in order to study the effect of some factors such as product locations, box positions, and chain steps on the temperature of product and box surface. The null hypothesis was that the analyzed factors have no influence on the temperature. Bonferroni correction was used in confidence interval adjustment for multiple comparisons of locations. Tukey's Multiple-comparison test was used to determine the statistical difference between steps. All tests were performed with significance level of 0.05.

Microsoft Excel 2003 was used to calculate means, standard deviation, and range for all measurements and to generate graphs.

The Seafood Spoilage and Safety Predictor (SSSP) software version 3.0 (DTU Aqua, Denmark) was used to predict the effect of time-temperature combination on the RSL based on the recorded temperature profile. Recorded data of cod loins and haddock fillets from different positions inside boxes were separately fitted into a Square-root model for relative rate of spoilage (RRS) of fresh seafood from temperate water. In SSSP, RRS at T °C has been defined as the shelf life at a reference temperature T_{ref}, which normally is 0 °C, divided by the shelf life at T °C (Dalgaard 2002), where shelf-life was determined by sensory evaluation. The SSSP uses the concept of accumulative effects of time and temperature. The SSSP is based on growth kinetics of specific spoilage organisms and empirical RRS secondary models (Dalgaard *et al.* 2002). A reference shelf life of 9 days (from catch) stored at 1.5 °C for fresh cod loins in EPS boxes (Wang *et al.* 2008) was used in this study. A shelf life of 12 days (from catch) at 0 °C was applied for fresh haddock fillets in EPS boxes (Olafsdottir *et al.* 2006a). In order to enable the comparison of the effect of different logistics practices on the RSL, it was assumed that all fish batches had undergone 3 days from catch of the same conditions before the temperature mapping started. Therefore, 3 days were subtracted from the SSSP's RSL outputs based on the temperature history during logistics to get the final RSL. The mapping data for haddock fillets in July 2008 were also used for cod loins, assuming that the product was cod, to compare the RSL between the shipments.

RESULTS AND DISCUSSION

Temperature mapping

Air freight in September 2007

Figure 2a reveals some hazardous parts of the chain because of the ambient temperature rise. The two most abusing steps were the flight followed by un-chilled storage at the arrival Humberside airport (step 8) and the un-chilled storage at the departure Keflavik airport (step 6), which caused the rise of temperature inside boxes in steps 6 – 8 (Fig. 2b). Unloading and reloading activities (steps 4 and 10) were also notable but with shorter durations (approximately 2 hours in step 4, and 3 hours in step 10). In total, the pallets were exposed to un-chilled conditions (up to 15 °C) for more than 16.5 hours, accounting for about 17.4% of the total time from processor to retailers.

In step 1, the temperature on the side of pallet 2 (P2_A_MC) was considerably higher than on the top of this pallet (P2_A_T) and on the side of pallet 1 (P1_A_MC) where the temperature was the lowest (Fig. 2a). This might be because pallet 2 was placed closer to the door of the cold store and with the mentioned side facing the door which was opened for the loading/unloading processes.

It can be seen from Fig. 2b that the temperature inside boxes was relatively high (up to about 5 °C) when the pallets were transferred into the cold storage after packing (step 1). This shows the possibility for the producer to improve the production, for example, by adding slurry ice chilling (or another chilling method) to the processing line in order to lower the product temperature before packaging. The time required to get the average temperature below 2 °C in the boxes was up to above 8 hours, despite the fact that the pallets were mostly facing ambient temperature around -20 °C. This is because the product was well insulated by the EPS boxes, and the palletization of the boxes.

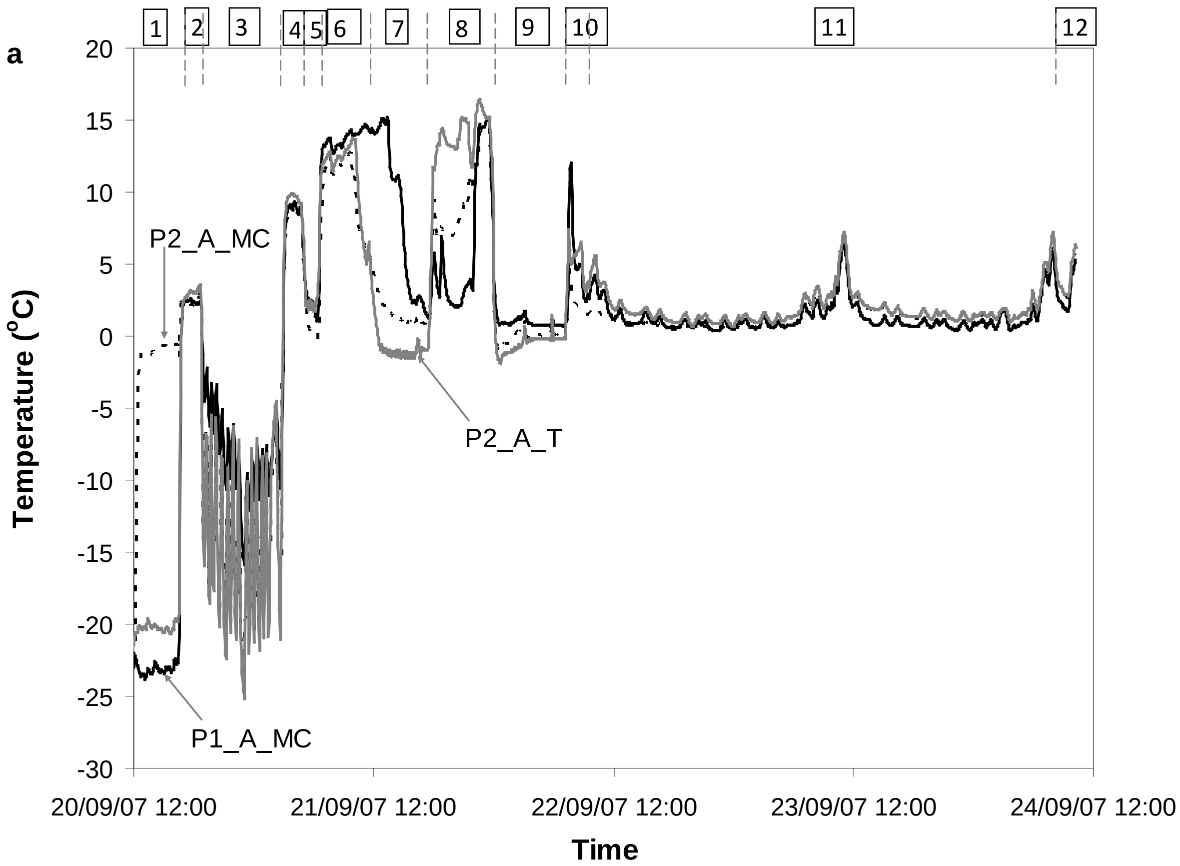


FIG. 2. AMBIENT TEMPERATURE ON THE BOXES (a), AVERAGE PRODUCT TEMPERATURE INSIDE THE BOXES (b), AND PRODUCT TEMPERATURE AT DIFFERENT LOCATIONS INSIDE EACH BOX (c) DURING THE AIR CARGO STUDY IN SEPTEMBER 2007.

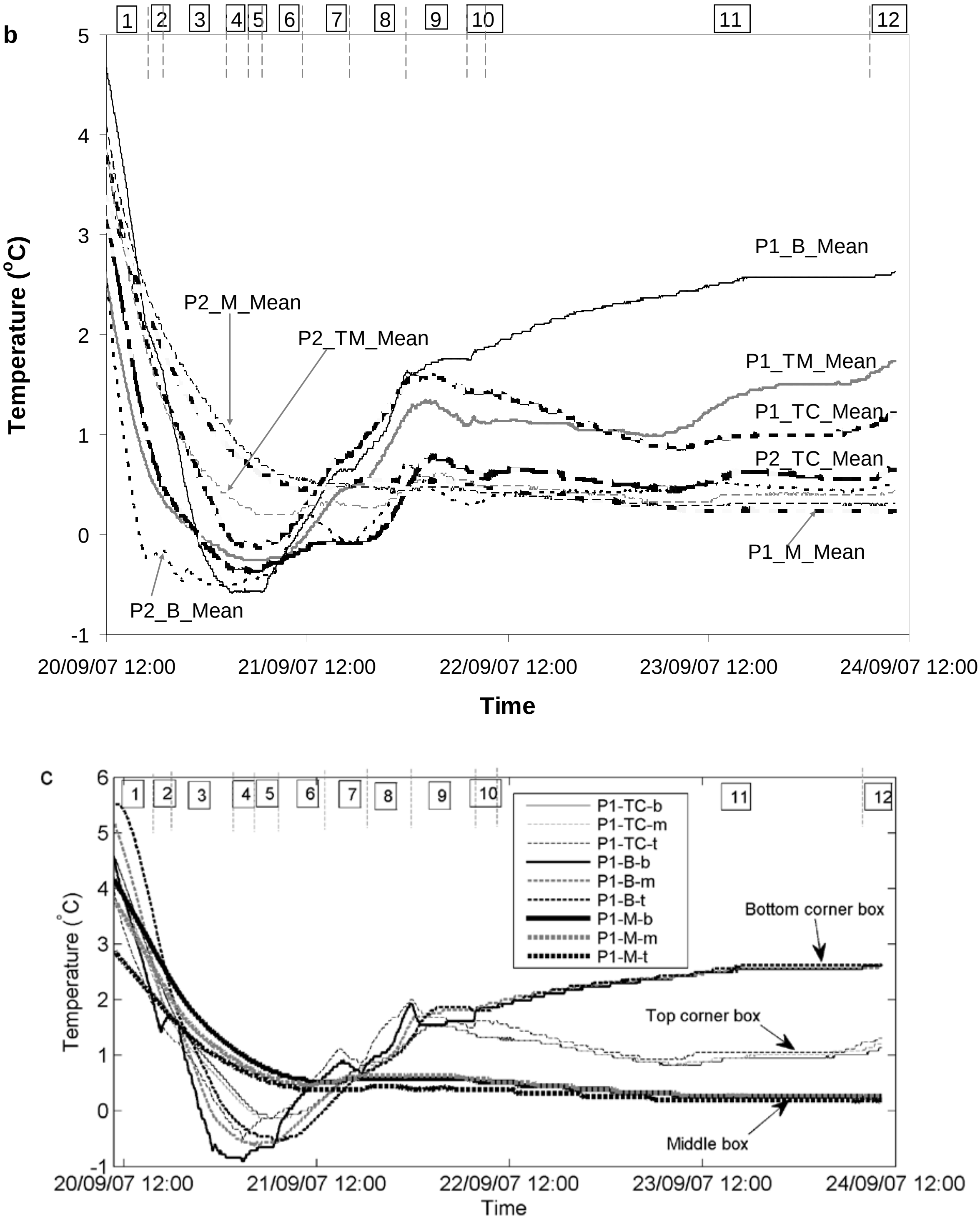


FIG. 2. *CONTINUED.*

Some relations can be noted between the placement of the boxes on the pallet(s) and the temperature evolution inside the packaging. The middle boxes (P1_M_ and P2_M_) with no free side required considerably longer time to be cooled down than the boxes with more free sides (Fig. 2b). Temperature in the boxes with more exposed surfaces, for example, the top and bottom corner boxes of the two pallets (P1_TC_, P2_TC, P1_B, and P2_B) has experienced more fluctuation. It is in a good agreement with other research results (Moureh and Derens 2000; Moureh *et al.* 2002). The bottom corner of pallet 1 has faced a continuous increase in product temperature from step 4 onward, that is, from the time when ambient temperature abuse started, and ending up with the highest temperature (2.6 °C) compared to other boxes (0.2 to 1.7 °C).

Interestingly, the patterns of temperature evolution of the same positions top corner (TC) and middle (M) on the 2 pallets are very similar (almost parallel curves: P1_TC_Mean and P2_TC_Mean; P1_M_Mean and P2_M_Mean) (Fig. 2b). For example, the temperatures of both the top corner boxes decreased sharply during steps 1 – 4, reaching the lowest points at about the end of step 4, increasing again in steps 5 – 8 and peaked in early time of step 9. After that, there are a slight decrease till the end of step 9 and some up and down changes afterward.

There is some noticeable difference between the two pallets. First of all, the temperatures on the top of product after packaging were not even for the two pallets, much lower for pallet 2 when comparing boxes at the same positions (that is, B and TC) (see Fig. 9). It might be because boxes of pallet 2 were packed earlier (with the ice mats on top) than those of pallet 1 before the loggers were activated to record the temperature. The product temperature of pallet 2 was far lower than that of pallet 1 (except for the middle box of P1) for the whole period from step 8 onward (Fig. 2b). It is mainly because pallet 2 has been exposed to lower temperature environment during a quite long refrigerated truck transportation to Reykjavik (for more than 8 hours in step 3), and also during the storage at Keflavik airport (for more than 11 hours in steps 6 and 7) (Fig. 2a). It is very likely that pallet 2 was placed close to the cooling equipment during chilled transportation (step 3) and storage (step 7).

It can be seen from Fig. 2c that the product temperature at different locations inside a box was not the same, with larger range at the beginning (steps 1 - 10), but becoming more even at the later stages of the logistics (steps 11 and 12).

When the results were analyzed with PCA (Fig. 3), a clear grouping was found between the samples with different degrees of temperature abuse exposure. Principal component 1 (PC1) explains 50% of the variance whereas PC2 explains 38%. Product at different locations in the bottom corner box on pallet 1 (P1_B_t, _m, and _b), which was the most influenced, forms 1 group of samples. Similarly, products in the top corner box (P1_TC_) and in the top middle box (P1_TM_) of this pallet make 2 other distinct groups. Those three boxes had higher temperature at the later stages of the chain (steps 8-12, Fig. 2b); of which the top product temperature inside the top corner box was the highest in step 8 (curve P1_TC_t, Fig. 2c), thus the sample score is located very close to the loadings of step 8. Product temperature of pallet 2 (P2) and in the middle box of pallet 1 (P1_M_) was more stable during the chain, grouping together in the PCA plot. Temperature in the middle boxes of the two pallets was the most resistant to change because these boxes are insulated by others; the change is mostly observed during steps 3-6 (Fig. 2b), making those scores and loadings group together (dash ellipse). This resistance is in a good agreement with the results of other studies (Moureh and Derens 2000; Moureh *et al.* 2002). Despite the fact that the temperature behavior at different positions inside each box was somewhat different, their PCA scores are located relatively close to each other, which in turn contribute to the discrimination of the product temperature between boxes. It would be possible to group the boxes with similar temperature evolution so as to have a better management for the quality, safety, and shelf life of the product. For example, it might support the sale managers in further utilization of the resources: highest end temperature in – first out.

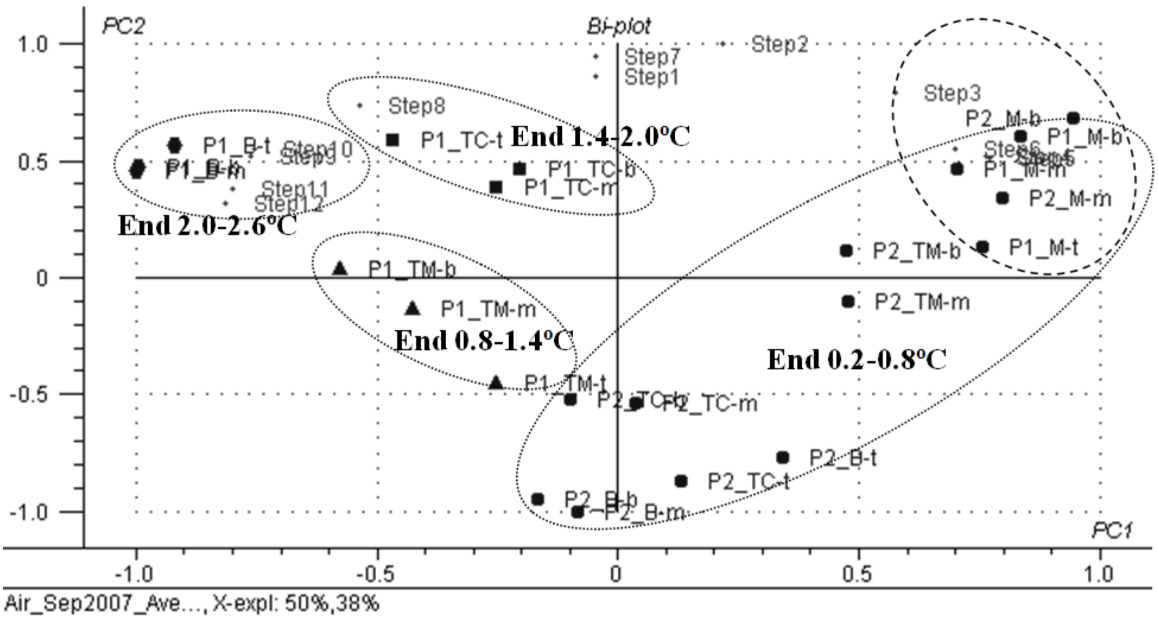


FIG. 3. PRINCIPAL COMPONENT ANALYSIS BI-PLOT BASED ON AVERAGE-WITHIN-STEP TEMPERATURE FROM THE AIR TRANSPORTATION STUDY IN SEPTEMBER 2007.

Samples are labeled with the pallet number (P1, P2), box position on the pallets (TC, TM, M, and B), and the location inside a box (t, m, b). Dotted ellipses group the samples with similar product temperature at the end of the logistics (end of step 12). The dash ellipse shows subgroup of those positions where the product temperature was the most stable.

Air freight in June 2008

Figure 4a reveals some hazardous parts of the chain considering the temperature abuse that the pallets have experienced. The two most noticeable steps were the storage overnight in Reykjavik (step 3) and the loading at Keflavik airport followed by the flight to the UK (step 6). During the loading period of the airplane (beginning of step 6), the top of pallet 2 experienced a rise of air temperature from 10 °C to 20 °C (see curve P2_A_T in Fig. 4a). The warming and cooling periods took about one hour. The explanation may be that sunlight might have reached a part of the pallet while loading the airplane (increasing the ambient air temperature for a short period). Total abusing time was about 14.5 hours (ambient temperature > 5 °C), which was 36.1% of the total logistics time from producer to final destination. This shows that a considerable time in air transportation is under non-refrigerated conditions as stated elsewhere (James *et al.* 2006).

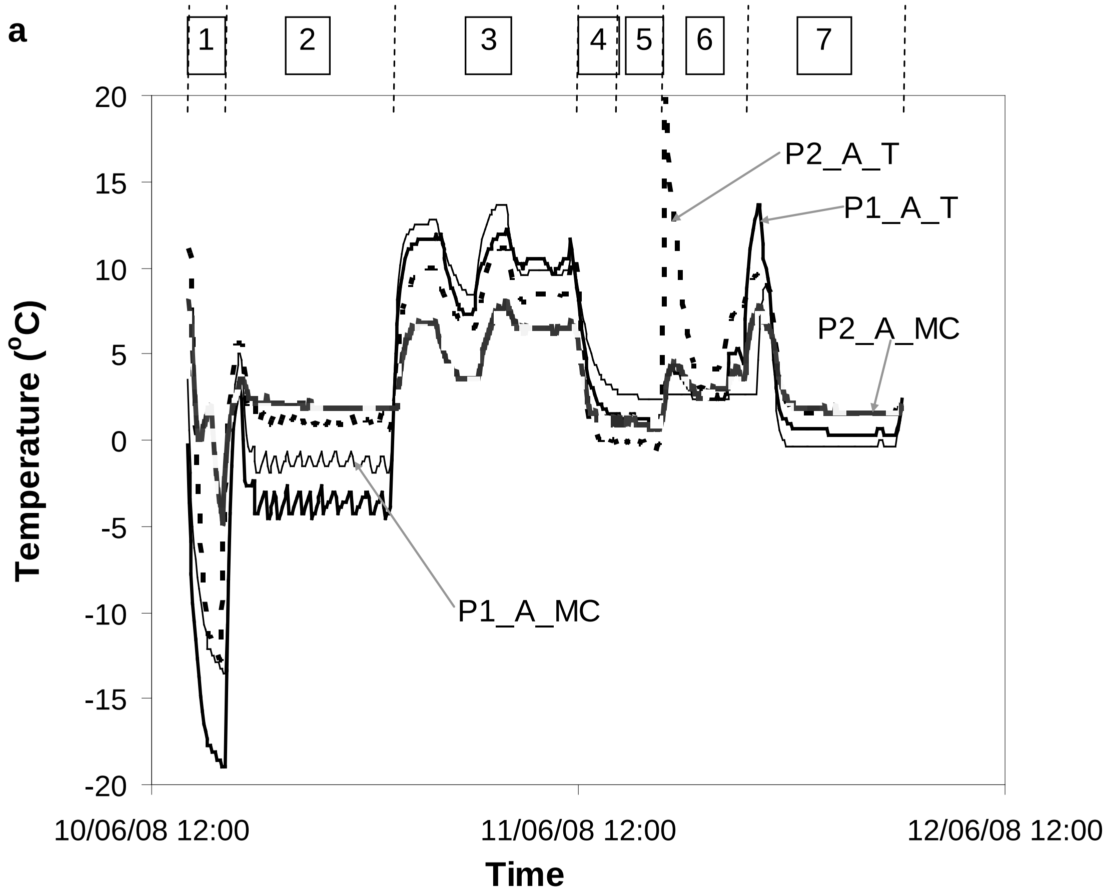
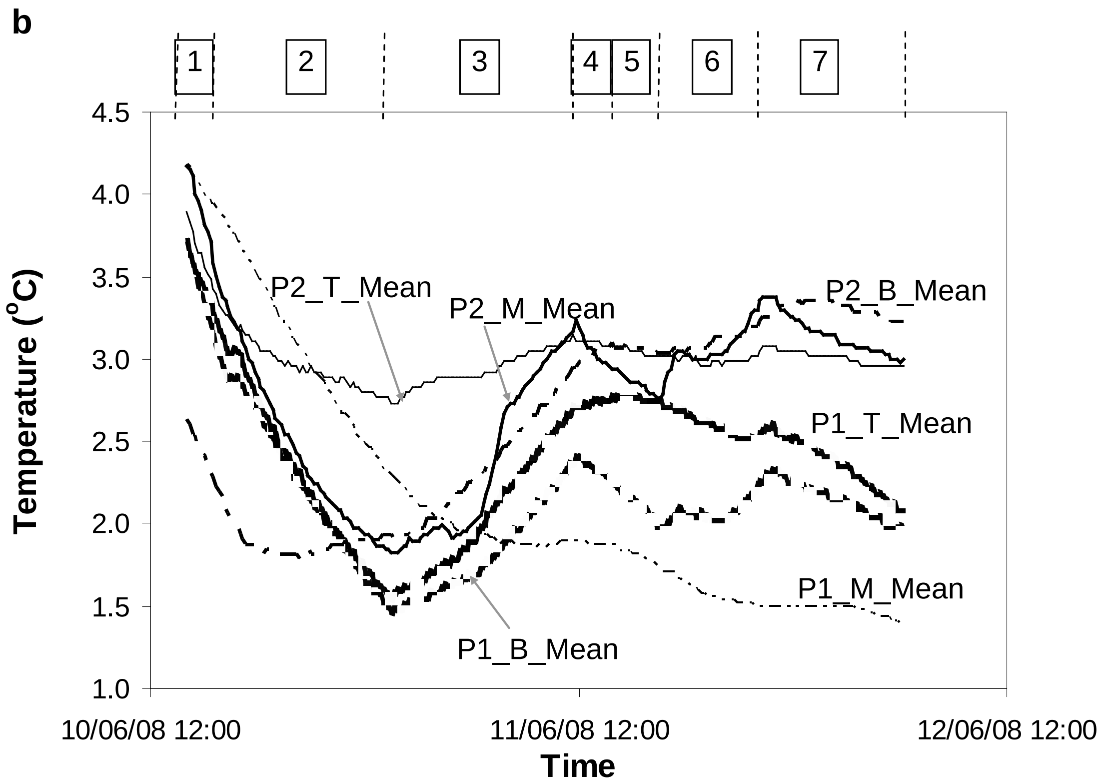


FIG. 4. AMBIENT TEMPERATURE ON THE BOXES ON THE TOP (T) AND SIDE (MC) OF THE PALLETS (a), AVERAGE PRODUCT TEMPERATURE INSIDE THE BOXES (b), AND PRODUCT TEMPERATURE RANGE OF DIFFERENT POSITIONS INSIDE EACH BOX (c) DURING AIR CARGO STUDY IN JUNE 2008.



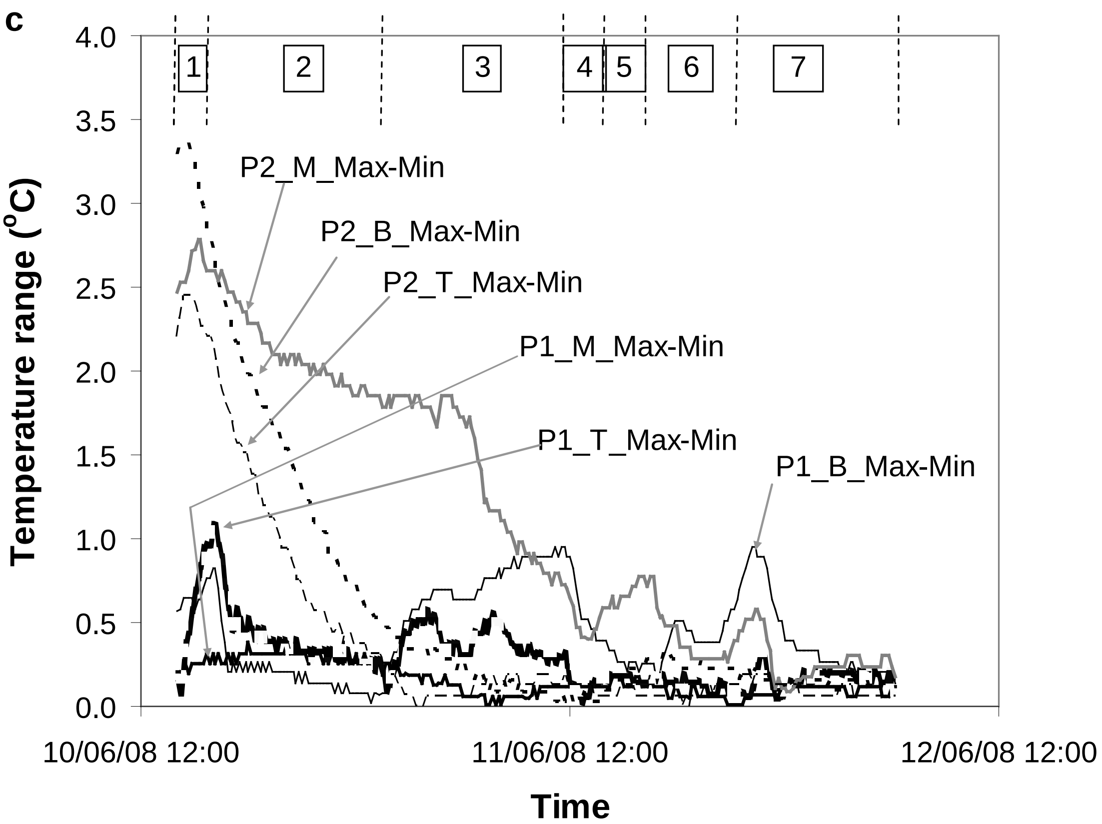


FIG. 4. *CONTINUED.*

The ambient air temperature was much lower for pallet 1 than pallet 2 in the cold storage after packaging (step 1), and the same but to a lesser extent in the following step (Fig. 4a). Therefore the temperature inside the boxes on pallet 1 has decreased faster than that of pallet 2 during the first 12 hours from the processor at Dalvik until the arrival in Reykjavik (steps 1 and 2) (Fig. 4b). Exposure of the pallets to un-chilled conditions for over 10 hours (step 3) caused a sharp increase of product temperature in the top and bottom corner boxes of pallet 1 and in the bottom corner box of pallet 2 (Fig. 4b). It is clear from Fig. 4b that the top corner box of pallet 1 (P1_T_) was more affected than the bottom one (P1_B_), especially from step 3 onward. The temperature in the middle box of pallet 1 (P1_M_Mean) was more resistant to change compared to those in the top and bottom boxes. This result is comparable with the one found during the mapping in September 2007, and with the results reported elsewhere (Moureh *et al.* 2002). Since the central boxes are better insulated to the ambient air, ambient temperature change affects them to a smaller degree than the other boxes.

Figure 4c shows the evolution of temperature range between different heights (top, middle and bottom) of product inside each box. The ranges in the first two steps of the boxes on pallet 2 were much higher than on pallet 1. It can be explained by 2 reasons. Firstly, it is because the top of boxes on pallet 2 had lower initial temperature (1.0 to 2.9 °C) than on pallet 1 (3.3 to 4.2 °C) (see Fig. 9). Meanwhile, the deeper layers of product inside boxes on pallet 2 had higher initial temperature (4.3 to 5.3 °C) than on pallet 1 (3.7 to 4.3 °C) (see Fig. 9). It is very likely that the boxes of pallet 2 were packed earlier (with the ice mats on top) than those of pallet 1. Secondly, higher ambient temperature of pallet 2 during steps 1 and 2 (Fig. 4a) caused slower cooling process for the product on pallet 2. The temperature behavior of the top corner box of pallet 2 (P2_T_Mean, Fig. 4b) showed that the top corner box was very sensitive to environmental changes, for example when the product was moved from a cold store (step 1) to a chilled store (step 2) and then to un-chilled conditions (step 3). Similar results were found in September 2007 and in other studies (Moureh and Derens 2000; Moureh *et al.* 2002). Colder environment temperature for pallet 1 during the first two step led to a faster product cooling (Fig. 4b) and depletion of the temperature range (Fig. 4c) over this time.

Large increase in ambient temperature of pallet 1 from step 1 to 3 and high fluctuation during steps 3 (Fig. 4a) led to an increase in variability of product temperature (temperature range) of the outer (B and T) boxes on this pallet in step 3 (Fig. 4c). It is understandable because the top product in a box is more sensitive to the environment change than the one in the middle or at the bottom due to higher thermal diffusivity of air relative to fish, causing the range of inside temperature become larger with higher degree of the ambient fluctuation.

The temperature inside the boxes at the beginning of the transportation was considerably high (up to 4.2 °C, Fig. 4b). A possible way to decrease the product temperature at this stage is to utilize some kind of pre-cooling methods, for example a CBC system or pre-cooling in liquid ice.

PCA loadings (Fig. 5) illustrate the correlation between the product temperature and the ambient temperature. PC1 explains 73% and PC2 explains 18% of the variance. The loadings of inside temperatures of the pallet 1 middle box, which was the most stable (see Fig. 4b), are located on the positive direction of PC1, oppositely to the loadings of ambient temperatures on the other side of this PC. The arrow shows the sensitivity trend of inside temperature, depending on the locations inside a box and box positions on a pallet, toward ambient changes. The loadings of temperature on top of product in boxes on pallet 2 (P2_T_t, P2_B_t, and P2_M_t), which were more sensitive to change compared to other locations, are located closer to variables “ambient”. It is because the top loggers were placed on the top of the fish in the boxes, and were influenced not only by the product surface temperature, but also by the air headspace condition, which was very sensitive to the outside temperature.

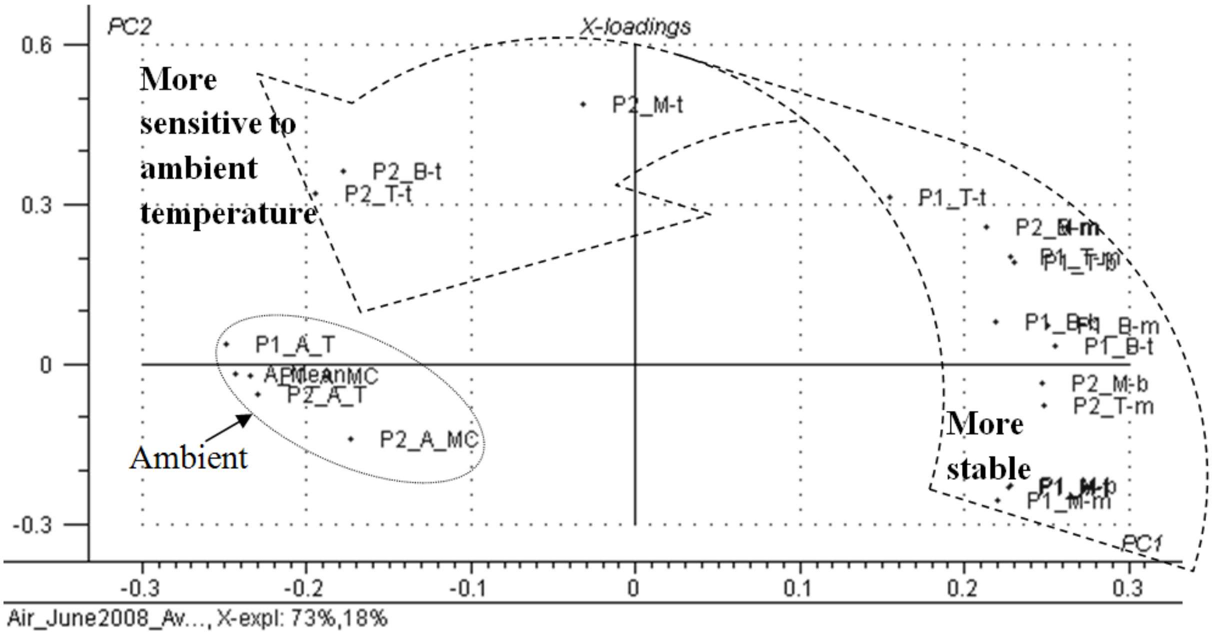


FIG. 5. PRINCIPAL COMPONENT ANALYSIS LOADING PLOT BASED ON THE AVERAGE WITHIN-STEP TEMPERATURE OF PRODUCT AND BOX SURFACE DURING AIR CARGO STUDY IN JUNE 2008.

The dash curved arrow shows the affecting trend of product positions to its temperature. The dotted ellipse groups the loadings of ambient temperatures on the box surfaces.

It could be seen that the results were comparable to the measurements in September 2007. The overall temperature of the product was noticeably higher in this measurement than in 2007 although the ambient air temperature was very similar. A probable explanation is that the pre-cooling period, which the product went through in the frozen storage room at the processor in Dalvik, was longer during the measurements in 2007 than in the 2008 trials. The set point temperature in the truck during transportation from Dalvik to Reykjavik was -20 °C in the measurements of 2007 but 0 °C in 2008. This resulted in better pre-cooling of the product, which was greatly needed, since the product temperature before packing was approximately 5 °C.

These measurements confirm that there are certain critical points which can be improved regarding the temperature control in the supply chain from Iceland to the UK. Cooling the product below 0 °C without freezing it is important to ensure the highest quality of the fresh product and to make the product less sensitive to temperature fluctuations during transportation and storage.

Air transportation (passenger flight) in July 2008

The mapping results for the ambient temperature in July 2008 (Fig. 6a) shows that boxes have undergone long temperature abuse from leaving the processor store to the storage at the destination airport (step 2 to 4), which lasted for 29.5 hours. This made 46.6% of the total logistics time, which was much longer than in the air cargoes in September 2007 and June 2008. The results agree with the fact that air transportation of perishable food faces such un-refrigerated temperature problem for much of its voyage (James and others, 2006).

From Fig. 6a and b it can be seen that small fluctuation of outside temperature in step 1 led to small variability (small range) of temperature inside the boxes. In contrast, high fluctuation of ambient temperature in other steps (steps 2 to 4) caused a very large variability of inside temperature, especially for boxes with many free sides such as bottom and top corner boxes. This result is comparable with the results found for the air freight in June 2008.

The temperature mapping results have shown that the product in the bottom corner box of the pallet was the one most influenced by the ambient, especially by high temperature fluctuation during steps 2 (transportation to the airport and storage at the airport before taking off) and 4 (storage at the airport after landing). This was well indicated by the fact that the temperature range between the center and the bottom of the product was large (up to 1.1 °C) during these steps, and the product temperature at end of the studied links was extremely high (4.6 °C at the secondary processor). The product in the top corner box was the second most affected by the environment, particularly with long temperature abuse from step 2 to step 4, causing large temperature range (0.7 °C) during this time and high end temperature (1.6 °C at the secondary processor). These facts point out that steps 2, 3, and 4 (that is, transportation and storage before taking off, during the flight, and storage at the destination airport, respectively), where the temperature was not well controlled, are the hazardous ones in the chain. It should be noticed that in this case study, the plane was a passenger aircraft and not a dedicated freight transport plane, resulting in a need to break the pallet up for loading the individual boxes in the plane hold before taking off. As apparent from Fig. 6a the ambient temperatures between boxes became clearly distinguished some hours before the taking off.

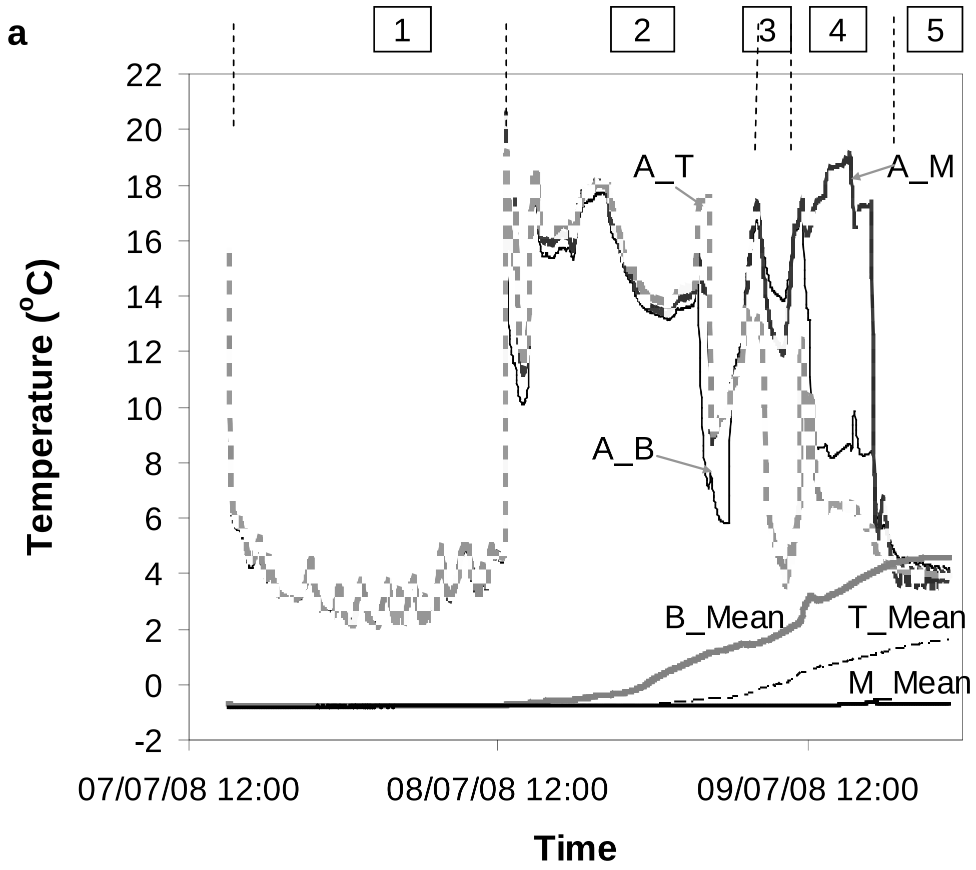


FIG. 6. AMBIENT AND AVERAGE PRODUCT TEMPERATURE (a), TEMPERATURE RANGE INSIDE THE BOXES (b), AND TEMPERATURE IN THE MIDDLE BOX (c) DURING PASSENGER AIR FREIGHT STUDY IN JULY 2008.

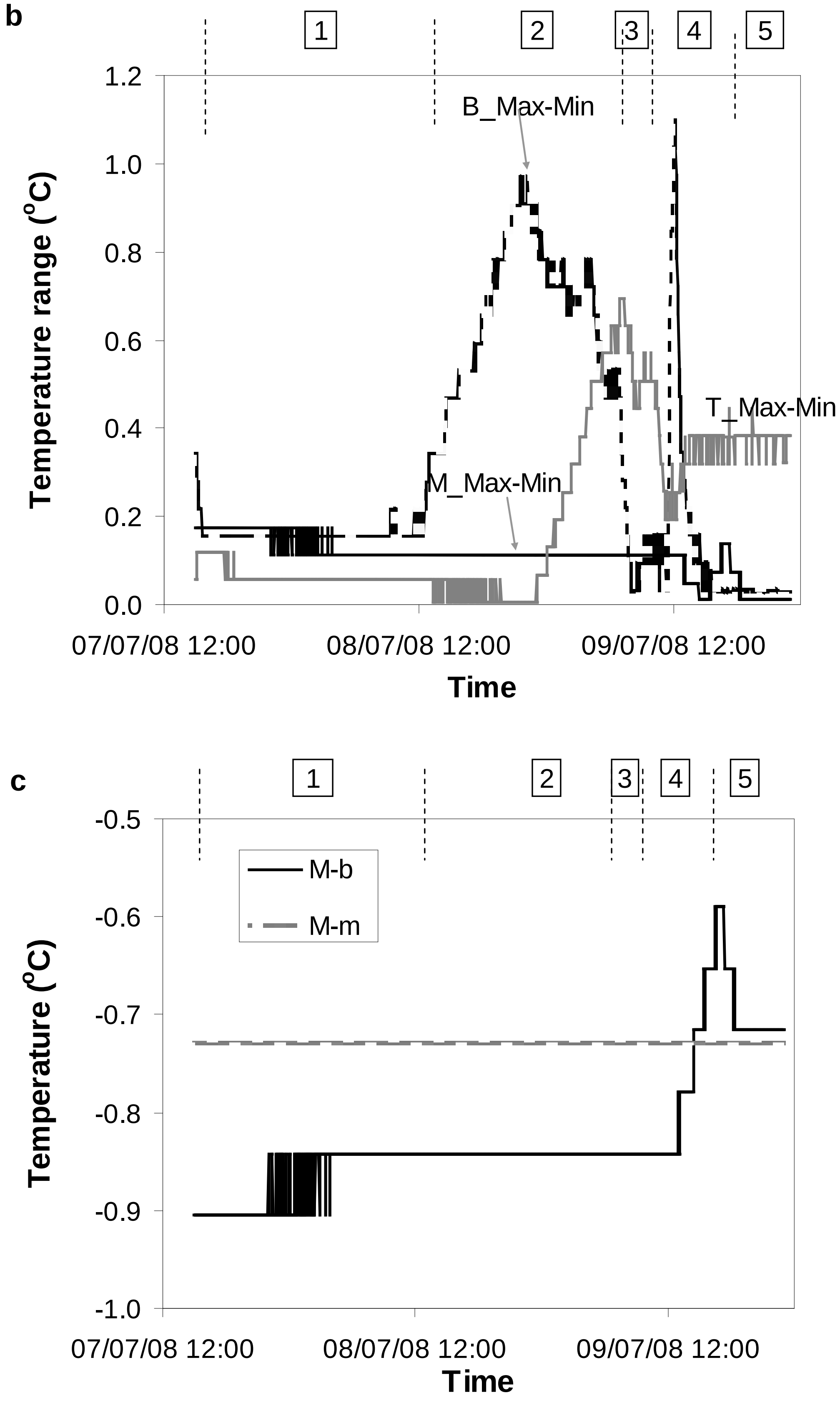


FIG. 6. *CONTINUED.*

The product temperature in the middle box was stable throughout the chain with relatively small temperature range between the product locations (< 0.2 °C, Fig. 6b) and with low final temperature (-0.7 °C, Fig. 6c). Interestingly, the temperature in the center of the product in this box remained constant (at -0.70 °C) in all the steps (Fig. 6c). Therefore, despite the lack of information on how the pallet was split and where the boxes have been placed afterward, it is reasonable to speculate that the middle box has been kept surrounded by other boxes all the time. This is based on the other two air cargo studies in September 2007 and June 2008, and on the results of other researchers (Moureh and Derens 2000; Moureh *et al.* 2002) that the temperature inside middle boxes is least voluntary to change. Because of high fluctuation in the ambient temperature of the middle box after the pallet break-up (see line A_M in Fig. 6a), it is also speculated that the side with ambient logger of this box has been exposed to the environment during this time.

The temperature in the center of product in the middle box was much more stable (actually kept constant) compared to that of the two previous air freights. This may be explained by the fact that the EPS boxes in this case were of 12 kg product, much larger compared to the other freight boxes (of 3 kg product). The center product of the middle box in this flight was therefore very well insulated by the surrounding fillets. It is also because the initial temperature in this case was -0.7 °C (fillets partially frozen thanks to the CBC pre-cooling), much lower than in the 2 freighter aircraft flights (3.8 to 4.6 °C, with no pre-cooling) (Fig. 9).

The difference in the end temperatures of products from different locations on a pallet again supports the statement above that the products should be grouped by the positions and handled in an appropriate way. The more abused products should be used earlier.

Sea transportation September 18th – 23rd 2008

The results of the temperature mapping showed that the box was kept at low and stable temperature (-0.2 ± 0.5) for the whole trip of 4.8 days (Table 1). Starting with relatively high ambient temperature (around 9.3 °C), the surface of the middle box was cooled down below 0 °C after about 3 hours of containerization (results not shown).

Sea transportation September 23rd – 29th 2008

Figure 7 shows that the surface temperature on the middle box (A_M) has decreased very fast, reaching a minimum temperature of -18.1 °C after about 3.3 hours of the cold storage at the producer (step 1). Meanwhile, the top corner (A_T) and the bottom corner (A_B) boxes of the pallet gained their coolest points at -13.5 and -10.3 °C, respectively, at later time of this step. This indicates that the middle height box was located closer to the air blast refrigeration unit than the other 2 boxes during step 1. During step 3 (partly-chilled hold in Reykjavik), the surface temperature of the boxes sharply increased due to the turning off of the cooling equipment. In step 4 when the cooling equipment inside the container was functioning, the temperatures of all boxes became stable, maintaining below 0 °C most of the time until the destination.

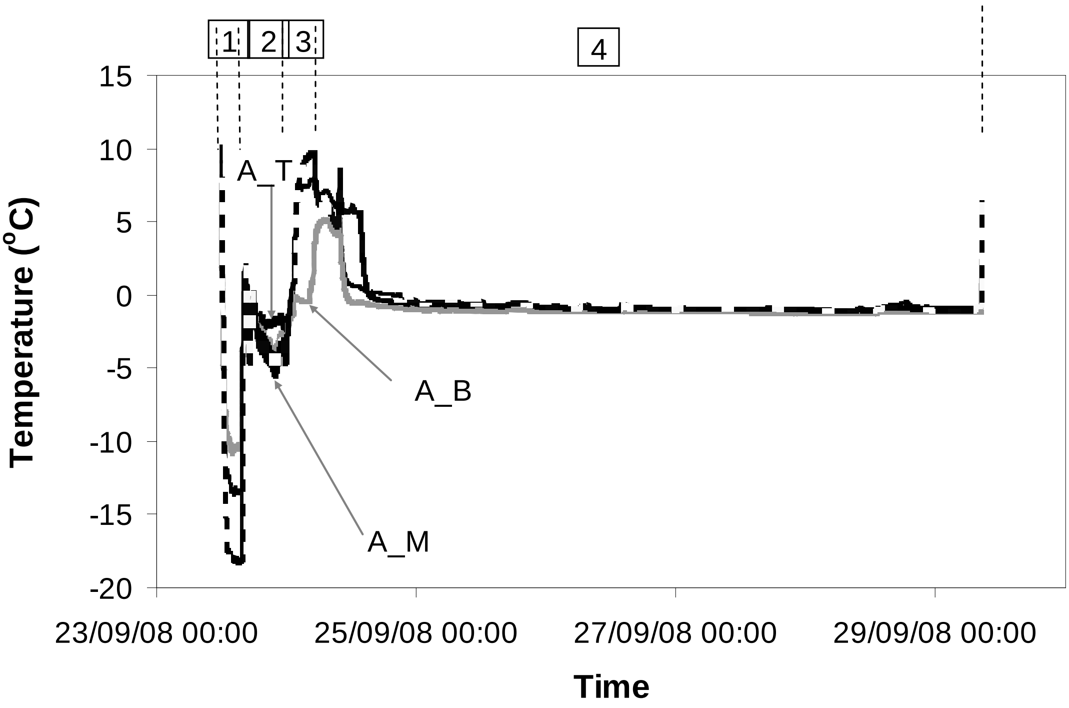


FIG. 7. SURFACE TEMPERATURE OF THE TOP CORNER (A_T), MIDDLE (A_M), AND BOTTOM CORNER (A_B) BOXES ON THE PALLET DURING THE SEA TRANSPORTATION STUDY ON SEPTEMBER 23RD – 29TH 2008.

Sea transportation September 24th – October 1st 2008

Figure 8a indicates that the temperature of product inside the boxes were very stable compared to the air transportation. It is because in the sea freight chain, the boxes were kept in a refrigerated container for the whole trip from processor to the final destination. The temperature difference between the locations inside a box was also small (≤ 0.2 °C most of the time) (Fig. 8b) because the fish was cooled during processing (by liquid and CBC cooling before skinning) and then put with ice on top of the fillets when packed into the EPS boxes. Despite the initial temperature difference of product between inside positions and between box locations on the pallet (see Fig. 9), all the inside temperatures dropped below 0 °C very soon after 2 hours of containerization (Fig. 8a). The temperature was then maintained stable between -0.9 and 0 °C for the remaining logistics process. This makes a clear distinction between sea and air transportations: in the latter case there are several critical steps where the product is subjected to temperature abuse.

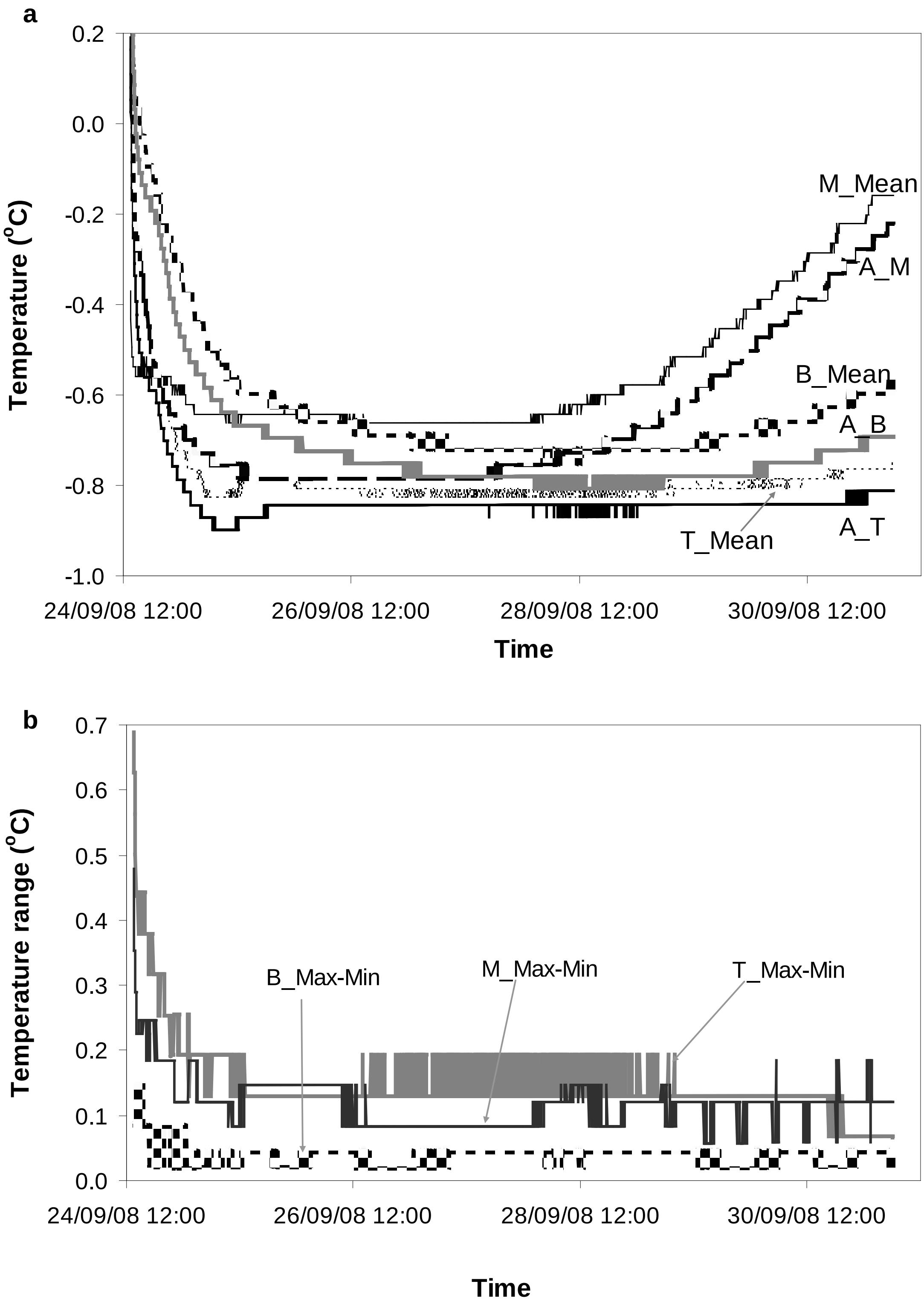


FIG. 8. TEMPERATURE INSIDE AND OUTSIDE (a) AND TEMPERATURE RANGE INSIDE (b) THE BOXES DURING SEA TRANSPORTATION SEPTEMBER 24TH – OCTOBER 1ST 2008.

The inside and outside temperatures of each box behave similarly. This can be seen from Fig. 8a where the temperature curves of each box are closer to each other than to the curves of other boxes. For long period (more than two days), the temperatures inside and outside the bottom corner box were higher than those at the top corner and in the middle of the pallet. The surface temperature of the bottom box reach 0 °C just after 1 hour of operation whereas it took only about 20 minutes for the top corner box to be cooled down to this temperature. The temperature inside the top corner box of the pallet was the fastest to change. This is comparable with the results from the air chains above and from other studies (Moureh and Derens 2000; Moureh *et al.* 2002) that the top corner box is very sensitive to the environment conditions.

Comparison between the freights

Initial temperature inside and outside the boxes

Figure 9 shows that normally the initial temperature of product in a box, or on a pallet is not even. Due to the insulation of the package and surrounding boxes, the product is very difficult to be cooled down after being packed. A good solution would be to use some superchilling technique, for example a CBC system or slurry ice, to chill the product before packing. In the experiments in July 2008 (passenger flight) and September 2008 (shipping), product was pre-chilled by CBC cooling, therefore its initial temperature (-0.6 to 0.6 °C) was much lower than in the other 2 air freights where the initial temperature was as high as 5.5 °C.

In most cases, the initial temperature on top of product is the lowest, and the one at the bottom is the highest. It is understandable because either ice mats (in September 2007 and June 2008) or ice (in September 2008) were placed on top of the product when packaged into boxes. There are some exceptional cases, such as the bottom corner box (B) of pallet 1 in September 2007 and top corner (TC) box of pallet 1 in June 2008, where the highest temperature was on the top of product. It may be because these products have been exposed to un-chilled conditions for rather long time before the ice mats were put on top and the temperature recording started.

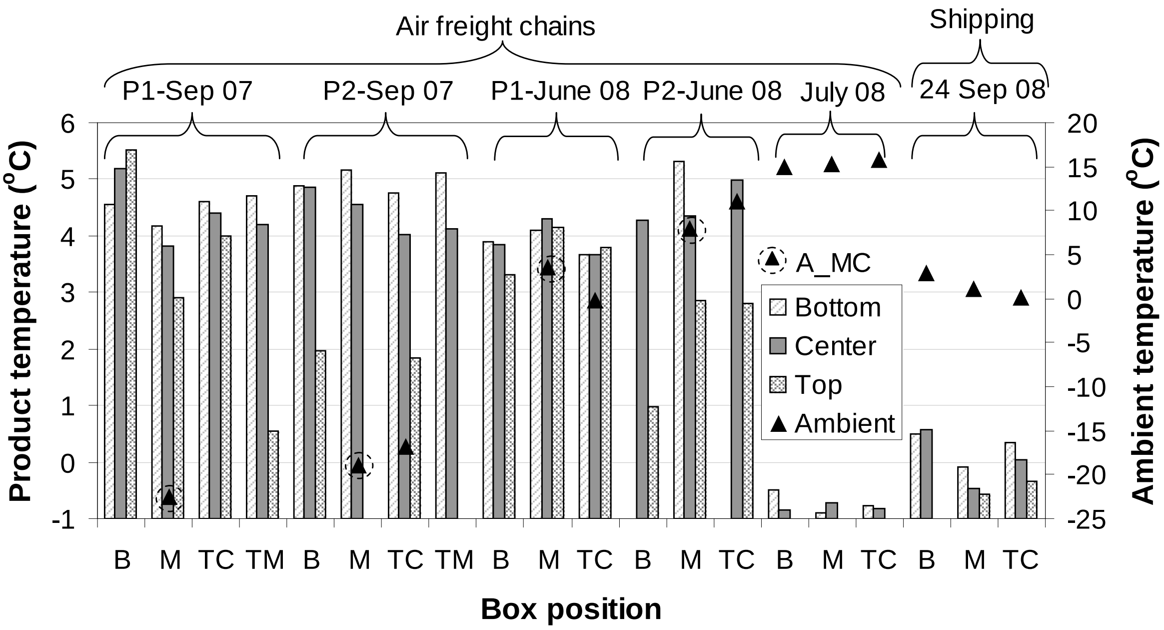


FIG. 9. INITIAL TEMPERATURE AT DIFFERENT POSITIONS INSIDE AND ON THE SURFACE OF BOXES PLACED AT THE BOTTOM CORNER (B), MIDDLE (M), TOP CORNER (TC), AND TOP CENTER (TM) OF EACH PALLET (P1: PALLET 1, P2: PALLET 2); AMBIENT TEMPERATURE ON THE SIDE OF PALLETS IS SHOWN AS A_MC.

Ambient temperature of the freights

The mean and standard deviation of box surface temperature in each step of the trips and in each trip are shown in Table 1.

A clear distinction between the surface temperature of sea and air freights was observed. The temperature in sea transportation was well below 0 °C and with smaller deviation whereas in the air trips it was much higher and with larger variation. The passenger flight yielded the highest average temperature on the boxes; this is because they became more exposed to the surrounding after the pallet splitting. Furthermore, the difference in surface temperature between pallets 1 and 2 as previously mentioned can also be clearly observed in this table.

Statistical test results regarding the effect of different factors on the temperature

The statistical test results shown in Table 2 indicate that the null hypothesis, i.e. that product locations, box positions, and chain steps have no influence on the temperature of product and box surface, is rejected. The average product temperatures over the whole logistics period at different locations inside each of the boxes, except for the top corner box of pallet 1 (P1_T) in June 2008, are significantly different ($p < 0.001$). For box P1_T in June 2008, only top temperature is different (p < 0.001) from the other parts in the box (see rows “Location”). The difference in product temperatures between the inside box positions is not the same for all the steps in the 3 air freights (p < 0.001 for all the studied boxes of the air freights, see rows “Location*Step”). The average product temperature inside each box is significantly different between the steps in the 3 air freights (p < 0.001 for all the studies boxes of the air freights, see rows “Step”).

TABLE 2. STATISTICAL TEST RESULTS FOR THE EFFECT OF PRODUCT LOCATIONS INSIDE A BOX, BOX POSITIONS ON A PALLET, AND LOGISTICS STEPS ON THE PRODUCT AND BOX SURFACE TEMPERATURES

Freight			**P1_TM**	**P1_TC**	**P1_B**	**P1_M**	**P2_TM**	**P2_TC**	**P2_B**	**P2_M**	**Inside Mean**	**A**
Air_ Sep 2007	Location	F	617.3	87.4	1222.6	13506.3	4067.8	1921.9	52.4	25021.8	4796.7	12.5
		df	1.0	1.1	1.2	1.3	1.0	1.1	1.1	1.0	3.1	1.8
			1476.1	1567.7	1690.9	1870.2	1422.0	1508.1	1538.5	1422.0	4408.0	2517.8
		p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
		Difference[a]	t, m, b	t, m, b	t, m, b	t, m, b	m, b	t, m, b	t, m, b	m, b	All 8 boxes	P2_A_T
	Location * Step	F	516.5	1096.1	1434.6	1963.7	1184.3	580.3	176.9	3102.7	1759.7	332.8
		df	11.4	12.1	13.1	14.5	11.0	11.7	11.9	11.0	34.1	19.5
		p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Step	F	698.1	858.8	1290.9	3044.4	1178.1	879.5	221.3	2134.4	829.0	1275.5
		df	11	11	11	11	11	11	11	11	11	11
		p	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Air_ June 2008	Location	F		140.9	462.5	334.0		370.5	598.2	875.4	839.8	103.5
		df		1.1	1.3	1.9		1.0	1.0	1.1	2.2	2.6
				248.8	304.0	451.8		235.0	235.0	262.0	520.6	607.1
		p		< 0.001	< 0.001	< 0.001		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
		Difference[a]		t	b, m, t	b, m, t		m, t	m, t	b, m, t	All 6 boxes	P1_A_T, P1_A_MC
	Location * Step	F		148.7	79.8	108.4		236.1	317.7	181.1	283.6	159.4
		df		6.4	7.8	11.5		6.0	6.0	6.7	13.3	15.5
		p		< 0.001	< 0.001	< 0.001		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Step	F		47.1	56.3	368.2		79.4	414.6	58.6	59.8	148.2
		df		6	6	6		6	6	6	6	6
		p		< 0.001	< 0.001	< 0.001		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Air_ July 2008	Location	F		3277.4	1417.2	3558.4					25286.0	1928.0
		df		1.0	1.0	1.0					1.0	1.9
				1676.0	1676.0	1676.0					1738.3	3179.7
		p		< 0.001	< 0.001	< 0.001					< 0.001	< 0.001
		Difference[a]		b, m	b, m	b, m					All 3 boxes	A_B, A_M, A_T
	Location * Step	F		688.3	1162.0	879.5					5118.6	1150.4
		df		4.0	4.0	4.0					4.1	7.6
		p		< 0.001	< 0.001	< 0.001					< 0.001	< 0.001
	Step	F		13997.1	5726.1	879.5					7494.5	2652.8
		df		4	4	4					4	4
		p		< 0.001	< 0.001	< 0.001					< 0.001	< 0.001
Sea_ Sep 24th 2008	Location	F		6878.3	350.6	3592.2					2153.1	6592.3
		df		1.5	1.0	1.3					1.2	1.5
				2939.5	1927.0	2431.9					2353.7	14068.0
		p		< 0.001	< 0.001	< 0.001					< 0.001	< 0.001
		Difference[a]		b, m, t	b, m	b, m, t					All 3 boxes	A_B, A_M, A_T

[a] Location(s) where the mean temperatures is/are significantly different

The inside-box product mean temperatures (named as inside mean) over the whole logistics are significantly different between the boxes of a trip ($p < 0.001$ for all the boxes, see rows “Location” – column “Inside Mean”), meaning that the product temperature depends on the locations of boxes during the logistics. The difference in inside mean temperature between the box locations is not the same for all the steps in the 3 air freights ($p < 0.001$ for all the boxes of the air freights, see rows “Location*Step” – column “Inside Mean”). The average of inside mean temperatures of all the boxes in a trip is significantly different between the steps ($p < 0.001$ for all the 3 air freights, see rows “Step” – column “Inside Mean”).

The average ambient temperatures (measured on the box surfaces) are different between the box locations on a pallet ($p < 0.001$ for all the 4 above freights, see rows “Location” – column “A”). For example, for the air trip in September 2007, the temperature on top of pallet 2 (P2_A_T) differs significantly from the temperatures measured on the sides of pallets 1 ($p < 0.001$, not shown in Table 2) and 2 ($p < 0.001$, not shown in Table 2). The difference in ambient temperatures between the box locations is not the same for all the steps ($p < 0.001$ for all the 3 air freights, see rows “Location*Step” – column “A”). The average ambient temperature from all the surface loggers of each trip is significantly different between the steps ($p < 0.001$ for all the 3 air freights, see rows “Step” – column “A”).

Predicted remaining shelf life of the product from different freights

Figure 10 gives an overview on all the 3 air and 1 sea trips regarding total used time, predicted RSL, and (average) temperatures of product and box surface. Of the three air freights, the September 2007 batch had the longest logistics. The product in June 2008 had the highest average temperature, but the shortest used time (less than 5 days). The July 2008 trip has undergone the most severe abuse by outside temperature, but with relatively low average product temperature. The sea trip during September 24th – October 1st 2008 took the longest time, but was the best regarding temperature control. The temperatures of both environment and product therein were the lowest (below 0 °C).

Although the product in the sea trip was kept at a very low and stable temperature, it has traveled for a long time, taking almost 7 days (or 10 total used days from catch). That explains why it has the shortest predicted RSL of less than 5 days. The short RSL of the sea freight verifies the fact that the quality of perishable product decreases apparently with time even under optimal conditions (Pawsey 1995).

The air September 2007 samples have the second shortest predicted RSL. It is because the trip was quite long (almost 4 days, total used time around 7 days) and the initial product temperature was high (up to 5.5 °C, see Fig. 9). This reveals the importance of pre-cooling the product before packing. It has also been reported by others (James *et al.* 2006) that pre-cooling products before transportation is essential. The air June 2008 samples have relatively long RSL due to short logistics (1.7 days).

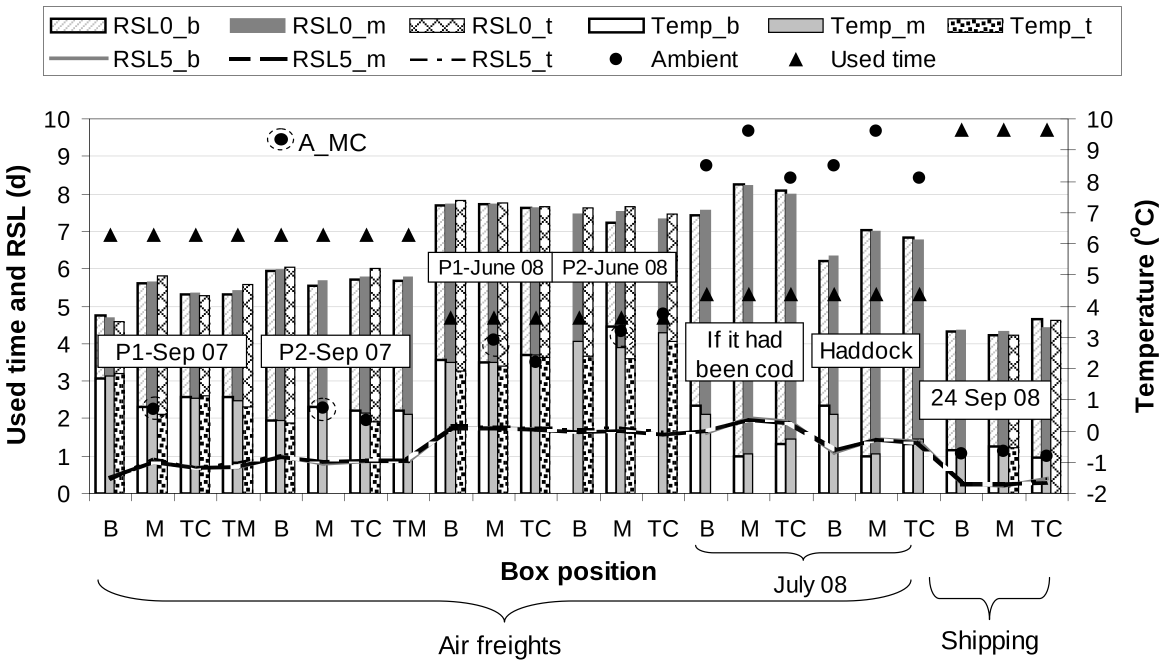


FIG. 10. TOTAL USED TIME FROM CATCH AND PREDICTED RSL OF PRODUCT AT 0 °C (RSL0) AND 5 °C (RSL5).

The average ambient and product temperatures over the whole logistics from different pallets (P1, P2), box positions on a pallet (B, M, TC, and TM), and locations inside a box (b, m, and t) are also shown. A_MC means the temperature on the side of a pallet. The 3 lines of predicted RSL at 5 °C (RSL5_b, _m, and _t) are almost identical on the graph.

The air July 2008 product also has long RSL because its temperature was relatively low. This once again indicates how important the pre-cooling is. The product of this set was cooled in a CBC cooler before packing into EPS boxes.

Difference in the predicted RSL between product and box locations and between pallets of the same trips indicates that the samples have different temperature evolutions.

It should be mentioned that the end product temperature of many measurements was considerably high, 2.2 – 3.3 °C and some up to 4.6 °C (that is, higher than rejection limit upon reception at most retailers which is 4 °C). The product was then kept in retailer and home refrigerators where it could hardly be chilled down to 0 °C. This is because the temperature in retail cabinets and household refrigerators is usually high (Laguerre *et al.* 2002; Kennedy *et al.* 2005), for example average 6.6 °C in home refrigerators in France (Laguerre *et al.* 2002).

These may dramatically reduce the shelf life of the fish. This can clearly be seen from Fig. 10 when comparing the predicted RSL of the same product location at temperatures 0 and 5 °C. For example, for the product in the top corner box (TC) of pallet 2 in the June 2008 study, the RSL is more likely below 2 days at 5 °C, instead of around 7.5 days at 0 °C, because the product temperature in this box at the logistics end was considerably high (about 3 °C, see Fig. 4b). Another example is the product in the bottom corner box (B) in July 2008; the RSL of haddock is very likely below 1.5 days at 5 °C, rather than above 6 days at 0 °C since the final temperature was very high (4.6 °C, see Fig. 6a).

The PCA bi-plot (Fig. 11) shows the ability to discriminate between the products of different trips based on the time - temperature history. A total of 89% of the variance is explained by the first two PC, 60% by PC1 and 29% by PC2. The right hand side of PC1 represents the total used time of the logistics. Samples located more to the positive part of PC1 and closer to the variable "UsedTime", for example the product from the sea trip in September – October 2008, has undergone longer logistics time. The lower left quarter of the plot represents the RSL, samples placed to the left of PC1 and closer to variable "RSL", for example the product from the air trip in July 2008, have longer RSL.

For the air trip in September 2007, the product in the bottom corner box (Sep07_P1_B_) had high initial temperature (4.5 to 5.5 °C, Fig. 9), located close to the variable "Initial_Temp" on the positive direction of PC2 (Fig. 11). The product of this box has been more exposed to high ambient temperature, the samples Sep07_P1_B_t; Sep07_P1_B_m; and Sep07_P1_B_b located more toward the variables "Final_Temp" and "Average_Temp" compared to other samples in the cluster "Sep 2007" (Fig. 11). This statement can be verified by the product temperature of this box against others: the average temperature was 1.7 to 1.8 °C against 0.3 to 1.1 °C of other boxes in this trip (Fig. 10), and the final temperature was 2.6 °C in contrast to 0.2 to 1.8 °C in other boxes (Fig. 2b). Thus the product of this bottom corner box has shorter RSL than of others (4.6 to 4.7 days versus 5.2 to 6.0 days, Fig. 10).

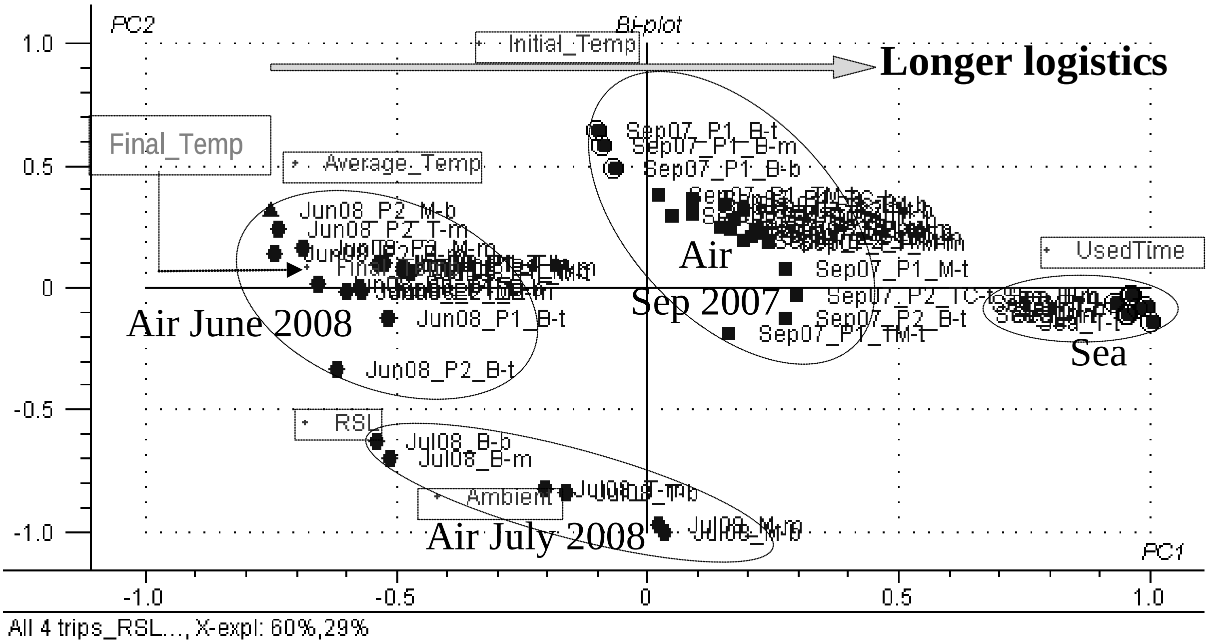


FIG. 11. PRINCIPAL COMPONENT ANALYSIS BI-PLOT BASED ON ALL THE TEMPERATURE MEASUREMENTS AND PREDICTED RSL FROM 3 AIR AND 1 SEA SHIPMENTS FOR COD LOINS

Sample scores are labeled with time or transport mode of the trip_(pallet number)_box position_product location. Loadings of variables RSL; total used time (UsedTime); average ambient temperature (Ambient); initial (Initital_Temp), final (Final_Temp), and average within product location (Average_Temp) temperatures are shown in rectangular. Dotted ellipses group the samples of the same trips. The same symbol of the samples shows similarity in RSL: the circles indicate a group of samples with the RSL of 4.2 – 4.7 days; the squares for group with RSL of 5.2 – 6.0 days; the triangle with RSL of 7.2 days; and the hexagons for the RSL of 7.3 – 8.3 days at 0 °C.

The July 2008 trip samples have undergone most ambient temperature fluctuations, located very close to the variable “Ambient”. Furthermore, samples of different box positions are differed on the bi-plot relatively to this variable, meaning that they were exposed to very different ambient conditions during the whole trip (see also Fig. 6a). This interesting point has already been discussed above, considering the fact that the pallet was broken up in this passenger flight.

Overall, the predicted RSL and PCA results (Fig. 10 and 11) support the need to continuously monitor time and temperature history of product (Giannakourou *et al.* 2005). Long exposure to high temperature also facilitates the pathogens to growth (Raab *et al.* 2008) which causes food safety problems. To better manage the fish quality and safety, it is useful to apply some technique such as temperature loggers, time temperature indicator (TTI) labels, radio frequency identification (RFID) tags with the temperature sensor and time recorder, and so forth on or inside the packaged product. Heat transfer modeling of individual and palletized EPS boxes containing fresh fish, similar to the modeling of frozen fish pallets by Moureh and Derens (2000) and Moureh *et al.* (2002), would be useful to predict product temperatures under dynamic ambient conditions as described in the current study. The models could even be used for improving packaging design in order to decrease the negative effect of ambient temperature fluctuations on product temperature.

Furthermore, trade-off between modes of transportation should be made based on: the quality and safety perspective regarding time – temperature history, customer requirement on delivery time, economic efficiency related to cost of transport, cost of more efficient packaging, and weighed against the resulting overall environmental impacts.

Air transportation is quick, but with several hazardous steps during ground and flight operations regarding temperature abuse. Pre-cooling the product before packing shows to be necessary to minimize the negative effect of abusive temperature, especially during passenger flights where boxes are more exposed to the environment due to the splitting up of pallets. Freighter aircraft flights are more fuel efficient than passenger flights, but affected more by fuel prices than passenger aircraft operators since their fuel cost is a much larger part of total expenses (Morrell 2008).

Sea transportation is considered as a cheaper but slower mean of transport. The product temperature is well-controlled during the whole logistics inside refrigerated containers. While air transport has several strong, but short lasting, effects on the global temperature, shipping emissions have a cooling effect on climate that lasts 30-70 years due to very high emissions of SO_2 and NO_x, but with dominating warming effect in the long term because of significant amounts of CO_2 emitted (CICERO 2008).

CONCLUSION

Abusive temperature during air freighting causes fluctuation and/or rise of product temperature inside boxes, especially in those with more free sides such as at top corner of the pallets. The more temperature around the boxes fluctuates, the larger the temperature range inside the packaged product becomes. Temperature on top of product inside the EPS boxes is more sensitive to environment changes than those deeper in the box. Thus, grouping products according to their positions during transportation is useful for further management of the resource.

There are several critical steps found in air freighting, especially in passenger flight, including the flight itself, loading/unloading operations, and holding storage at un-chilled conditions.

This reveals the importance of pre-cooling product before packing. Temperature during sea transportation in refrigerated containers is well maintained at low temperature. However, long shipment time causes a relatively short remaining shelf life of product in sea freight. This indicates that the trade-off between transportation modes would need to be based on several aspects such as quality and safety, available time to reach market, as well as differential costing of transport (air versus ship), and the resulting environmental impact for the different options.

NOMENCLATURE

P	Pallet
A	Ambient (box surface)
T or TC	Top corner box of a pallet
TM	Top center (top middle) box of a pallet
MC	Middle side box: box at the middle of a pallet side
M	Middle box: box in the middle of a pallet
B	Bottom corner box of a pallet
t	Top of product inside a box
m	Middle of product inside a box
b	Bottom of product inside a box
Mean	Average, e.g. temperature average
Max	Maximum
Min	Minimum
Max-Min	Range, e.g. temperature range
RSL	Remaining shelf life
PCA	Principal component analysis
EPS	Expanded polystyrene

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PAPER IV

Temperature controlled transportation alternatives for fresh fish – air or sea?

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IV

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Temperature controlled transportation alternatives for fresh fish – air or sea?

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ABSTRACT

Purpose of this paper

The importance of stable low temperature during the transportation of fresh fish is critical to ensure the quality of the products and thereby the remaining shelf life after delivery. In this study, processes in air and sea transportation are analysed and by using real life temperature measurements, the activities that contribute to temperature augments during transport operations are identified.

Design/methodology/approach

Building on a previous work on temperature measurements of fresh cod loins during long distance transportation, a full scale process mapping and analysis has been done to identify the processes that are included and are causing undesirable rise in temperature.

Findings

The major finding of this work is that air transportation results in serious temperature fluctuations due to loading, unloading, and waiting times compared to sea transportation using temperature controlled containers.

Practical implications

The practical implications of this work is that sea transportation using temperature controlled containers is a serious alternative for transportation of fresh fish, even if up to four days of transportation is added to the total transit time.

What is original/value of paper

The originality of the paper is that real life temperature measurements have been used to prove that more fluctuations are found in air transportation compared to sea transportation chains. In addition, the processes that cause the fluctuations are identified and analysed.

Keywords: Chilled food transportation, air transportation, sea transportation, temperature control, logistics

1. INTRODUCTION

Consumption of fresh fish has been growing worldwide (Vannuccini 2004; FAO 2009) and the importance of the transportation and logistics activities dealing with fresh fish has increased (Mai et al. 2010). The world production of fresh seafood has grown from around 30,000,000 tons in 1994 to around 50,000,000 tons in 2002 (Vannuccini 2004). The attention the transportation and logistics activities draw is not the least due to the fact that temperature is considered as the main factor that affects the safety and quality of perishable products such as fish. Abusive and/or fluctuating temperature accelerates rapid growth of pathogens and specific spoilage organisms (Jol et al. 2005; Raab et al. 2008), causing safety problems and economic losses. Fresh fish is often stored and transported at melting ice temperature (Pawsey 1995; ATP 2007) or even at super-chilled temperature (below 0 °C) (Olafsdottir et al. 2003) to maintain its safety and quality for a certain period. However, the fresh fish supply chains may face certain hazards when the desired/required conditions are not met.

Air freight is a very common mean of transport for perishable products such as fresh fish since this is the fastest transportation mode. However, during logistics operations such as loading, unloading, truck and air transportation, interim storage and holding the product is often subjected to temperature abuse and/or fluctuations (Brecht et al. 2003; Nunes et al. 2003), meaning that the products are un-protected during much of their journey (James et al. 2006). Even short time temperature abuse and/or fluctuations might cause severe damage to the products, leading to a significant reduction in the product shelf life, e.g. in a case of chilled modified atmosphere packaged Pacific hake (Simpson et al. 2003), or the rejection, e.g. of a whole strawberry load (Nunes et al. 2003).

Another mean of fresh fish transport is sea freight where the product temperature is well controlled in refrigerated containers during the whole voyage (Mai et al. 2010). This mode of transportation, however, consumes more time than air freighting, which may reduce the quality of perishables even at optimum conditions of handling (Pawsey 1995; Mai et al. 2010). The quality of the fish when delivered at customer site is directly related to its shelf life which is very important as it indicates the marketing life span left for the product.

The purpose of this work is to identify the logistics processes that contribute to most temperature increase within a supply chain of fresh fish, from producer to distributor, during a relatively long transportation period using two different transportation modes. To do so, the temperature changes of the surroundings were measured as well as the temperature of fresh cod loins themselves inside expanded polystyrene (EPS) boxes. Even though packaging with less environmental impact compared to EPS has been increasing its market share during the last decade, the majority of fresh fish products are still transported in EPS boxes. Thus, only using EPS should not be seen as a great limitation in the current study. The study was graphically limited to Iceland, UK and France since the studied supply chains only covered producers in Iceland to markets in the UK and France by air and sea freight transportation. This somewhat limits the ability to generalise about the logistic processes but should give a good view on both air and sea transport processes in Europe and areas with similar circumstances.

2. METHODOLOGY

The methodology used in this paper is divided into three different parts. First, a literature study was carried out to identify the most relevant contributions found in the major journals within the field of logistics, food science and refrigeration of fresh food. This was done using the following keywords: fresh/chilled/perishable food, fresh/chilled/fish, logistics, supply chain, cold chain, transport, transportation, shipping, air freight/freighting/transport/transportation, product temperature, temperature history, temperature abuse/fluctuation, temperature distribution, food quality, food safety, shelf life. Secondly, an activity and temperature mapping was done to find out the temperature fluctuations during the transportation process and the associated activities, and finally, an analysis of the associated processes was conducted to find out the major reasons for the temperature augmentation during the different logistics operations.

The temperature mappings were performed for two air freight transportation trips and two sea freight transportation trips of fresh fish supply chains from the processors in Iceland (IS) to the markets (distributors, retailers, or secondary processors) in the UK and France (FRA) during several time periods in September 2007, and June, July, and September 2008.

The studied products were in all instances fresh cod loins from a processing company in North of Iceland. The cod was caught east of Iceland. Onboard it was bled, gutted, washed and iced in insulated tubs. The fish was put in alternating ice layers with a fish to ice ratio of about 3:1. The raw material was hold in tubs in a ship refrigerator until landing approximately 2-4 days post catch. Onshore it was transported by un-refrigerated trucks to the processing plant which was a few hundred meters away from the harbour. The fish was processed the following day after a chilled storage overnight.

Fish for air shipment was headed, filleted, skinned, and cut into portions (approximate size: 26 x 5 x 2.3 cm, approximate weight: 0.32 kg). The cod loins were then immediately packed in EPS boxes (outer dimensions: 400 x 264 x 118 mm) containing about 3 kg of fish with 2 frozen gel mats (September 2007) or 1 gel mat (June 2008) of 125 g lying on top of the loins, and with a plastic film in between. The EPS boxes were stacked on Euro-pallets (120 x 80 cm) with 8 - 9 boxes in each row and 12 - 13 rows high, and then wrapped in a thin plastic sheet for protection.

For the products prepared for sea freight, the processing steps included heading, filleting, liquid cooling, Combined Blast and Contact (CBC) cooling, skinning and trimming. After processing, the cod loins of the same size as for air transport were immediately packed in EPS boxes (400 x 264 x 135 mm) which contained 5 kg of fish. The boxes were equipped with drainage holes at the bottom for draining the melting ice (about 0.3-0.5 kg) which was put on top of a thin plastic sheet above the loins. The boxes were palletized on Euro pallets with 9 boxes in each row and 12 rows on each pallet. A few layers of thin plastic film were wrapped around the palletized boxes before the containerization.

Each mapped box was equipped with 3 loggers inside (one at the bottom, one in the middle height of product, and another on top of product) and a logger on the box surface (top or side). This gave the actual temperature history of product at different position inside a box, as well as the actual temperature changes on the box surface.

DS1922L temperature loggers iButton® were used for recording the product temperature, with resolution: 0.0625 °C; accuracy: ± 0.5 °C and ± 1 min/wk; recording intervals 2-10 min. TBI32-20+50 Temp Data Loggers were used for measuring the box outside surface temperature, with resolution: 0.3 °C; accuracy: ± 0.4 °C and ± 1 min/wk; recording intervals 1-5 min. All loggers were calibrated in thick mixture of freshly crushed ice and water before use.

The final step of the research was then to look at the involved logistics activities and try to recognize what activities contribute to most increase in temperature and thereby affect the quality of the fish most.

3. RELEVANT LITERATURE

A literature study was carried out to identify the issues that are relevant to the field that is in focus in this work. The identified issues deal with fresh and chilled food, fresh food logistics, cold chain transportation, traceability and more.

Supply chains of fresh food do differ somewhat from traditional supply chains of ordinary goods to some extent. The requirement of monitoring the processes and tracing the activities is higher as stable, low temperature is necessary and lead times often need to be short, not allowing any delays. A traditional fish supply chain is shown in Figure 3.1, integrated from farm to fork with flows of materials, information and cash.

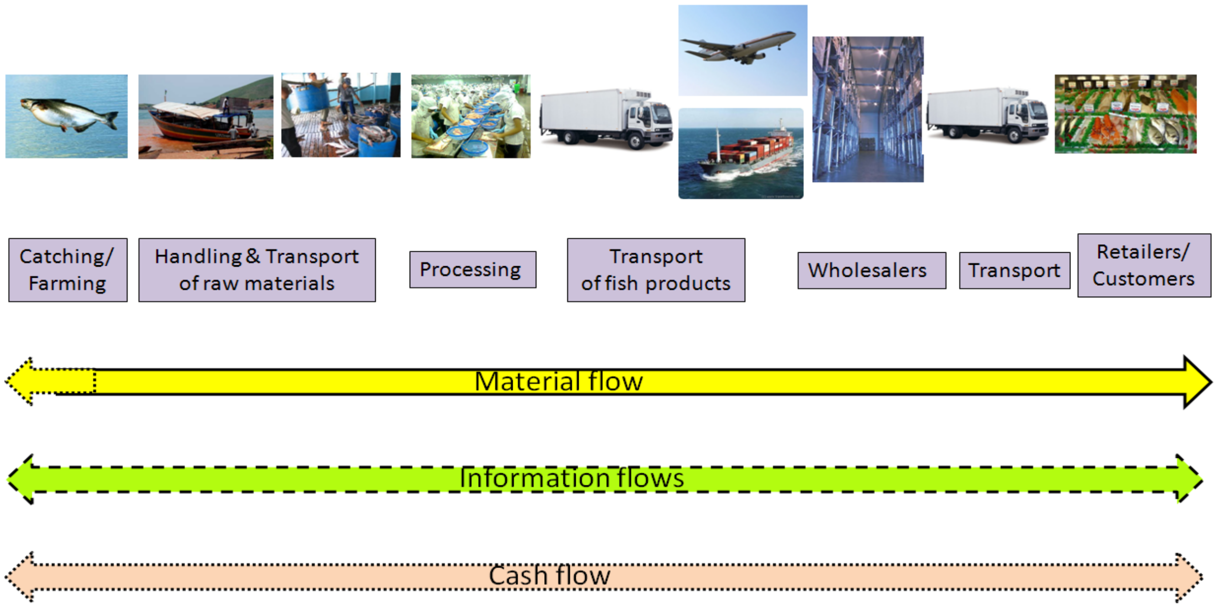

Figure 3.1. Integrated fish supply chain, (Adopted and modified from Coyle et al. 2003; EAN, 2002)

Material flows are in focus in logistics (Coyle et al. 2003), where quality of products delivered to the immediate and/or final customers is emphasized. Once a product does not meet the market requirements, standards or regulation, it can be rejected (Nunes et al. 2003), returned (Coyle et al. 2003) or even recalled in case of a food safety problem (Buhr 2003).

Information flow is considered vital in supply chain management (Coyle et al. 2003). It is a fundamental factor to enable product traceability, tracking and tracing the material flow and history. Logistics is a collection of functional activities that are repeated many times throughout the channel through which raw materials are converted into finished products (Ballou, 1999). The most dominant definition of logistics is given by the Council of Supply Chain Management Professionals (CSCMP) in 2010 as follows:

> *"Logistics management is that part of the supply chain management that plans, implements, and controls the efficient, effective forward and reverses flow and storage of goods, services, and related information between the point-of-origin to the point-of-consumption in order to meet customers' requirements…."*

This definition explicitly states that logistics management is a part of SCM and contains a variety of activities and related processes in different operations. Warehouse operation is an important part of logistics where products are stored at and between point of origin and point of consumption (Lambert et al., 1998). In addition to storage, there are two other major operations associated with warehousing: movement and information transfer (ibid.). Distribution Centers have a narrower role, including receive and ship as the main activities – while receive, store, ship, and pick are part of the warehouse activities. Terminals are facilities where load units are shifted between links in a transportation network. Examples of terminals are seaports, airports, crossing points of transport modes (e.g. between road and rail), and facilities specialized in fast throughput of load units which makes cross-docking possible. Examples of terminal activities are transshipments, coordination and cross-docking (Lumsden, 2006).

Different transportation modes have diverse characteristics such as length of transit time, cost, reliability and environmental impacts (Coyle et al. 2003). Air transportation takes shortest time and is most expensive. Operations related to air transportation can include steps that affect the products due to the fact that the products are often not containerized, especially in smaller passenger airline operation. Similar situation is with chilled products, the operations prior to air transit, such as warehouse or terminal operations, can include serious temperature abuses. Pre-cooling the product before packing shows to be necessary to minimize the negative effect of abusive temperature, especially during passenger flights where boxes are more exposed to the environment due to the splitting up of pallets. Sea transportation is less expensive but slower. However, products are often well protected as majority of consumer products are containerized in sea transportation (Lumsden, 2006).

Traceability is defined as "the ability to trace the history, application or location of that which is under consideration" (ISO 9000:2000 - Part 3.4.2); or ''the ability to trace and follow a 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 regulation No 178/2002, Article 3 (EC, 2002)).

Improving traceability can potentially reduce the costs to downstream actors (e.g. retailers or processors) of monitoring the activities of upstream steps (e.g. raw material supply) (Hobbs 2003). Good traceability in food supply chains has the potential to reduce risks and costs associated with food borne disease outbreak (ibid.), e.g. reduce their magnitude and possible health impact; reduce or avoid medical costs; reduce labour productivity losses; reduce safety costs arising from a widespread food borne illness (Can-Trace 2007). Reduction of costs associated with product recalls, e.g. reduced recall scope and time, is considered as another main economic incentive for implementing traceability (Can-Trace 2007; Golan *et al.* 2004).

In a recommended guide to good traceability practices (GTP) in the food industry (SINTEF 2007) traceable units can be trade units (TUs); logistic units (LUs); or production batches (raw materials' or ingredients' batches; and product batches). The production batches are considered an internal matter and do not need to have globally unique identifiers; while TUs and LUs are recommended to be assigned with GS1 (Global Solution) numbers (GS1 2009). Information related to history (e.g. temperature record, information related to production process), application (information related to property: weight, species, fat content, etc.) and location (distribution route) should be recorded and linked to a traceable unit. From the chain traceability perspective, it is required to record identifications (IDs) of supplier and transporter of received TUs (raw materials and/or ingredients) and ID's of buyer and transporter of dispatched TUs.

There are several studies about the effect of different factors in the cold chains on the temperature distribution and/or quality of food products such as fresh cut endive (Rediers et al. 2009), strawberry (Nunes et al. 2003), asparagus (Laurin 2001), chilled chicken breast (Raab et al. 2008), frozen fish (Moureh and Derens 2000), chilled gilt-head seabream (Giannakourou et al. 2005), to mention some. However, scientific publication on the temperature mapping and comparison for a real supply chain of fresh food from processing to market by air and sea transportation are scarce.

4. TEMPERATURE MEASURES AND LOGISTICS ACTIVITIES DISCUSSION

In this section, the results from the studies will be shown and discussed. The activities carried out during the two different transportations modes will be shown and different temperature mapping discussed and the major results analysed.

4.1. Air freight transportation

The first air freight transportation study was carried out in September 2007 and the second one in June 2008. The transportation studies will be discussed separately below.

4.1.1. Air freight transportation study in September 2007

The first air transportation study in September 2007 was done on cod loins caught east of Iceland and processed on board as described in the Methodology section above. The transportation was carried out in a dedicated freight airplane operation. Table 4.1 shows the logistics activities carried out during the air transportation study and the temperature measurements done. Two pallets were used for temperature measurements and the average temperature is shown.

Table 4.1 presents the outside surface temperature of the boxes at different positions on the two studied pallets. High fluctuation and several abuses of temperature were observed during loading/unloading processes (steps 4 and 10), interim storage at the airports and the wholesaler (steps 6, 9, and 10), and the flight (step 8). The pallets were exposed to un-chilled conditions (up to 15 °C) for more than 16.5 hours, accounting for about 17.4% of the total logistics time from processor to retailers. These led to a temperature increase of the product inside the boxes in steps 6-8 and high-end temperature of the product at the retailers as shown in Figure 4.1.

Table 4.1 List of logistics activities and temperature measures during the air freight transportation study in September 2007 (Source: adopted from Mai et al. 2010).

Step	Description	Duration	Ambient temperature of pallet 1 Mean ± STDEV (°C)	Ambient temperature of pallet 2 Mean ± STDEV (°C)
1	Frozen storage at producer after packing	6 h	-22.5 ± 3.3	-13.0 ± 9.6
2	Chilled storage at producer	2 h	2.3 ± 0.3	2.5 ± 0.5
3	Transportation from producer to Reykjavik (RVK, IS) in a refrigerated truck	8 h 20 min	-8.1 ± 3.5	-14.4 ± 5.9
4	Unloading and loading in a chilled truck in RVK	2 h	8.4 ± 1.1	8.7 ± 1.3
5	Transportation from RVK to Keflavik airport (KEF, IS) in a chilled truck	1 h 20 min	2.2 ± 0.7	1.3 ± 1.1
6	Un-chilled storage at KEF airport	5 h 20 min	13.3 ± 2.0	10.3 ± 3.0
7	Chilled storage at KEF airport	6 h	8.1 ± 5.3	0.5 ± 1.6
8	Flight from KEF to Humberside airport (HUY, UK) and un-chilled storage at HUY	6 h 15min	6.4 ± 4.8	11.7 ± 3.1
9	Storage at HUY and transportation to Carlisle (UK)	7 h 15 min	1.0 ± 0.4	-0.2 ± 0.6
10	Unloading/un-chilled storage at wholesaler in Carlisle	3 h	4.7 ± 2.7	3.6 ± 1.7
11	Storage in Carlisle	45 h 45 min	1.3 ± 1.0	1.7 ± 1.1
12	Distribution to retailers	2 h 12 min	3.0 ± 1.2	4.0 ± 1.2
Total	3.9 d at distributor; or 4 d at retailers		0.7 ± 8.0	0.5 ± 7.6

The initial product temperature inside boxes was considerably high (up to about 5 °C) (beginning of step 1, Fig. 4.1) and the time to chill the product to the average temperature below 2 °C was up to above 8 hours, despite the fact that the pallets were mostly facing ambient temperature around -20 °C. This is because the product is well insulated by the EPS boxes and their stack on pallet. This shows the possibility for the producer to improve the production, for instance, using pre-cooling (e.g. liquid cooling or other chilling method) to lower the product temperature before packaging.

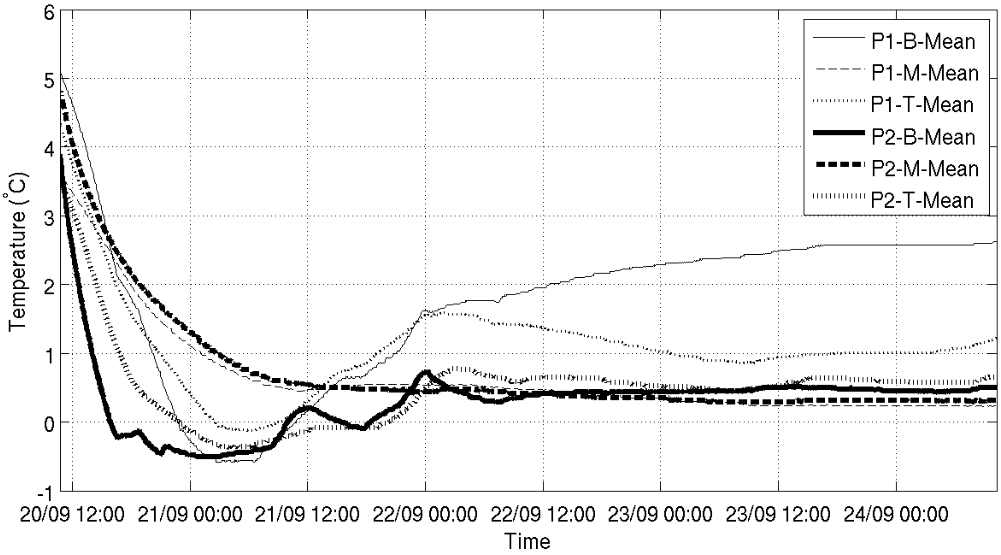

Figure 4.1 Average product temperatures during the air cargo study in September 2007. P stands for pallet; T indicates top corner box; B is bottom corner box; and M is middle row box on the side of a pallet.

The box locations on a pallet have influenced the temperature evolution inside the packaging. It took considerably longer time to cool down the middle boxes (P1_M_ and P2_M_) than those boxes with more free sides, e.g. the top (P1_T_, P2_T_) and bottom (P1_B and P2_B) corner boxes. Furthermore, boxes with more exposed surfaces such as the top and bottom corner boxes have experienced more temperature fluctuations compared to the middle ones.

4.1.2. Air freight transportation study in June 2008

The second air freight transportation study in June 2008 was done as well on cod loins caught east of Iceland. The logistics setup differs from the previous study as more handling was necessary in the first study due to time constrains and airplane schedule. The transportation was as before carried out in a dedicated freight airplane operation. Table 4.2 shows the logistics activities carried out during the second air transportation study and the temperature measures done. Two pallets were used as before for temperature measures and the average temperature is shown. Total time of operation was 1.7 days.

Table 4.2 shows some hazardous parts of the supply chain concerning the temperature abuse on the pallets. The two most noticeable steps were the holding storage in step 3 and the loading followed by the flight in step 6. The short time increase of the ambient temperature at the top corner of pallet 2 (P2_A_T) at the beginning of loading the airplane (step 6) might be attributed to the effect of sunlight on that part of the pallet. Total abusing (ambient temperature > 5 °C) time is about 14.5 hours, amounting to 36.1% of the total time from producer to final destination. This shows that a considerable time in air transportation is under non-refrigerated conditions as stated elsewhere (e.g. James *et al.* 2006).

Table 4.2 Descriptions of logistics activities during the air freight transportation study in June 2008 (Source: adopted from Mai et al. 2010)

Step	Description	Duration	Ambient temperature of pallet 1 Mean ± STDEV (°C)	Ambient temperature of pallet 2 Mean ± STDEV (°C)
1	Cold storage after packing at producer	2h	-11.5 ± 6.0	-2.2 ± 7.4
2	Loading truck and transportation to RVK	9 h 35 min	-2.4 ± 2.8	1.7 ± 1.1
3	Un-chilled storage over night in RVK	10 h 10 min	10.5 ± 1.7	7.1 ± 2.0
4	Transportation in refrigerated truck to KEF	2 h 15 min	4.5 ± 2.5	2.2 ± 2.7
5	Chilled storage at KEF airport	2 h 45 min	1.9 ± 0.7	0.5 ± 0.6
6	Loading at KEF and flight from KEF to Nottingham (UK)	5 h 30 min	3.6 ± 2.6	5.6 ± 3.2
7	Transportation from processors storage	7 h 55 min	1.0 ± 2.6	2.3 ± 1.8
Total		1.7 d	2.6 ± 6.3	3.5 ± 3.7

Exposure of the pallets to un-chilled conditions for over 10 hours in step 3 caused a sharp increase of product temperature in the top and bottom corner boxes of pallet 1 and in the bottom corner box of pallet 2 as shown in Figure 4.2. Again the effect of box locations on a pallet on the product temperature distribution could be clearly observed in this case study, for example, the product temperature in the top corner box of pallet 1 (P1_T_Mean) was more affected than that in the bottom one (P1_B_Mean). The temperature in the middle box of pallet 1 (P1_M_Mean) was more resistant to change compared to those in the top and bottom boxes.

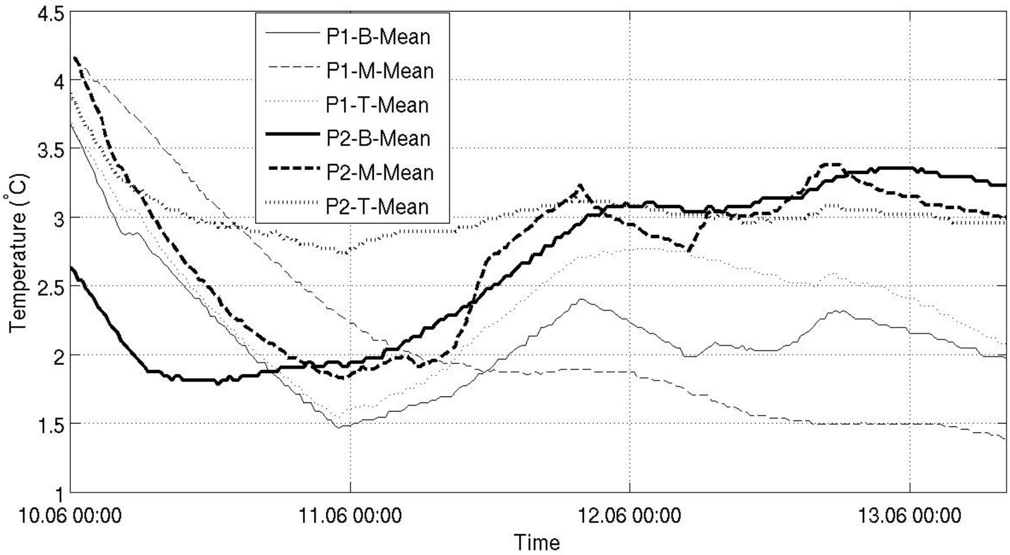

Figure 4.2 Average product temperatures during the air cargo study in June 2008: P stands for pallet; T indicates top corner box; B is bottom corner box; and M is middle row box on the side of a pallet.

This result from this study is in good correlation with the findings for the case study in September 2007 and the results of Moureh et al. (2002). Since the middle boxes were better insulated, ambient temperature change affected them to a smaller degree than the other boxes.

4.2. Sea transportation

The two sea freight transportation studies were carried out during a short period in September to October 2008. Both studies included a supply chain including the catching process, handling and storage processes, and transportation processes. The sea freight transportation studies will be discussed separately below.

4.2.1. Sea transportation September 23rd – 29th 2008

The first sea transportation study in September 2008 was done on cod loins caught east of Iceland as described in the Methodology section above. The transportation was carried out in temperature controlled sea containers. Table 4.3 shows the logistics activities carried out during the sea transportation study and the temperature measures registered. The measures are not anymore limited to two pallets as the temperature inside the whole container is measured.

Table 4.3 Descriptions of logistics activities during the Sea transportation study in September 23rd – 29th 2008 (Source: adopted from Mai et al. 2010)

Step	Description	Duration	Ambient temperature Mean ± STDEV (°C)
1	Cold storage at the producer	3 h 35 min	-11.6 ± 5.5
2	Loading into container and transportation to RVK	8 h 30 min	-2.8 ± 2.1
3	Partly-chilled hold in RVK	4 h 50	3.5 ± 4.3
4	Transportation and handling in refrigerated container: trucked from producer to RVK; shipping to Immingham (UK); and land transportation till final destination (Grimsby, UK)	5 d 3 h 30 min	-0.4 ± 1.5
Total		5.9 d	-0.7 ± 2.8

As can be seen from Table 4.3, the temperature during logistics processes after leaving the producer were very stable and the long duration processes such as transportation (steps 2 and 4) were carried out in a low and stable temperature conditions. During step 3 the surface temperature of the boxes increased due to the turning off of the cooling equipment. In step 4 when the cooling equipment inside the container was functioning, the temperatures of all boxes became stable, maintaining below 0 °C most of the time until the destination. Figure 4.3 shows the surface temperatures during the logistics operations described above.

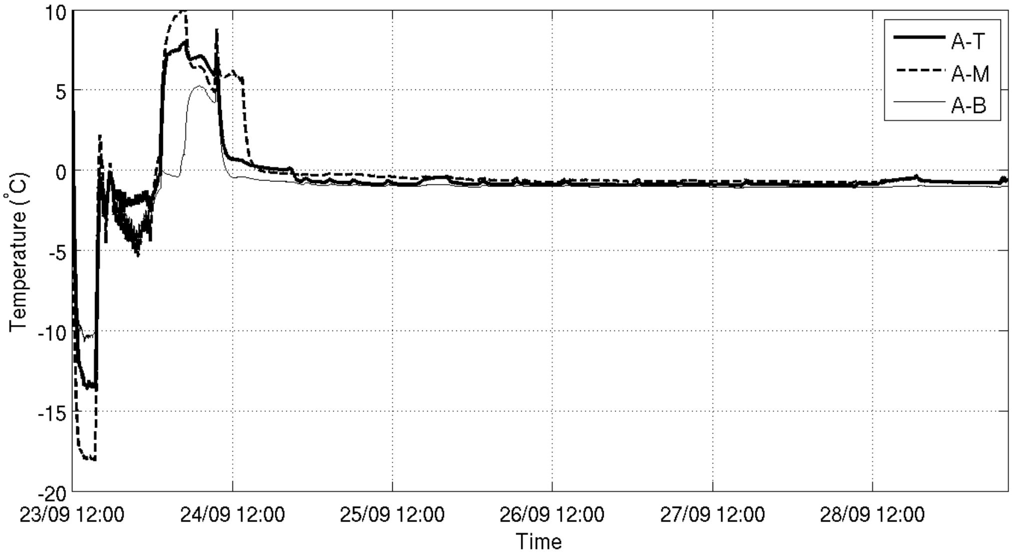

Figure 4.3 Surface temperature (A) of the top corner (T), bottom corner (B), and middle side boxes on a pallet during the sea transportation study on September 23rd-29th 2008.

As can be seen, the major temperature fluctuations occurred during the processing at the processor site but after the container loading and during transportation, a very stable situation was reached where a temperature measures around 0 °C were registered.

4.2.2. Sea transportation September 24th – October 1st 2008

The final study included containerized fresh fish transportation as before but the details of the activities were not logged as before, only single activity of handling and transportation was reported as show in Table 4.4 below.

Table 4.4 Descriptions of logistics activities during the Sea transportation study in September 2008 (Source: adopted from Mai et al. 2010)

Step	Description	Duration	Ambient temperature Mean ± STDEV (°C)
1	Handling and transportation in refrigerated container: trucked from producer to RVK; shipping to Immingham (UK); and land transportation till final destination (Grimsby, UK)	6 d 16 h 35 min (6.7 d)	-0.7 ± 0.2

Table 4.4 shows a very stable temperature with a low deviation in the ambient temperature. Further, Figure 4.4 below shows the product temperature, which was very stable since in the sea freight chain the boxes were kept in a refrigerated container for the whole trip from the processor to the final destination. The product temperature difference between the locations inside a box is small (≤ 0.2 °C most of the time) thanked to the pre -cooling (by liquid and CBC cooling) before skinning and adding of ice on top of the fillets when packing into the EPS boxes.

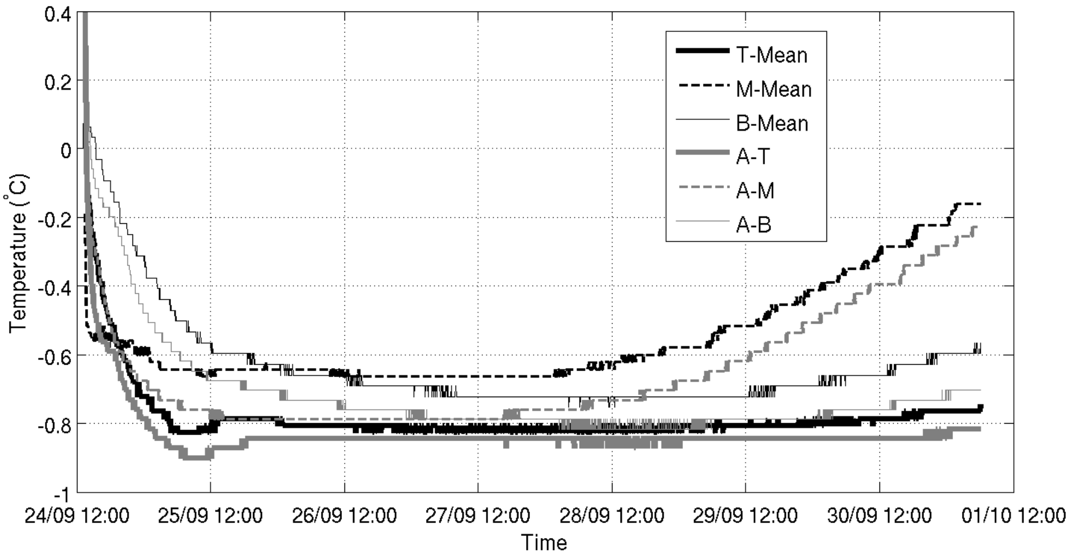

Figure 4.4 Surface temperature (A) and average product temperature (Mean) of the top corner (T), bottom corner (B), and middle side boxes (M) on a pallet during the sea transportation study September 24th - October 1st 2008.

The temperature results show a very stable situation where temperature is kept close to 0 °C as contracts state.

5. ANALYSIS OF THE TRANSPORTATION AND LOGISTICS PROCESSES

The logistics processes described above can be divided into three different areas including *handling, storage,* and *transportation*. Table 5.1 summarizes the highest ambient temperature registration during the different processes and the time period (in hours:minutes) the exposure lasted.

Table 5.1 Mean ambient temperature registrations during the four studies

Study	Storage	Handling	Transportation
Air freight (September 2007)	11.3 °C / 5h:20m	8.6 °C / 2h	9.9 °C / 6h
Air freight (June 2008)	8.8 °C / 10h:10m	4.6 °C / 5h:30m	3.4 °C / 2h:15m
Sea freight (Sept. 23rd – 29th 2008)	3.5 °C / 4h:50m	-0.4 °C / 123h: 30m	
Sea freight (Sept. 24th – Oct 1st 2008)	-0.7 °C / 160h: 35m		

As can be clearly seen from Table 5.1 above, the air freight transportation study results in the highest temperature fluctuations compared to the sea transportation. Of the activities, carried out in the air freight transportation solutions, the storage function had the highest ambient temperature and the longest duration as well. This is not a good combination for fresh food as it puts a lot of temperature load on the products that will easily affect the shelf life in a negative way. The reported storage times included waiting times between mode changes such as road transportation and air transportation, which often is carried out in uncontrolled temperature situations. The situation can involve the product standing on the ramp waiting for loading to take place to the airplane or similar. This is the single largest contributor to temperature augmentation in both of the air freight studies. This situation is, however, not coherent when it comes to the product temperature increase. Due to the fact that the producers prepare the products for these severe externals temperature exposures by installing cooling enablers such as gel mats or similar into the well thermally insulated packaging (EPS boxes), the ambient temperature does not affects the product temperature to such extent as one might suggest. This has clearly surfaced in the figures shown in earlier sections and shown in Figures 4.1 and 4.2. Despite this costly preparation, the temperature augmentation is much higher for the air freight transportation compared to sea transportation. It should still be noted that the freshly crushed ice provides thermal protection for the sea transported fish in a similar way as the more expensive cooling mats do for the air transported fish.

In addition, another result from the study showed that the product temperatures turned out to be non homogeneous depending on the different locations of the boxes on the pallet. As shown in Figure 5.1, steps 1 – 10 show considerable change in temperature measured but becoming more uniform in later stages (11 and 12). On the other hand, the temperature differs based on the location of the box. As shown during steps 11 and 12 in Figure 5.1, the most temperature augmentation takes place in the bottom corner of the pallet and the least in the middle of the pallet, top corner being in-between. Similar results are found in the literature (e.g. Moureh and Derens 2000; Moureh et al. 2002).

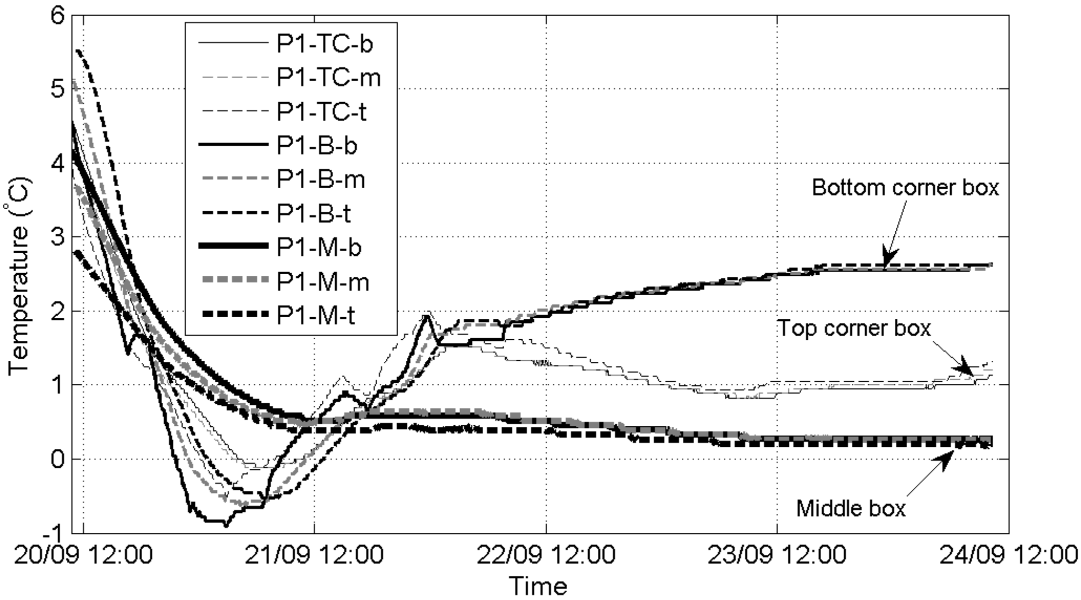

Figure 5.1 Product temperature at different locations inside the boxes during the air cargo study in September 2007: P stands for pallet; T indicates top corner box; B is bottom corner box; and M is middle row box on the side of a pallet; t is top; m is middle height; and b is bottom product inside a box.

These results indicate that it is possible to group the boxes according to their positions on pallets and collect boxes with similar temperature evolution during the pallet unloading. This would improve the quality management of the product and have potential increase in the market duration and possible shelf life of the products which have been exposed to lower ambient temperature. Jedermann et al. (2009) have also mentioned the possibility of grouping products with equal temperature in batches.

6. CONCLUSIONS

Temperature abuse during the logistics processes of air freight transportation causes fluctuation and/or augmentation of product temperature inside boxes, particularly in those with more free sides such as at bottom corner boxes of a pallet. The higher fluctuation in the ambient temperature around the boxes and the longer the thermal load duration, the larger temperature range of the product becomes. Grouping products according to their positions during transportation is therefore useful for downstream management of the products and can influence the shelf life depending on pallet location. Temperature on top and bottom of product inside an EPS box is more sensitive to environment changes than the products found deeper in the box.

The results from the air freight transportation study turned out to include several critical steps, including pre and post transportation and the flight itself (transportation), loading/unloading operations (handling), and holding storage at un-chilled conditions (storage). The single process contributing to the highest rise in product temperature turned out to be the storage process in the air freight transportation study. This indicated that most potential for improvements is during this process, which would in most cases require access to a cool storage within the airport area, where products can then be moved fast to the airplanes for loading and further transportation to distributors or retailers.

Compared to air freight transportation, temperature during sea transportation in refrigerated containers is well controlled, keeping a very stable temperature during the whole transportation process.

The trade-off in selecting transportation mode needs to be based on different aspects including the product quality and remaining shelf time as the sea transportation takes approximately 3 - 4 days longer than air freight transportation in total, available time to reach the market, costs of transportation, in addition to the environmental impact of the transportation process.

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PAPER V

Performance of a new photochromic time-temperature indicator under simulated fresh fish supply chain conditions

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Summary

The objective of this study was to investigate the performance of a new photochromic time-temperature indicator (TTI) under dynamic temperatures conditions simulating real fresh fish distribution chain scenarios. The work also aimed to test the possibility to extend the application of the TTI kinetic model, developed for specific temperature range of isothermal conditions, at low temperatures. The results show that the TTI has presented reproducible responses after being charged and during the discolouration process under different conditions, which reveal the reliability of the indicator. The TTI has reflected well the temperature conditions of the simulated field scenarios, which indicates its potential application to continuously monitor the temperature history of fresh fish supply chains. The kinetic model has given good fits in non-abused scenarios at temperatures below 2 °C, presenting the potential to apply the model for determining the right charging level to suit a product shelf life at low temperatures.

Keywords: TTI, temperature history, nonisothermal condition, fresh fish supply chain, kinetic model

Introduction

Temperature abuse and fluctuations are main concerns in the fresh food supply chains as they may cause safety and quality problems, thus also economic losses (Labuza and Fu 1995, Raab et al. 2008). Time-temperature indicators (TTIs) have shown a great potential to continuously monitor temperature conditions along the chains from packaging to consumption (Taoukis and Labuza 1989a, Kreyenschmidt et al. 2010, Tsironi et al. 2008, Riva et al. 2001), to indicate the abuse (Labuza and Fu 1995), as well as to replace direct temperature recordings (Riva et al. 2001).

TTIs, inexpensive small devices, are normally based on mechanical, chemical, electrochemical, enzymatic or microbiological reaction systems that change irreversibly after being activated (Taoukis and Labuza 1989a, Fu and Labuza 1992, Wells and Singh 1988, Labuza and Fu 1995, Taoukis et al. 1999, Giannakourou et al. 2005b, Kreyenschmidt et al. 2010). TTIs can be attached to the food or the package close to the food and show an easily measurable, irreversibly time temperature dependent change which is correlated to the food deterioration process and remaining shelf life (RSL) (Taoukis and Labuza 1989a).

The applicability of different TTI types to monitor the food quality and shelf life has been studied for various perishable products such as vegetables (Wells and Singh 1988, Taoukis et al. 1998, Giannakourou and Taoukis 2002); refrigerated dairy products (Fu et al. 1991); fresh meat (Taoukis 2006); and fresh fish (Taoukis et al. 1999, Nuin et al. 2008). The practicality of TTIs has been extended with the introduction of Least Shelf Life First Out (LSFO) TTI-based systems to replace the First In First Out (FIFO) practice in the cold chains (Taoukis et al. 1998, Giannakourou and Taoukis 2003, Oliva and Revetria 2008, Taoukis 2006) and with the development of TTI-based Safety Monitoring and Assurance System (SMAS) (Koutsoumanis et al. 2005) to reduce risk of illness and optimize the quality of fresh food products (Giannakourou et al. 2005a, Taoukis 2006).

Kinetic approach proposed by Taoukis and Labuza (1989a) based on Arrhenius expression allows the correlation of the TTI response with the quality changes and the RSL of a product that had undergone the same temperature history. Various TTI types have been kinetically modelled and applied to monitor the product quality and shelf life (Taoukis and Labuza 1989a, Kreyenschmidt et al. 2010, Tsironi et al. 2008, Taoukis et al. 1998, Yan et al. 2008, Nuin et al. 2008, Shimoni et al. 2001, Taoukis and Labuza 1989b, Giannakourou and Taoukis 2002, Taoukis et al. 1999).

Behaviour of the novel photochromic OnVu™ TTI under specific activation levels and constant temperature conditions has been kinetically characterised (Kreyenschmidt et al. 2010). However, the performance of the new TTI under nonisothermal conditions simulating real fresh/chilled food supply chain scenarios need to be tested as a necessary procedure for a new TTI (Labuza and Fu 1995, George and Shaw 1992). In addition, the test for possible application of the developed TTI model under simulated field conditions is desirable.

The objective of this study was to investigate the performance of the novel OnVu™ TTI under dynamic temperature conditions simulating real chilled fish distribution chain scenarios. The work also aimed to test the possibility to extend the application of the mathematical approach of Kreyenschmidt et al. (2010), developed for specific temperature range of isothermal conditions from 2 to 15 °C, under low temperature conditions as they are usually in the fresh fish chain.

Materials and methods

To carry out a comprehensive study of the labels' performance under dynamic temperature conditions of a chilled chain, an experiment set up based on real supply chain temperature conditions of fresh cod loins sea freighted from Iceland to Europe was used. It is common that the fish is either stored under superchilled (around -1 °C) or chilled (around 0-0.5 °C) conditions and very often subjected to temperature fluctuations and/or abuse during logistics processes. The experiments took placed (1) firstly at a fish processing factory until packaging in expanded polystyrene (EPS) boxes, palletisation, and containerisation, following sea transport simulation, and finally at the laboratory for simulating retailer-consumer conditions; and (2) at the laboratory for both control and simulating consumer purchase and handling conditions.

Preparation of fish boxes and plexiglass plates

Expanded polystyrene (EPS) boxes were packed in the fish processing factory with 2 absorbent pads on the bottom, 2 plastic bags of cod loins (fish temperature around -0.5 °C) in two layers, and a 250-g cooling mat on top. The net weight of fish in each EPS box was 5 kg. The boxes were later stacked on 2 pallets and loaded into a refrigerated container for simulating sea transport conditions.

Twenty four plexiglass plates were stuck with 1-2 layers of white labels. These plates were prepared for placing TTI labels after them being charged. The white labels were used to eliminate possible effect of the plate background on the colour measurement results. Each plate was equipped with a DS1922L iButton® temperature logger (Maxim Integrated Products, Inc., CA) recording the temperature at 10-min intervals with a precision of ± 0.5 °C.

TTI preparation and activation

The OnVu^{TM} TTI B1+090807 (Ciba Specialty Chemicals & Freshpoint, Basel, Switzerland) was used in this study. The TTI labels were activated in an automated UV light charger GT 240 Bizerba (Bizerba GmbH & Co. KG, Balingen, Germany) with a speed of 10 labels min^{-1} and covered after the charging with an UV-filter TTR 70QC 53141 to prevent any further light-induced reactions. The charging conditions (ambient temperature and relative humidity RH) are shown in Table 1. Ambient temperature and RH were measured by Testo 171-3 loggers (Testo AG, Lenzkirch, Germany; temperature range: -20 to +70 °C; temperature accuracy: ± 0.5 °C; humidity range: 0-100 % RH; humidity accuracy: ± 3 % RH).

To analyze the effect of the charging time with UV light and the dependency of temperatures under 2°C on the discolouration process, three different charging times/initial square values, (SVo), namely SVo 56.5; 57.5; and 59.0 ± 0.3, and several temperature scenarios simulating chain temperature fluctuations were investigated (Table 1). The charging time range investigated was based on a pre-trial study of the TTI lifespan of about 9.6-15.0 days at -1 to 0.5 °C, similar to the shelf life of fresh cod fillets/loins under these conditions (Einarsson 1994, Lauzon et al. 2009, Olafsdottir et al. 2006, Einarsson 1992). Differently charged TTI labels were stuck on the previously prepared plexiglass plates using 3 labels per charging time, resulting in 9 labels on each plate. In total, 216 TTI labels were used.

Design of storage conditions

Storage conditions of the TTI plates can be viewed in Table 1. They were designed to simulate different real supply chain scenarios of fresh cod loins in EPS boxes transported from Iceland to retailers in Europe by sea-freight and followed further till end customer consumption.

Table 1 Definition of sample groups, activation and storage conditions

	Sample name	Description	Charging conditions	Storage conditions
1	SP	Superchilled plates at the laboratory	Ambient temperature 7 °C; RH 60 %	Set at -1 °C
	SP_nonabused			- Without abuse
	SP_abused			- Abused*
2	P	Chilled plates at the laboratory	Same as SP plates	Set at 0.5 °C
	P_nonabused			- Without abuse
	P_abused			- Abused*
3	EPT	Chilled plates from EPS box without abuse during transport	Ambient temperature 10 °C; RH 65 %	In container set at -1 °C days 0-6; from day 6 in laboratory simulator set at 0.5 °C (same as P plates)
	EPT_nonabused			- Without abuse on day 8
	EPT_abused			- Abused*
4	EPA	Chilled plates from EPS box with 6-h abuse during transport	Same as EPT plates	In container set at -1 °C during days 0-6 with abuse** on day 5; from day 6 in laboratory simulator set at 0.5 °C (same as P plates)
	EPA_nonabused			- Without abuse on day 8
	EPA_abused			- Abused*

* The abuse was on day 8 for 2.5 hours at ambient temperature, followed by a simulated home refrigerated storage (6-7 °C);
** The abuse was done during transport phase on day 5 for 6 hours at outdoor temperature condition.

Six TTI plates were stored in a laboratory climatic chamber set at -1.0 °C (described as superchilled plates or SP) from day 0. On day 8, three SP plates were abused (coded as SP_abused) by placing them on a table at room temperature for about 2.5 h and then storing them at simulated home refrigerator conditions (6-7 °C) until end of the study (day 16). This was done to simulate handling and storage conditions of the end consumers for fresh food products.

Six other TTI plates were stored in a laboratory climatic chamber set at 0.5 °C (described as chilled plates or P) from day 0. On day 8, three P plates were abused (coded as P_abused) and then stored in the same conditions as for SP_abused plates.

Regarding the EPS boxes, two of them were put with TTI plates. To check the effect of placement on the TTI discolouration during the transport phase, the plates were put at different positions inside the boxes. Each box contained 6 plates with the following configuration: two plates on the bottom, 2 in the middle between the fish layers, and 2 on top of the fish bags right below the cooling mat. The plates were coded (EPT for box on the first pallet or EPA for box on the second pallet) and numbered (from 1 to 6). Position of each plate in a box was recorded, e.g. right-bottom, left-middle, etc. Transported EPS boxes were stored in a sea-freight container set at -1 °C for 6 days simulating sea-freight transport and distribution. On day 5, the EPS box with EPA plates, however, was taken out from the container and placed at ambient temperature for 6 h, then put back to the container till day 6. This was to simulate the possible abuse due to unloading and interim holding of the product during transport phase. Upon arrival at the laboratory, plates from the transported box (EPT plates) and abuse-transported box (EPA plates) were taken out from the boxes and transferred to a climatic chamber set at 0.5 °C. Half of the plates (3 EPT and 3 EPA plates) were abused on day 8, followed by a simulated home refrigerated storage (coded as EPT_abused and EPA_abused in Table 1) similarly to the SP_abused group.

All of the plates during the time at the laboratory were stored in grid racks to ensure that they were not stacked on top of each other. This was made to ensure that all plates encountered the same ambient conditions.

Measurement of TTI discolouration

TTI colour changes were measured with the Gretag Macbeth OneEye spectrophotometer (X-Rite, Regensdorf, Switzerland) at D65 illumination and 2° observation angle conditions. The square value (SV) in CIE-Lab space (Eqn 1) was used to characterize the TTI-charging and discolouration process:

$$SV = \sqrt{L^2 + a^2 + b^2} \qquad (1)$$

Where L represents the lightness of the labels; a represents their redness and greenness; and b represents their yellowness and blueness.

The applied charging times led to initial square values SVo 56.5; 57.5; and 59.0 ± 0.3.

Around the region where the photochromic dye is on the TTI label, there is a small area with a reference colour, which corresponds to a SV value of 71. When this colour is reached, the end of the shelf life is also reached (Kreyenschmidt et al. 2010).

Most of the measurements were done at the laboratory at an ambient temperature of 7 °C; only the first measurements of EPT and EPA plates were done at the factory at 10 °C under the same conditions as their TTI labels were charged.

The discolourations of the TTI labels (with the same SVo) on EPT, EPA, P, and SP plates were then compared to find out the effect of different time-temperature history on the TTIs.

Validation of the TTI kinetics under low non-abused temperatures

Kreyenschmidt et al. (2010) have modelled the response of an activated OnVu TTI label, i.e. its square value SV at time t, by a sigmoidal Slogistic1 function (Eqn 2):

$$SV(t) = \frac{d}{1 + e^{-k(t-c)}} \qquad (2)$$

Where d is the amplitude of the colour change; c is the reversal point; k is the rate constant of the colour change, which is temperature-dependent; and t is the storage time.
The data from non-abused samples were fitted using Eqn 2 to test if the model worked for the temperature below 2 °C.
Based on pre-test results, it was observed that the lifespan of TTI (time to reach SV 71) showed an exponential decay of charging level SVo, which is described in Eqn 3:

$$t_L = \exp\left(\frac{b_2 - SV_o}{a_2}\right) \qquad (3)$$

Where t_L: the lifespan/shelf life time of TTI (h); a_2: the decay constant; and b_2: factor.
Therefore, a charging level required to suit a shelf life of product can be recalculated using Eqn 4 with the same parameters as in Eqn 3:

$$SVo = -a_2 * \ln(t_L) + b_2 \qquad (4)$$

In this case t_L equal the shelf life of the product concerned.

Data analysis

Microsoft Excel 2003 (Microsoft, Redmont, WA, USA) was used to calculate mean, standard deviation and to build graphs. Origin 7.5 (OriginLab, Northampton, MA, USA) was used to fit the TTI data to obtain model parameters, their standard errors and to build graphs. One-way ANOVA (analysis of variance) with post hoc Tukey (if there were more than 2 groups), two-independent-samples t-test (if there were 2 groups), and non-parametric two-independent-samples Wilcoxon W test (if number of samples in each group was ≤ 6) were conducted to compare the means of SVs or the means temperatures on the plates. Differences in average temperatures of the plate surfaces were also analyzed. The statistical analysis software SPSS version 16.0 (SPSS, Chicago, Il, USA) was used for this purpose. All tests were performed with a significance level of 0.05.

Results and discussion

Reproducibility of the charging process

It is known that the reliability of a TTI is an important issue to enable the application of the TTI in cold chain management (Shimoni et al. 2001, Kreyenschmidt et al. 2010). A reproducible charging process of the TTI is therefore a requirement to control the reproducibility of the TTI shelf life (Kreyenschmidt et al. 2010). Figure 1 presents the reproducibility of the charging process for the specified OnVu™ TTI. Low variation in the SVo was observed for all the charging times tested in both of the two charging environments. The standard deviations (STDEV) of the SVo from 36 labels per charging time range from 0.25 to 0.28 (for labels charged at 10 °C; 65% RH); or from 0.11 to 0.13 (for labels charged at 7 °C; 60% RH). The results are in a good agreement with the findings of Kreyenschmidt et al. (2010) that the novel TTI have demonstrated good reproducibility during the charging process.

Figure 1 also shows that the charging conditions have affected the initial square values (SVo) of the activated labels. To obtain similar SVo as planned (Table 1), the charging times had to be adjusted between the two charging environments. Interestingly, it seems that the charging environment affects the variation of the SVo, smaller variation at lower ambient temperature and relative humidity (e.g. compare Fig. 1b to Fig. 1a). These differences might also be attributed to the faster discolouration rate at 10°C, meaning that the reaction might have already begun during the measurements. Further investigation is needed to clarify the relationship between SVo and charging environments. The results support the recommendation of Kreyenschmidt et al. (2010) to have a stable ambient condition during charging.

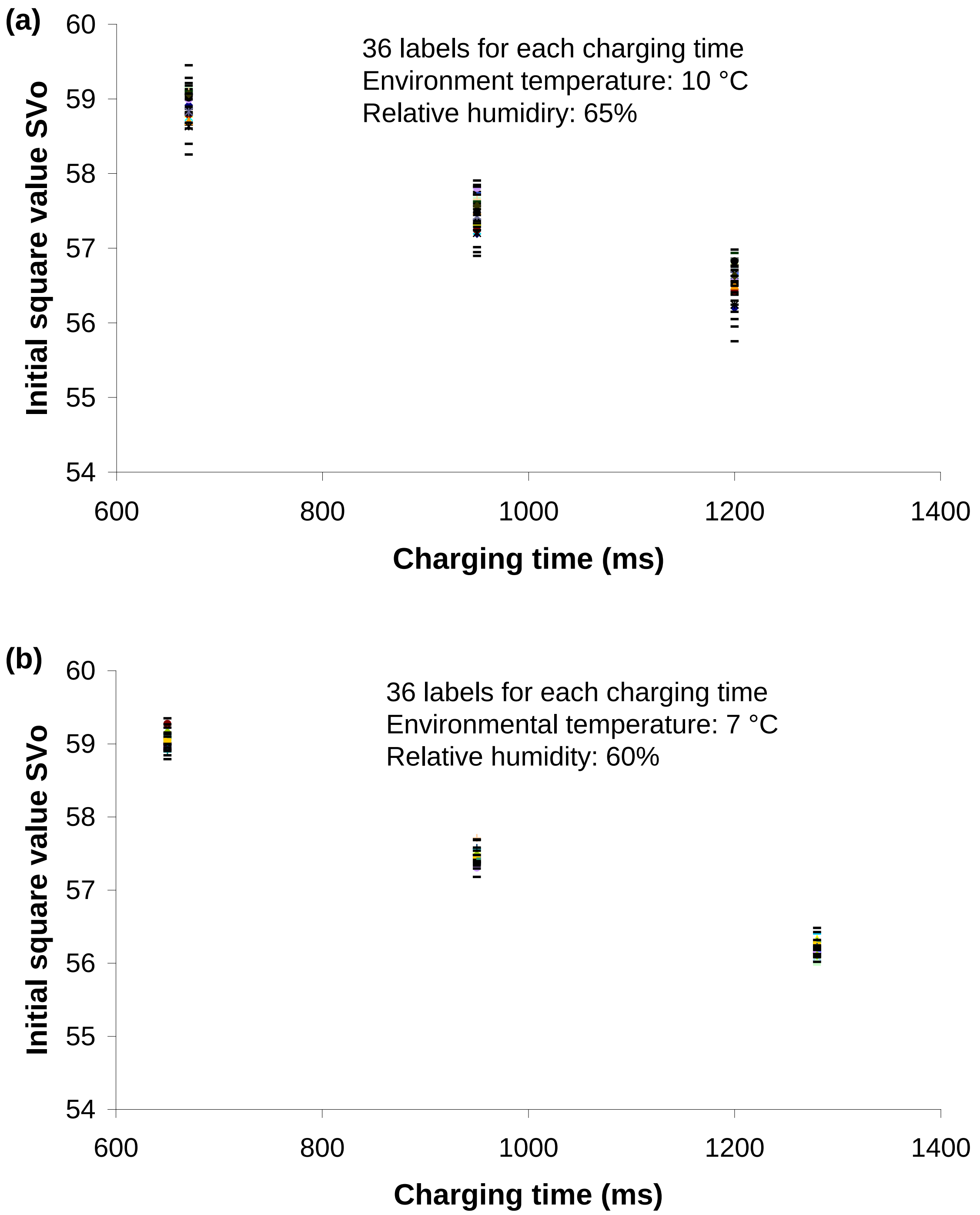


Figure 1 Reproducibility of the OnVu^{TM} TTI charging process at ambient conditions of (a) 10 °C; 65% RH and (b) 7 °C; 60% RH.

Reproducibility of the discolouration process

The TTI presented a good reproducibility of the discolouration process both under isothermal and dynamic storage conditions (Fig. 2). At constant storage temperature 0.5 °C, small variation of the SVs was observed with the STDEV range of 0.11-0.44. The results are very similar to the deviations reported by Kreyenschmidt et al. (2010) for non-abused storage. Under nonisothermal conditions, wider range of STDEV was observed: 0.05-0.56 for P plates; 0.30-1.14 for EPT plates; and 0.17-0.80 for EPA plates (Fig. 2b). High deviation of SVs of the labels on EPT (STDEV up to 1.14) and EPA (STDEV up to 0.80) plates might be attributed to their different positions inside the boxes. In general, standard deviation was less than 3% of the dynamic range of the label SV.

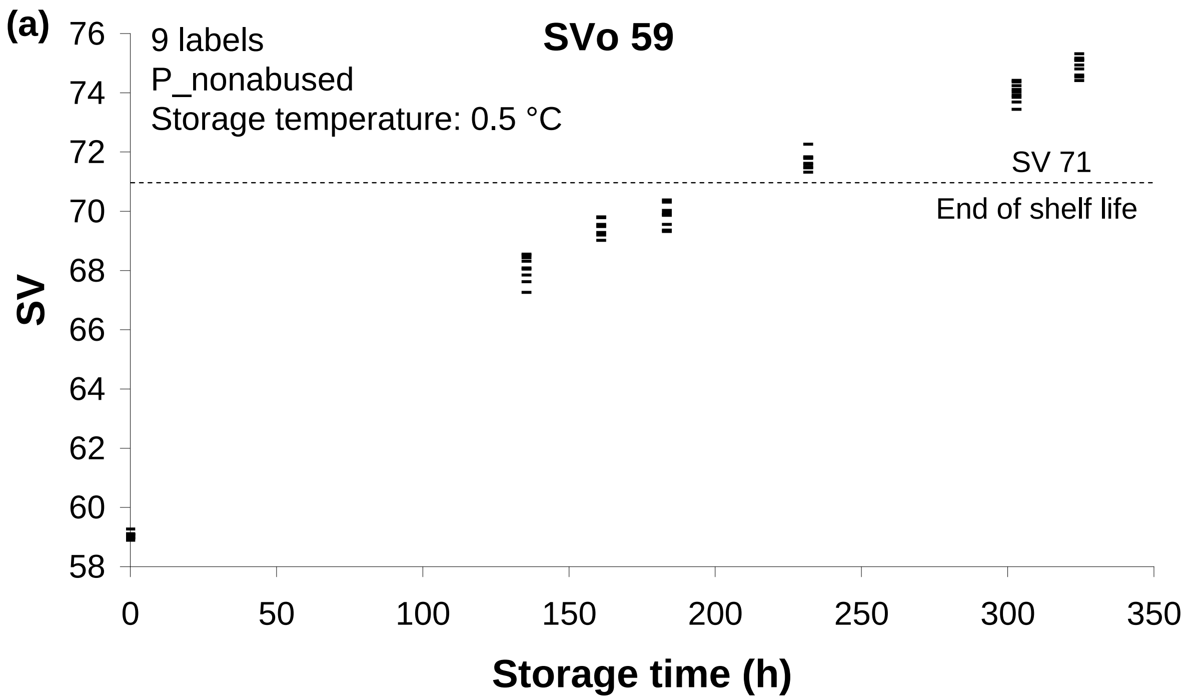


Figure 2 Reproducibility of the TTI discolouration process under isothermal (a) and nonisothermal (b) conditions.

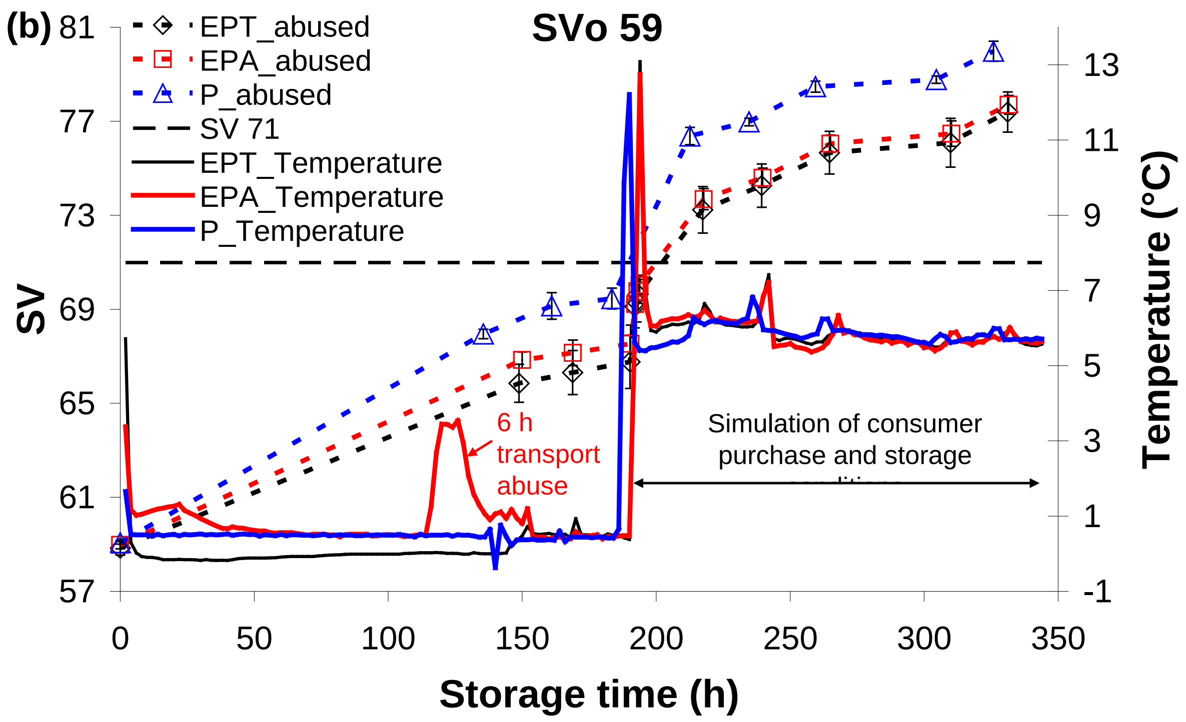


Figure 2 *Continued.*

The EPT or EPA plates from different positions inside an EPS box did not give significant difference in SVs directly after the transport phase ($p > 0.05$) despite the fact that there was some significant difference ($p < 0.05$) in the temperatures between left- and right-positioned plates of the same height levels during transport (data not shown). The TTI labels on EPT and EPA plates from different positions in a box neither resulted in significant difference of SVs for the whole studied period ($p > 0.05$). Therefore SVs of labels from different plates of a box could be averaged as shown in Figures 2b and 3a.

When comparing the end point of TTI shelf life between the non-abused and abused groups, e.g. P_nonabused (Fig. 2a) and P_abused (Fig. 2b), it can be seen that the abuse caused a reduction in the labels' shelf life, e.g. of 42 h for P samples. This indicates that the TTI has satisfactorily reflected the abuse, similarly to the findings of Kreyenschmidt et al. (2010).

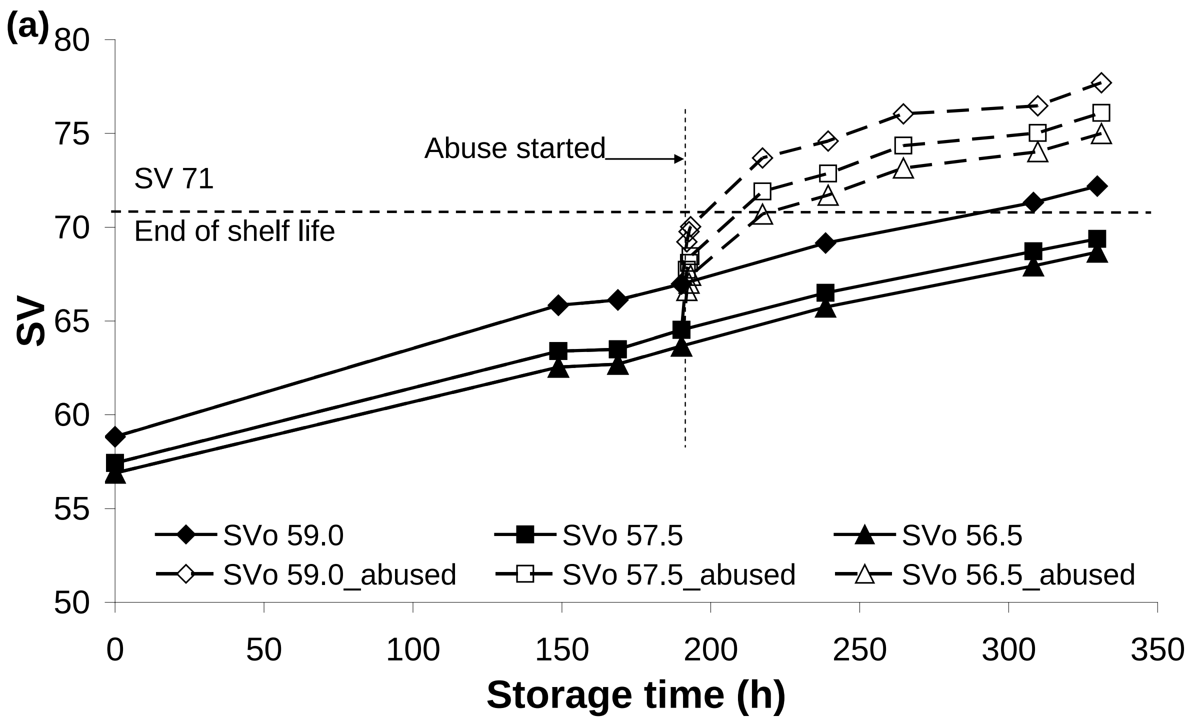
Figure 2b also shows the effect of temperature on the discolouration process of TTI labels. EPT labels discoloured at the slowest rate compared to EPA and P counterparts since the temperature of EPT plates was the lowest during the transport phase. The SV mean of the transport-abused EPA plates right after the transport phase is significantly different ($p < 0.0001$) from that of the EPT plates which were not abused during the transport. This indicates that the TTI has reflected well the abuse at the early stage of the chain. Despite of the exposure to lower temperature condition of the P plates compared to the EPA plates during the early phase, P labels discoloured faster than EPA labels. This reveals the effect of charging conditions, such as ambient temperature and relative humidity (EPA labels were charged at 10 °C; 65% RH while P labels at 7 °C; 60% RH, Table 1), on the discolouration process of TTI. This result supports the findings of Kreyenschmidt et al. (2010) that the higher temperature and the higher humidity of the charging environment, the slower discolouration process at constant charging times due to a higher energy transfer to the label.

Another measure of the quality of the homogeneity of the charging and the kinetics is the time difference between the first and last label to reach the reference colour (or end point tolerance). For those labels that reach the SV of 71 at the end of the studied period, the difference is found to be 2.2-5.0% of the TTI lifespan (data of labels on 3 P plates stored at 0.5 °C, not shown); smaller difference was observed for TTI of shorter charging time. The tolerance range is sometimes higher than the maximum tolerance 2.5% for TTIs as stated by several authors (George and Shaw 1992, Labuza and Fu 1995).

Discolouration process of TTI labels of different charging times and storage conditions

As expected, the discolouration of the labels was obvious as time elapsed, sooner with those labels of shorter charging times (i.e. higher SVo) (Fig. 3 and 4). This is in accordance with the findings of Kreyenschmidt et al. (2010). Similar results were observed for abused samples.

The plates, which had undergone 2.5 hours of temperature abuse on day 8 followed by storage at refrigerated conditions, discoloured faster than those without abuse (Fig. 2 and 3). The difference between the abused and non-abused groups could be clearly observed from the day of abuse. At the abuse, a considerable increase in the SV values is visible and afterwards, the discolouration happens faster due the increased temperature. In all experiments, the simulation of inappropriate handling of the chilled product by consumers can be clearly seen in the kinetics. Particularly, TTI labels with initial square value of 59 stored at 0.5 °C have reached the shelf life (i.e. SV 71) after 230 h (Fig. 3b), which is very close to the shelf life of air packed fresh cod fillets at these conditions (9.6 days) based on microbiological counts of log 6 CFU g^{-1} (Einarsson 1992). All these indicate great potential to use TTI labels to monitor the time temperature history and the shelf life of the product.



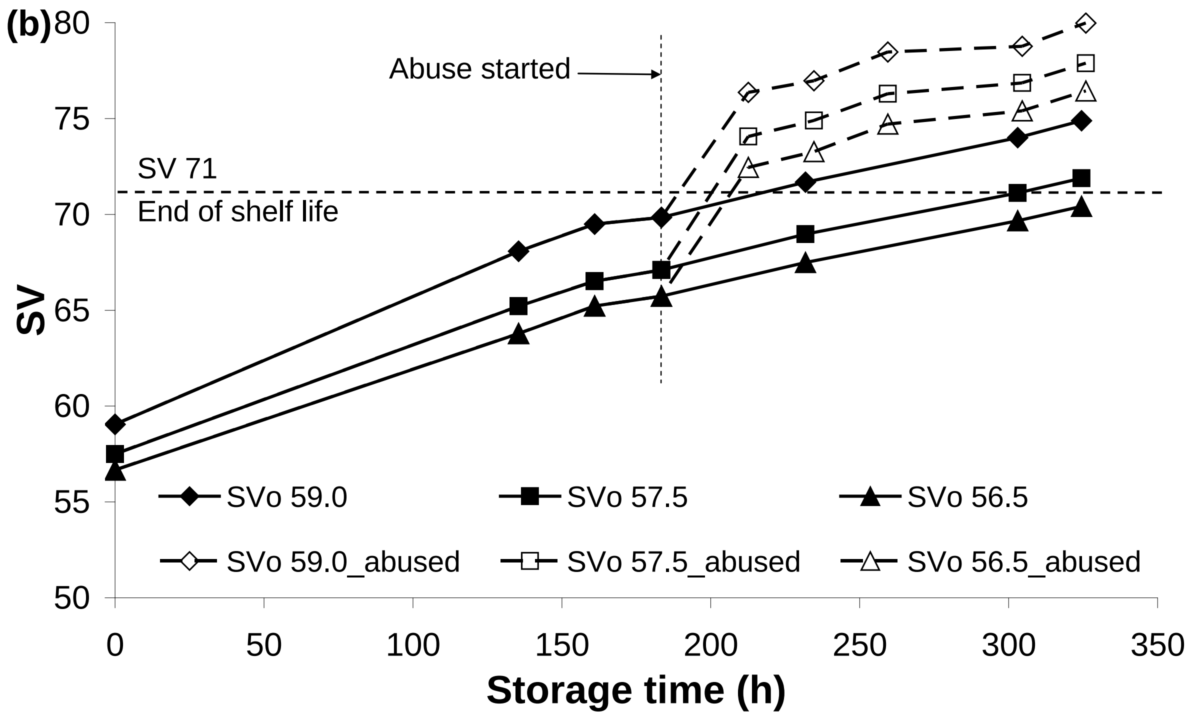


Figure 3 Discolouration process of TTI labels on EPA plates with 6-h abuse during transport phase, followed by storage at 0.5 °C (a) and P plates stored at 0.5 °C (b) without and with temperature abuse on day 8.

All the labels from non-abused superchilled plates (SP_nonabused) did not reach the reference colour after 360 h (data not shown) as expected. This is mostly due to the fact that the temperature in the simulator set -1 °C was far lower than the designed value, causing very low temperatures (-3.2 °C in average and as low as -8.8 °C) on the plate surfaces (data not shown).

Fitting of data from non-abused storage

The data of the non-abused labels could be fitted with Eqn 2, the fitting curves and parameters are shown in Fig. 4 and Table 2. Table 2 shows that the fits converge well with a high correlation coefficient (R^2), 0.996 in average and 0.993 as the lowest. The general trend is that, with increasing charging time, parameters d and k decreased and the absolute value of the parameter c increased. This is what one would expect as with increasing charging time the label discolouration develops more slowly (Kreyenschmidt et al. 2010). Lowering the storage temperature results in smaller d values and higher c absolute values, and therefore, a slower discolouration of the labels with the same charging times.

Table 2 Fit parameters of the non-abused labels stored at set 0.5 °C (P plates) and -1 °C (SP plates)

Charging time (ms)	SVo ± 0.3	d	Standard error	k (h^{-1})	Standard error (h^{-1} x 10^{-5})	c (h)	Standard error (h)	R^2
P samples at set 0.5 °C (P_nonabused)								
650	59.0	79.199	1.125	0.00528	0.00049	-204.330	12.211	0.997
950	57.5	77.740	0.768	0.00443	0.00025	-235.770	7.084	0.999
1280	56.5	76.962	1.038	0.00410	0.00029	-250.900	8.746	0.999
SP samples at set -1 °C (SP_nonabused)								
650	59.0	70.983	0.573	0.00529	0.00054	-305.260	26.399	0.994
950	57.5	68.595	0.781	0.00442	0.00059	-374.210	38.898	0.993
1280	56.5	67.578	0.752	0.00412	0.00051	-400.030	37.295	0.994

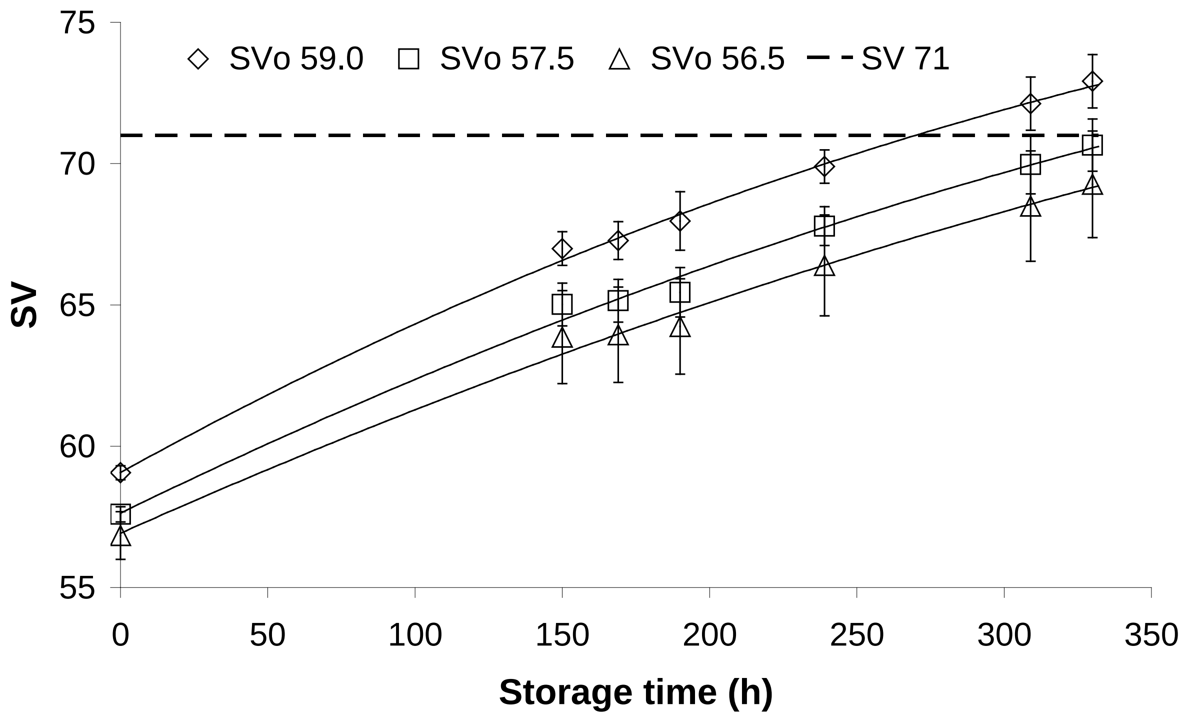


Figure 4 Response (experimental points with error bars and fitted curves) of TTI labels with different initial square values (SVo) on the transported EPT plates without abuse on day 8.

The fitting results clearly show that the kinetic model of Kreyenschmidt et al. (2010), which was developed for the temperature range of 2-15 °C, could also be applied for lower temperature conditions. This indicates the potential to extend their quality contour diagram to a lower temperature such as 0.5 °C, so that a charging level can be defined to suit the shelf life of a product stored at the same temperature.

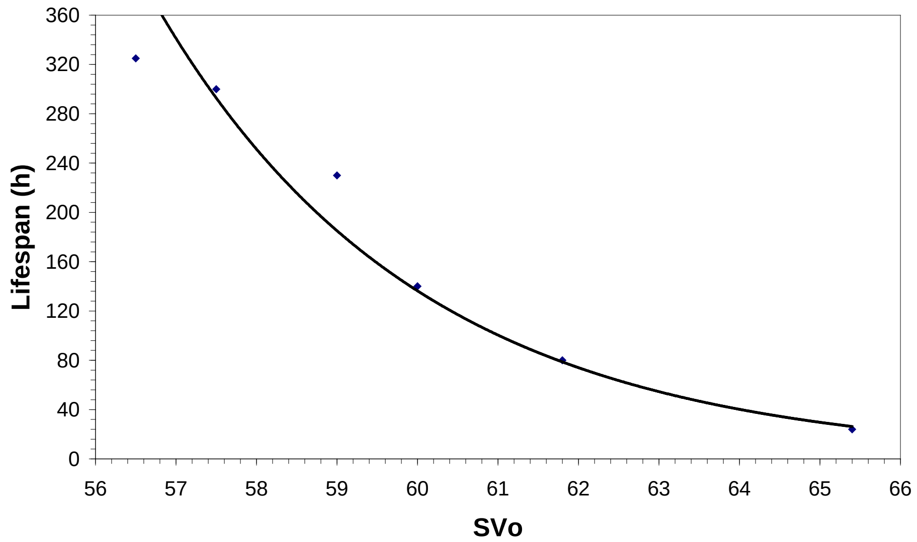


Figure 5 Lifespan of the TTI with different charging levels at a storage temperature of 0.5 °C. Experimental data and fitted curve are shown.

Alternatively, the choice of the right charging level(s) to suit the shelf life (lives) of fish product(s) of the same storage conditions can be done using the correlation of TTI lifespan (t_L) and charging level (SVo) at specific temperature conditions as described in Eqn 3 by using Eqn 4 and the parameters estimated from Eqn 3. For the case of storage at 0.5 °C, the parameters a_2 and b_2 are estimated equal $a_2 = 3.205 \pm 0.226$; $b_2 = 75.755 \pm 1.128$; and the coefficient of correlation (R^2) is 0.980. This was found based on the results of this study and a pre-test investigation. The correlation is shown in Fig. 5.

Kinetic characterisation of the TTI discolouration process under dynamic conditions is under development and will be described in another future publication.

Conclusions

In this study, the behaviour of the new OnVu TTI under simulated field conditions of chilled fish products was investigated. The results show that the TTI have presented a good reliability under different temperature conditions as it gave reproducible responses after charging as well as during the discolouration process. The TTI reflected well the temperature conditions of the simulated field scenarios, which indicates its potential use to monitor the cold chains of fresh fish.

The new insights obtained from this comprehensive investigation show that it is possible to control the cold chain of fresh cod: at charging time with initial square value of 59 the shelf life of the TTI at 0.5 °C has been reached after 230 h, which is very close to the shelf life of air packed cod fillets at these conditions.

Charging conditions such as ambient temperature and relative humidity have showed some influence on the response of a newly charged label and its discolouration process. Therefore, maintaining constant conditions during charging of the labels is necessary (Kreyenschmidt et al. 2010).

The kinetic model of Kreyenschmidt et al. (2010) worked well with data from non-abuse storage at temperatures below 2 °C, which indicates the potential to extend their quality contour diagram to low temperatures so that a charging level can be defined to suit the shelf life of a product stored under the same conditions. The charging levels can also be chosen based on the correlation between the charging levels and lifespan of the TTI found in this study. Future work is required to characterise the discolouration of the TTI under abused/dynamic conditions.

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PAPER VI

Continuous quality and shelf life monitoring of retail-packed fresh cod loins in comparison with conventional methods

Mai, N. T. T., Gudjónsdóttir, M., Lauzon, H. L., Sveinsdóttir, K., Martinsdóttir, E., Audorff, H., Reichstein, W., Haarer, D., Bogason, S. G. and Arason, S.

VI

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Continuous quality and shelf life monitoring of retail-packed fresh cod loins in comparison with conventional methods

Abbreviated running head:

Continuous quality and shelf life monitoring of fresh fish

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ABSTRACT

This study investigated the applicability of a new photochromic time-temperature indicator (TTI) to monitor the quality and shelf life of fresh cod loins in retail packs at different storage conditions; also compared this automatic recording method with other methods of quality control, such as sensory, chemical and microbiological analyses; and with a shelf life prediction model. TTI placed on the bottom of the packs effectively reflected the temperature condition of the product. TTI with the initial square value of 61 was suitable for continuous monitoring of the quality and shelf life of the product repacked on day 6 after processing. The estimated product shelf lives based on TTI and on the square-root model for relative rate of spoilage of fresh seafood were well correlated.

Keywords: TTI, continuous monitoring, shelf life, fresh cod

1. Introduction

Effective management of chilled food supply chains, particularly fresh fish supply chains, is of utmost importance to ensure food safety and quality. Temperature is considered as the main factor that affects the safety and quality of perishable products (Kreyenschmidt, Christiansen, Hübner, Raab, & Petersen, 2010; Labuza & Fu, 1995; Raab et al., 2008). During the logistics process (e.g. loading, unloading, transport, and hold storage), as well as during the consumer purchasing process and home storage, the product is often subjected to temperature fluctuations and/or abuse (Brecht et al., 2003; Laguerre, Derens, & Palagos, 2002; Nunes, Emond, & Brecht, 2003). Time-temperature integrators/indicators (TTIs) offer the possibility for continuous monitoring and control of temperature conditions along the chains, from the point of packaging to consumption (Kreyenschmidt et al., 2010; Riva, Piergiovanni, & Schiraldi, 2001; Taoukis & Labuza, 1989; Tsironi, Gogou, Velliou, & Taoukis, 2008).

TTIs are small devices that can be attached to the food or the food package which is in close contact to the food (Taoukis & Labuza, 1989). They can show an easily measurable, irreversibly time and temperature dependent change which is easily correlated to the food deterioration process and remaining shelf life (Taoukis & Labuza, 1989). TTIs are normally based on chemical, enzymatic, mechanical, electrochemical or microbiological reaction systems, which change irreversibly after being activated (Fu & Labuza, 1992; Giannakourou, Koutsoumanis, Nychas, & Taoukis, 2005; Kreyenschmidt et al., 2010; Labuza & Fu, 1995; Taoukis, Koutsoumanis, & Nychas, 1999; Taoukis & Labuza, 1989a; Wells & Singh, 1988). The concept of time-temperature indicators shows to be well accepted by the consumers regardless of their extra costs (Lahteenmaki & Arvola, 2003; Sherlock & Labuza, 1992).

The applicability of different TTI types has been studied for various perishable products such as refrigerated dairy products (Fu, Taoukis, & Labuza, 1991); fresh tomatoes and naked wrapped lettuce (Wells & Singh, 1988); chilled Russian and eggplant salads (Taoukis, Bili, & Giannakourou, 1998); frozen green peas and white mushrooms (Giannakourou & Taoukis, 2002); modified atmosphere packed fresh pork cuts (Taoukis, 2006); chilled Mediterranean fish boque (Taoukis, Koutsoumanis, & Nychas, 1999); and fresh farmed turbot (Nuin et al., 2008).

Kinetic models of various TTI types have been developed to correlate with the quality changes and the remaining shelf life (RSL) of a product, which has undergone the same temperature history (Giannakourou & Taoukis, 2002; Nuin et al., 2008; Shimoni, Anderson, & Labuza, 2001; Taoukis et al., 1998; Taoukis et al., 1999; Taoukis & Labuza, 1989a, 1989b; Tsironi et al., 2008; Yan et al., 2008). Least Shelf Life First Out (LSFO) TTI-based systems were proposed for chilled (Taoukis et al., 1998) and frozen (Giannakourou & Taoukis, 2003) food products to alter the "First In First Out" (FIFO) practice (Oliva & Revetria, 2008; Taoukis, 2006). Koutsoumanis, Taoukis, & Nychas (2005) developed a Safety Monitoring and Assurance System (SMAS) for chilled food products and emphasized the use of TTI as a system input on the product time-temperature history. Kinetics of a new printable photochromic TTI under different activation levels and temperature conditions has been studied by Kreyenschmidt et al. (2010). However, the integration of the novel TTI into packaging for fresh food products, such as chilled cod, to monitor the product quality and shelf life requires further research.

Besides the use of this automatic recording method, other conventional methods, such as sensory evaluation, chemical and microbiological analyses, have been widely used to monitor the quality of fish products. Quantitative descriptive analysis (QDA) and Torry scheme are among the most common sensory methods for fish freshness evaluation (Bonilla, Sveinsdottir, & Martinsdottir, 2007; Cyprian, Sveinsdóttir, Magnússon, & Martinsdóttir, 2008; Mai, Martinsdóttir, Sveinsdóttir, Olafsdóttir, & Arason, 2009; Olafsdóttir et al., 1997; Sveinsdóttir et al., 2009). Total volatile basic nitrogen (TVB-N) and trimethylamine (TMA) are also used as freshness indicators of fish (Olafsdóttir et al., 1997). *Pseudomonas* spp. and *Shewanella putrefaciens* are known as the specific spoilage organisms (SSO) of fresh chilled aerobically stored fish regardless of the fish origin (Gram & Huss, 1996). Monitoring the changes of these bacteria together with the total viable psychrotrophic counts (TVC) during storage of chilled fish is therefore of great interest (Bonilla et al., 2007; Olafsdottir, Lauzon, Martinsdottir, & Kristbergsson, 2006a).

Shelf life models are very useful to assess the effects of temperature changes on product quality (Jedermann, Ruiz-Garcia, & Lang, 2009). The data set of time-temperature history recorded by temperature data loggers can be fitted to predict the product RSL by using available models such as the square-root model for relative rate of spoilage (RRS) of fresh seafood (DTU-Aqua, 2008).

This study aimed to investigate the applicability of the novel OnVu^{TM} TTI to monitor the quality and shelf life of fresh cod loins in retail packs at different storage conditions in simulating real distribution chain scenarios. The work also aimed to compare this automatic recording method with other methods of quality assessment such as sensory evaluation, chemical and microbiological analyses, as well as with a shelf life prediction model.

2. Materials and methods

2.1. Fish processing and packaging in bulk

Whole Atlantic cod (*Gadus morhua*) were obtained from the fish market in Grindavík, Iceland. The fish was caught by Danish Seine on November 21st 2009, gutted, and sorted (average weight 1.38 kg; average length 0.35 m). The cod was iced in tubs with alternating layers of flake ice to keep the fish temperature around 0 °C. On November 23rd the fish arrived to the processing plant, where it was stored overnight in a cooling chamber, until processed in the afternoon, 3 days post catch. In this study the processing day is referred to as day 0. The fish tub was emptied into a water bath for rinsing, followed by de-heading, filleting, deskinning, trimming and cutting the fish into loins and tails. Thereafter, the loins were chilled by liquid ice to a temperature of -0.5 °C and packed into expanded polystyrene (EPS) boxes of 5 kg. The EPS boxes were packed with 2 absorbent pads on the bottom, lined with a plastic bag and a 250-g cooling mat on top of the closed bag. The product temperature during the transport phase was monitored by DS1922L iButton® temperature loggers (Maxim Integrated Products, Inc., CA) at 10-min intervals with a precision of ± 0.5 °C.

2.2. Retail packaging in trays

Upon arrival at the laboratory, cod loins were repacked into yellow polystyrene trays (Linstar E39-34, 175 x 225 mm) with approximately 770-850 g of fish per tray (about 6 loins). The trays were sealed in a plastic bag (250 x 350 mm, 20 PA/50 PE; Samhentir, Iceland) under 40% vacuum. White labels were stuck in 2 layers on both the top and bottom surfaces of packed trays. One DS1922L iButton® temperature logger was put on each tray surface recording temperature at 10-min intervals. Loggers were also placed in direct contact with the fish inside some trays. Ten trays were packed on day 0 (ST, superchilled trays) and another ten on day 6 (TT, trays packed after transport and distribution simulation of bulk fish). These trays were later equipped with TTI labels as described in the next section. Additionally, 18-20 trays were prepared with the same procedure on each repacking day for sensory, chemical, and microbiological analyses. The repackaging was done to simulate a real supply chain situation with Icelandic fresh fish which is often repacked 6-7 days after processing upon arrival to retailers in Europe.

2.3. TTI preparation and activation

The OnVu^{TM} TTI B1+090807 (Ciba Specialty Chemicals & Freshpoint, Basel, Switzerland) used in this study was a solid state reaction TTI based on the inherent reproducibility of reactions in crystal phase. Initially colourless photosensitive compound became dark blue after being charged by UV light. The activated labels faded at a temperature-dependent rate as time elapsed. The shelf life of the activated TTI could be seen by comparison to a light blue printed reference. By controlling the charging time length, TTI temperature sensitivity could be set to suit the shelf life of the product. The TTI labels were activated in an automated UV light charger GT 240 Bizerba (Bizerba GmbH & Co. KG, Balingen, Germany) with a speed of 10 labels min^{-1} and covered after the charging with an UV-filter TTR 70QC 53141 to prevent any further light-induced reactions. The charging was done at an ambient temperature of 6-7 °C and a relative humidity (RH) of 60-64%. Ambient temperature and RH were measured by Testo 171-3 loggers (Testo AG, Lenzkirch, Germany; temperature range: -20 to +70 °C; temperature accuracy: ± 0.5 °C; humidity range: 0-100% RH; humidity accuracy: ± 3% RH).

To analyze the effect of placement and the dependency of different environmental temperatures on the TTI discolouration process, two positions (top and bottom tray surfaces) and four temperature scenarios simulating chain conditions were investigated (Table 1). For superchilled trays (ST), a charging level corresponding to an initial square value SVo 59 was used, based on a previous study of the TTI lifespan (Mai et al., unpublished data) and the shelf life of cod loins at -1 °C (Lauzon, Magnússon, Sveinsdóttir, Gudjónsdóttir, & Martinsdóttir, 2009; Olafsdottir, Lauzon, Martinsdottir, Oehlenschlager, & Kristbergsson, 2006b), which was expected to be around 15 days (repacked on day 0). For chilled trays (TT) two different charging levels of SVo 61 and 60 were investigated, which corresponded to the TTI lifespan of 100 and 136 hours at 0.5 °C (Mai et al., 2010). These charging levels were chosen based on the shelf life of air packed cod loins at 0.5 °C of about 10-12 days (or 4-6 days from repackaging done on day 6 after processing) (Lauzon et al., 2009; Olafsdottir et al., 2006b) and the lifespan of the TTI in dependency with SVo at the same temperature (Mai et al., 2010). Charged TTI labels were stuck on the white labels both on top and bottom surfaces of packed trays using 3 labels per charging time, resulting in 3 (ST case) or 6 labels (TT case) on each pack side. In total, 180 TTI labels were used.

2.4. Storage of fish products

Superchilled ST trays were stored in a laboratory climatic chamber set at -1.0 °C from day 0 (processing day). On day 8, five trays with TTI labels (ST_abused trays) were abused by placing them on a table at room temperature for about 2.5 h and then storing them at simulated home refrigerator conditions (6-7 °C) (Table 1) until end of the study (days 13-16). This was done to simulate handling and storage conditions of the end consumers.
Transported EPS boxes were stored in a sea-freight container set at -1 °C for 6 days simulating sea-freight transport and distribution. Trays prepared on day 6 were stored in a laboratory climatic chamber set at 0.5 °C. Five trays with TTI labels (TT_abused trays) were abused on day 8 (2 days after retail packaging), followed by a simulated home refrigerated storage (Table 1) similarly to the ST_abused group.

Table 1. Definition of sample groups, TTI activation values and storage conditions

	Sample name	Description	Repackaging day	TTI initial square value SVo	Storage conditions
1	ST ST_non-abused ST_abused	Superchilled trays	0 (processing day)	59	Set at -1 °C - Without abuse - Abused on day 8 for 2.5 hours at ambient temperature, followed by a simulated home refrigerated storage (6-7 °C)
2	TT TT_non-abused TT_abused	Chilled trays repacked from transported EPS boxes	6	61; 60	Set at 0.5 °C - Without abuse - Abused on day 8 for 2.5 hours at ambient temperature, followed by a simulated home refrigerated storage (6-7 °C)

2.5. Measurement of TTI discolouration

TTI colour changes were measured with the Gretag Macbeth OneEye spectrophotometer (X-Rite, Regensdorf, Switzerland) at D65 illumination and 2° observation angle conditions. The measurements were done at the laboratory at an ambient temperature of 6-7 °C. The square value (SV) in CIE-Lab space (Eq. 1) was used to characterize the TTI-charging and discolouration process:

$$SV = \sqrt{L^2 + a^2 + b^2} \qquad (1)$$

Where L represents the lightness of the labels; a represents their redness and greenness; and b represents their yellowness and blueness.

The reference scale corresponds to a measured SV value of 71, which is regarded as the end of a charged OnVu label's shelf life (Kreyenschmidt et al., 2010).

The square values SV of the non-abused labels were fitted with a sigmoidal function (Eq. 2) (Kreyenschmidt et al., 2010):

$$SV(t) = \frac{d}{1 + e^{-k(t-c)}} \qquad (2)$$

Where d is the amplitude of the colour change; c is the reversal point; k is the rate constant of the colour change, which is temperature-dependent; and t is the storage time.

2.6. Reference laboratory methods

Of the four retail groups created (Table 1), only two (ST and TT, non-abused) of them were evaluated by reference methods.

Sensory evaluation

The main purpose was to determine shelf life of the ST and TT products according to sensory evaluation by a trained panel. QDA introduced by Stone & Sidel (1985) and a freshness score sheet modified from the Torry scale originally described by Shewan, Macintosh, Tucker, & Ehrenberg (1953) were used to assess cooked samples of cod loins. Ten panellists all trained according to international standards (ISO 8586, 1993); including detection and recognition of tastes and odours, trained in the use of scales and in the development and use of descriptors, participated in the sensory evaluation. The members of the panel were familiar and experienced in using the QDA method and Torry freshness score sheet for cod. The panel was trained in recognition of sensory characteristics of the samples and describing the intensity of each attribute for a given sample using an unstructured scale (from 0 to 100%). Most of the attributes were defined and described by the sensory panel during other projects (Sveinsdóttir et al., 2009). Based on the sensory vocabulary for cooked samples of cod described in Sveinsdóttir, Martinsdóttir, Hyldig, & Sigurgísladóttir (2010), 30 attributes (except putrid odour) were used in this study.

Samples weighing ca. 40 g were taken from the loins and placed in aluminium boxes coded with three-digit random numbers. The samples were cooked for 6 minutes in a pre-warmed oven (Convotherm Elektrogeräte GmbH, Eglfing, Germany) at 95-100 °C with air circulation and steam, and then served to the panel. Each panellist evaluated duplicates of each sample in a random order in nine sessions (maximum four samples per session). A computerized system (FIZZ, Version 2.0, 1994-2000, Biosystèmes) was used for data recording.

Microbiological analysis

Loins were aseptically minced, assessing 3 pooled loins for each sample (tray). Three replicate samples were evaluated for each group. Minced flesh (20 g) was mixed with 180 mL of cooled Maximum Recovery Diluent (MRD, Oxoid, UK) in a stomacher for 1 minute. Successive 10-fold dilutions were done as required. Total viable psychrotrophic counts (TVC) and counts of H_2S-producing bacteria (black colonies) were done on iron agar (IA), modified from Gram, Trolle, & Huss (1987) by using 1% NaCl and no overlay. Plates were spread-plated and incubated at 17°C for 5 days. Enumeration of presumptive pseudomonads was performed using modified Cephaloridine Fucidin Cetrimide (mCFC) agar as described by Stanbridge & Board (1994). *Pseudomonas* Agar Base (Oxoid) with CFC selective Agar Supplement (Oxoid) was used and the plates were incubated at 22°C for 3 days. Counts are reported as logarithmic average values (log_{10} colony-forming units (CFU) g^{-1}).

Chemical analysis

The previously prepared mince was used for chemical analysis of TVB-N and TMA, performed by the methods described by Malle & Tao (1987). After extraction of the fish mince with a 7.5% aqueous trichloroacetic acid (TCA) solution, TVB-N was steam distilled (Struer TVN distillatory, STRUERS, Copenhagen, Denmark), collected in a boric acid solution and finally titrated with sulfuric acid solution. TMA was measured in TCA extract by adding 20 mL of 35% formaldehyde. All chemical analyses were performed in triplicate. The pH was measured in 5 g of mince moistened with 5 mL of deionised water. The pH meter was calibrated using the buffer solutions of pH 7.00 ± 0.01 and 4.01 ± 0.01 (25°C) (Radiometer Analytical A/S, Bagsvaerd, Denmark).

2.7. Data analysis

Microsoft Excel 2003 (Microsoft, Redmont, WA, USA) was used to calculate means, standard deviations and to build graphs. Origin 7.5 (OriginLab, Northampton, MA, USA) was used to fit the TTI data and to build graphs. One-way ANOVA (analysis of variance) with post hoc Tukey (if there were more than 2 groups), two-independent-samples t-test (if there were 2 groups), and non-parametric two-independent-samples Wilcoxon W test (if number of samples in each group was ≤ 6) were conducted to compare the means of temperatures or SVs. The statistical analysis software SPSS version 16.0 (SPSS, Chicago, Il, USA) was used for this purpose. All tests were performed with a significance level of 0.05.

QDA data was corrected for level effects, caused by level differences between assessors and replicates, by the method of Thybo & Martens (2000). ANOVA was carried out on QDA corrected data in the statistical program NCSS 2000 (NCSS, Utah, USA). The program calculates multiple comparisons using Duncan's multiple comparison test. The significance level was set at 5%.

The Seafood Spoilage and Safety Predictor (SSSP) software version 3.0 (DTU Aqua, Denmark) was used to predict the effect of time-temperature combination on the RSL based on the recorded temperature profile. Recorded temperature data of cod loins were fitted into a square-root model for relative rate of spoilage (RRS) of fresh seafood from temperate water. In SSSP, RRS is defined by the ratio of sensory shelf life at a reference temperature, normally 0 °C, to the sensory shelf life of the product under evaluation at T °C (Dalgaard, 2002). A reference shelf life of 10.5 days (from processing) stored at average temperature of -0.1 °C for fresh cod loins in retail packs (based on sensory evaluation in this study) was used.

3. Results and discussion

3.1. Discolouration process of TTI labels of different charging times at different storage conditions

As expected, the discolouration of the labels was obvious as time elapsed; labels of shorter charging times (i.e. higher initial square values SVo) reached the reference colour earlier (Figs. 1 and 2). This is in accordance with the findings of Kreyenschmidt et al. (2010).

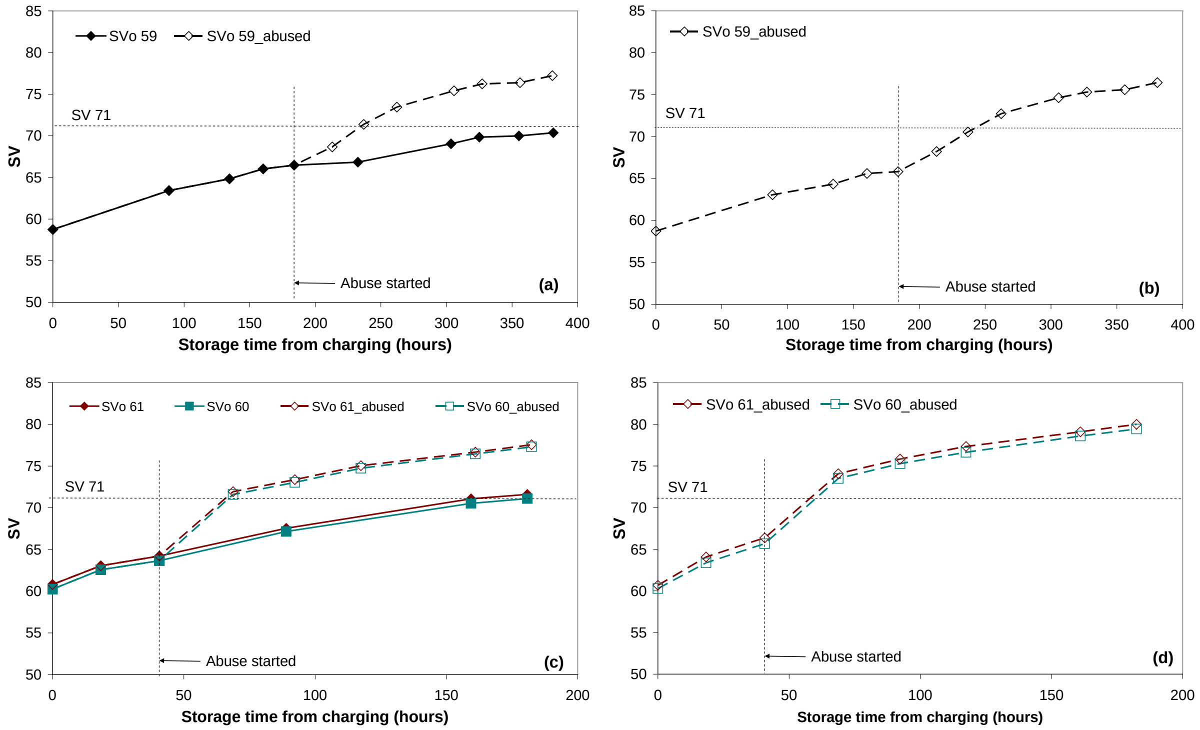

Figure 1. Discolouration process of TTI labels on the (a) top of superchilled ST packs; (b) bottom of abused superchilled (ST abused) packs; (c) top of chilled (TT) packs; and (d) bottom of abused chilled (TT abused) packs.

There is no clear difference in the discolouration of the TTI labels positioned on the top and bottom of the trays stored at -1 °C without abuse (Figs. 1a and 2a). However, the labels on top of the abused ST trays discoloured faster than those on the bottom to some extent (Figs. 1a and 1b), which might be caused by the difference in temperature distribution on the top and bottom surfaces of the ST trays during storage. The tray bottom was in close contact with the table surface during abuse on day 8, i.e. with limited exposure to ambient air, while the top was more exposed to the surroundings. This resulted in a lower temperature (2.6 °C) and smaller fluctuation of temperature (± 3.3 °C) on the bottom of the ST abused trays than on the top (2.8 ± 3.5 °C) during the abuse period and the time after the abuse (data not shown).

The discolouration of the TTI labels on the bottom surface of the chilled TT trays stored at 0.5 °C was faster than that on the top surface (Figs. 1c, 1d and 2b). These differences in the discolouration rates were observed for both abused and non-abused TT groups. The differences were around ΔSV = 2 at the end of the storage period. Difference in the discolouration rates of the labels between ST and TT groups and between abused and non-abused samples is attributed to different storage temperature conditions (Kreyenschmidt et al., 2010).

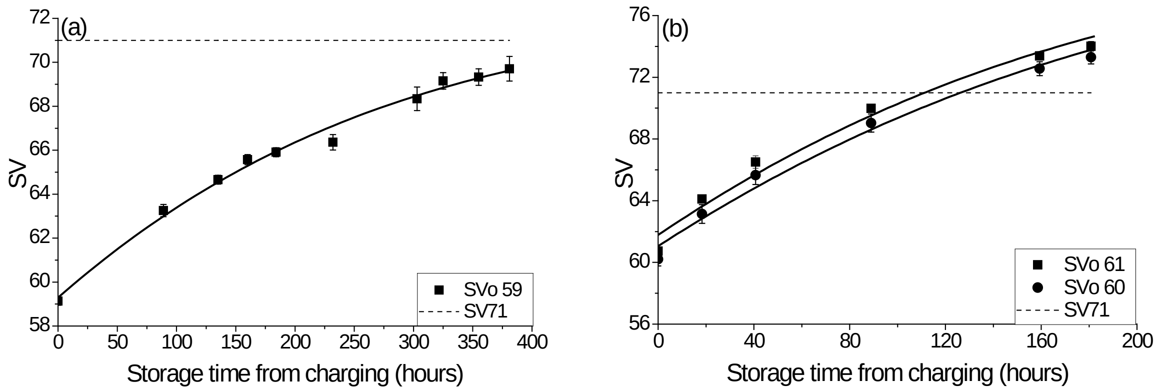

Figure 2. Response (experimental points with error bars and fitted curves) of TTI labels on the bottom surface of superchilled ST (a) and chilled TT (b) non-abused retail packs.

The TT trays, which had undergone 2.5 h of temperature abuse on day 8 followed by the storage at refrigerated conditions, discoloured faster than those without abuse (Fig. 1c). The difference between the abused and non-abused groups could be clearly observed from the day of abuse. At the abuse, a steep increase in the SV values is visible followed by a faster discolouration due to the increased temperature. In all experiments, the simulation of inappropriate handling of the fish by consumers can be clearly seen in the kinetics. All these indicate a great potential in using TTI labels to monitor the time temperature history of the product.

3.2. Comparison of the temperature history based on the TTI response and temperature monitoring data

The temperature in the simulator set to -1°C, in which the superchilled samples (ST) were stored, was not stable, causing high fluctuations (from -8.8 to +2.0 °C) in temperatures of the ST tray surfaces and product (Fig. 3). It might be because of some malfunction of the simulator and also because of opening the simulator for loading and sampling. The product was therefore partially frozen at this condition. This temperature history explains why the TTI labels on the ST non-abused trays did not reach the reference colour after 14-16 days of storage (Figs. 1a and 2a) as expected. Product temperature in the range of -1 to -10 °C might cause significantly negative effect (freeze-concentration effects) on the product quality due to phase changes of the water in the product (Taoukis, Labuza, & Saguy, 1997). In this temperature range, non-enzymatic reactions are expected to be notably accelerated (Fennema, Powrie, & Marth, 1973; Taoukis et al., 1997). There was no significant difference ($p > 0.05$) in the average temperatures between the top surface, the bottom surface, and the product in both the non-abused and abused ST cases. This indicates that the TTI labels on the surfaces of the retail packs and the product inside the packs have undergone similar temperature conditions.

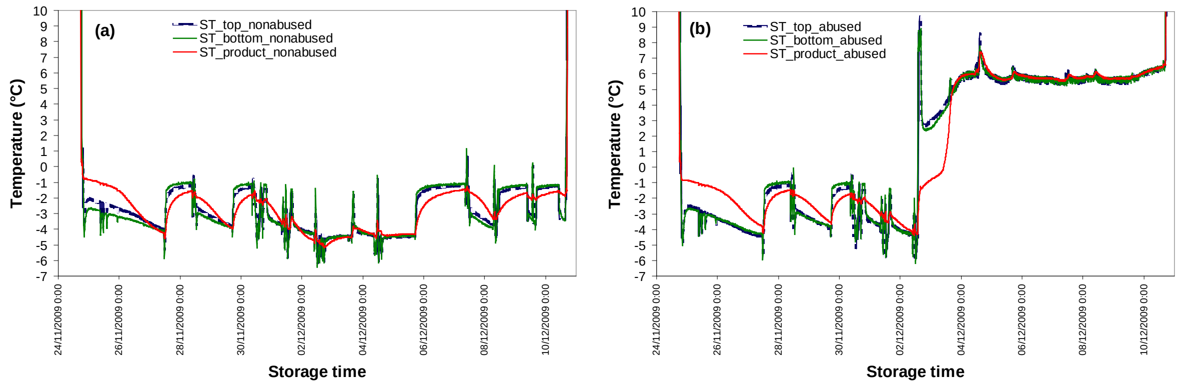

Figure 3. Temperature conditions of the top surface, the bottom surface, and the product of superchilled ST packs without abuse (a) and with abuse on day 8 (b).

For non-abused retail packs stored at set 0.5 °C (TT), it was observed that the average temperatures on the top surfaces significantly differed ($p < 0.001$) from the average temperature of the product (Fig. 4a). No significant difference ($p > 0.05$) was found in the average temperatures between the bottom surface and the product (Fig. 4a). This indicates that TTI labels on the bottom surface and the product had undergone similar temperature conditions, meaning that the TTI on the bottom would give a better estimation of the temperature condition of the product than the top labels. Furthermore, lower temperatures observed on the pack surfaces than the set value (0.5 °C) explain why the lifespan of the TTI with SVo 61 and 60 are longer than expected.

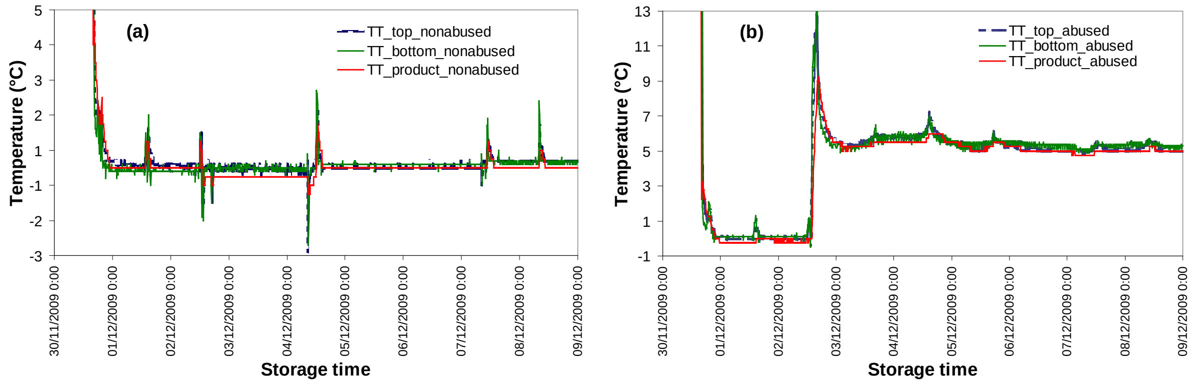

Figure 4. Temperature conditions of the top surface, the bottom surface, and the product of chilled TT packs without abuse (a) and with abuse on day 8 (b).

Concerning the chilled TT packs stored at set 0.5 °C, with temperature abuse from day 8 (Fig. 4b), no significant differences ($p > 0.05$) were found between any of the top or bottom surface or product temperatures.

Overall, the temperature history of the tray surfaces (Figs. 3 and 4) are in good correlation with the discolouration rate of the TTI labels as seen in Figs. 1 and 2. This supports the statement of Riva et al. (2001) that TTI can replace direct temperature recording in fresh food supply chains.

3.3. Reference laboratory results

Sensory analysis

When the average Torry score is around 5.5 most of the sensory panellists detect spoilage attributes, and these limits have been used as the limits for consumption (Olafsdottir et al., 2006b). According to this criterion, superchilled ST and chilled TT groups reached end of shelf life after 10-11 days (Fig. 5).

End of shelf life is usually determined when sensory attributes related to spoilage become evident. When the average QDA score for those attributes is around the value 20 (on the scale 0 to 100) most panellists detect them (Bonilla et al., 2007; Magnússon, Sveinsdóttir, Lauzon, Thorkelsdóttir, & Martinsdóttir, 2006). Based on QDA, the chilled TT group was close to the end of shelf life on day 10, with obvious table cloth odour (score 27), sour odour (score 27), and off flavour (score 22) and with hints of TMA odour (score 19) (data not shown).

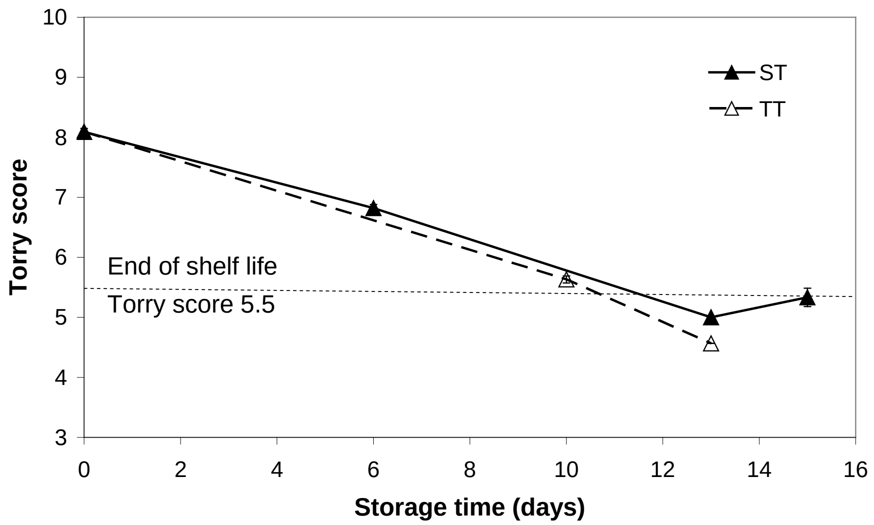

Figure 5. Average Torry freshness scores of the superchilled ST and chilled TT non-abused groups.

Regarding the superchilled ST group, only hints of off flavour were detected (score 17) on days 13 and 15. However, the ST group, stored at undesirable conditions (product temperature -2.8 ± 1.2 °C), was described with more dark colour, precipitation and discolouration, more rubbery texture and less tender, flaky, soft and mushy texture (Table 2) than the TT group (product temperature -0.2 ± 0.4 °C during the later storage in the laboratory chamber, or -0.1 ± 0.7 °C during the whole study period including transport phase). This indicates chemical and enzymatic spoilage in the superchilled ST group rather than bacterial spoilage, which is supported by the knowledge that microbiological activity is more temperature sensitive than chemical reactions in food systems (van Boekel & Tijskens, 2001). Furthermore, interactions between lipid oxidation products and proteins cause undesirable property changes of proteins including texture deterioration and change in colour. Conformational changes in the protein structure can significantly affect functional properties important to final products (Xiong & Decker, 1995). Because of the negative influence of too low temperature on the appearance and texture of the ST group, the shelf life was concluded to be 11 days. Based on these results, the shelf life of ST group did not differ from that of TT group which was 10-11 days according to Torry scheme and QDA.

Table 2. Appearance and texture attributes of the superchilled ST and chilled TT non-abused groups

	Appearance			Texture							
	Dark	Discolouration	Precipitation	Flaky	Soft	Juicy	Tender	Mushy	Meaty	Clammy	Rubbery
p-value	0.0001	0.0000	0.0000	0.0000	0.0000	0.0006	0.0001	0.0001	0.2741	0.0036	0.0095
D-00	23^{b}	20^{b}	20^{d}	64^{a}	81^{a}	64^{a}	77^{a}	70^{a}	12	6	4^{b}
ST-D06	23^{b}	32^{b}	45^{ab}	60^{a}	56^{d}	53^{b}	60^{bc}	43^{b}	24	10^{c}	7^{b}
ST-D13	44^{a}	52^{a}	53^{a}	41^{b}	53^{cd}	49^{b}	54^{bc}	47^{bc}	24	13	14
ST-D15	35	38^{b}	46^{ab}	37^{b}	50^{d}	41^{b}	50^{c}	33^{c}	19	20^{a}	16^{a}
TT-D10	21^{b}	29^{b}	36^{bc}	55^{a}	67^{bc}	54^{b}	60^{bc}	50^{b}	25	16^{ab}	10
TT-D13	27^{b}	33^{b}	36^{bc}	58^{a}	64^{b}	51^{b}	66^{ab}	50^{b}	19	10^{bc}	6^{b}

Different superscript letters ($^{a,\ b,\ c,\ d,\ ab,\ bc}$) indicate significantly different values between samples for each attribute. D stands for days from processing.

Chemical analysis

TVB-N and TMA content as well as pH were measured in all tray samples over the storage period (Fig. 6). Figure 6 shows that TVB-N and TMA production was minimal in the samples during the first 10 days of storage, after which a rapid increase occurred in the TT group, correlating with the sensory rejection of this group. It has been stated elsewhere that the levels of TVB-N and TMA only increase at the later time of storage when spoilage becomes evident (Oehlenschläger, 1998; Olafsdottir et al., 2006b). Little change was observed in these parameters in the superchilled samples (ST) during the storage period. Similarly muscle pH was rather stable, except in the TT trays on day 13, where a sudden increase was observed. This increase coincides with the production of TVB-N and TMA in this group.

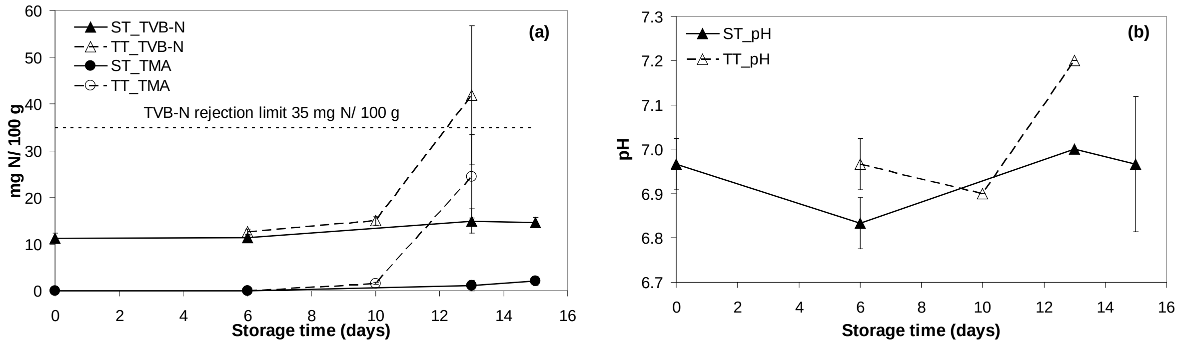

Figure 6. Changes in TVB-N and TMA (a) and pH (b) of the non-abused groups during storage. ST, superchilled trays repackaged on day 0 (processing day); TT, trays repackaged on day 6.

Since the TVB-N limit for acceptability of human consumption for gadoids is 35 mg N/100 g (EU, 1995; Olafsdottir et al., 2006b), the product shelf life was estimated to be about 10-11 days for the non-abused chilled TT trays and more than 15 days for non-abused superchilled ST trays based on the TVB-N results.

Microbial analysis

Microbial proliferation was evaluated on different media to evaluate the proportions of SSO (H_2S-producing bacteria and pseudomonads) in comparison to TVC. The results are viewed in Figure 7. Total viable psychrotrophic counts (TVC) of the raw material amounted to log 5.3 ± 0.2 CFU g^{-1}, while H_2S-producing bacteria showed a count of log 2.3 ± 1.0 CFU g^{-1}, and *Pseudomonas spp*. log 3.5 ± 0.1 CFU g^{-1}. Pseudomonads were generally found to dominate over H_2S-producing bacteria in both groups tested. Superchilled storage delayed the growth of both SSO for at least 6 days. Due to temperature differences, SSO growth developed faster in TT than ST samples. This explains the lower concentration of TVB-N and TMA in ST samples as H_2S-producers along with some other psychrotrophic species, such as *Photobacterium phosphoreum*, contribute to the formation of these volatile compounds (Koutsoumanis & Nychas, 2000; Olafsdottir et al., 2006b). The results are in a good agreement with other studies that the proliferation rate of these bacterial species is lower at superchilled storage conditions compared to chilled storage for aerobically packed cod fillets (Olafsdottir et al., 2006b) or loins (Wang, Sveinsdóttir, Magnússon, & Martinsdóttir, 2008).

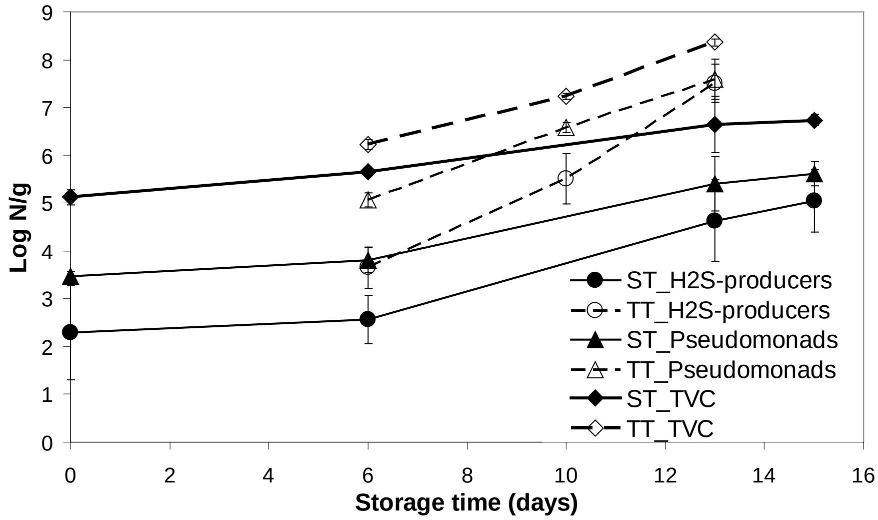

Figure 7. Microbial growth in the non-abused groups during storage. ST, superchilled trays packaged on day 0 (processing day); TT, trays repackaged on day 6.

3.4. Comparison of shelf life estimation methods

Table 3 shows that a charging time of 450 ms at 7 °C (or SVo 61) for the TTI labels on the bottom tray surface suited best for the monitoring of shelf life of the fresh cod loins in retail polystyrene trays repacked 6 days post processing and stored thereafter at 0.5 °C. According to Table 3 the TTI shelf life of the retail trays stored at 0.5°C (TT non-abused) showed a 2-day difference between the labels positioned on the top and bottom of the trays. The labels on the bottom showed a colour fading indicating a shelf life comparable to the sensory shelf life of the group (10-11 days) while the labels on top of the trays showed a longer estimated shelf life of 12-13 days. This confirms our previous statement (based on the temperature data) that placing the TTI labels on the bottom of the trays gives a better estimate of the shelf life than placing them on the top surface of the trays.

The TTIs also showed that the abuse on day 8 resulted in a reduction of about 2 days (i.e. 8-9 days of RSL) in the product shelf life of the TT group, which reflected the abuse during simulated consumer purchasing, handling, and home refrigerated storage conditions. Here again the TTI labels show a very good potential as a mean to monitor the temperature conditions of the product.

Table 3. Comparison of product shelf life (days from processing) given by sensory evaluation, TVB-N level, TTI discolouration, and square-root spoilage model in SSSP

		ST		TT	
		Non-abused	Abused	Non-abused	Abused
Sensory shelf life (days)		11		10-11	
TVB-N based shelf life (days)		> 15		10-11	
TTI_top (days) [a]	Measured	> 15.9	9.8	12.7	8.7
	Simulated	15.9 [b]		12.7 [b]	
TTI_bottom (days) [a]	Measured	> 15.9	10.1	10.7	8.5
	Simulated	> 15.9 [b]		10.7 [b]	
SSSP, RRS model (SL) (days)		> 15.3	10.8	10.2	8.8

[a] Charging time of TTI labels at 7 °C were 650 ms (SVo 59) on day 0 (packaging day, i.e. 3 days from catch) for ST samples and 450 ms (SVo 61) on day 6 for TT samples;

[b] Simulated using Eq. (2).

Regarding the ST trays at the set temperature of -1 °C, the sensory shelf life is far shorter than the shelf life given by the TVB-N limit, the RRS model in SSSP, and the TTI evaluation. It is due to the fact that partial freezing of the samples, caused by the temperature fluctuations in the cooling chamber, led to negative changes in appearance and texture of the product, while microbial spoilage was of lesser importance.

In both ST and TT cases, the square-root spoilage model in SSSP, based on the product temperature, and TTI labels on the bottom surface represent similar shelf life. TTI revealed to be a good device to continuously monitor the temperature history of the product. By adjusting the charging time, the TTI shelf life can be adapted to suit the shelf life of the products concerned (Kreyenschmidt et al., 2010).

4. Conclusions

TTI placed on the bottom of the packs has effectively reflected the temperature conditions of the product and can therefore be used to monitor the abuse and fluctuations in temperatures during storage of fresh cod loins in retail packs. The TTI of a suitable charging level can be used to continuously monitor the quality and shelf life of the studied product. For instance, placement of TTI labels with the initial square value of 61 on the bottom surface of the retail trays repacked on day 6 post process, stored at 0.5 °C, gives similar shelf life as the product shelf life declared by sensory evaluation. In general, the TTI of suitable activation level(s) can potentially be applicable for quality and shelf life monitoring of other chilled fish product(s). However, severely superchilled conditions, which cause negative effects on the sensory attributes of the products, other than those induced by microbial spoilage, might influence the precision of shelf life estimation by the TTI.

Shelf lives given by the TTI on the bottom tray surface and predicted by the SSSP square-root spoilage model (based on product temperature) are in good agreement for all the studied scenarios. This strengthens the aim to use TTI to replace direct temperature recordings in the fresh food supply chains of Riva et al. (2001).

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