Food traceability in theory and in practice

(UiT Template page)

Preface and acknowledgements

The articles presented in this thesis were written at Nofima during the years 2010-2017, but the underlying work started before the year 2000. The work has been primarily financed by the European Commission, through the Framework Programme 5 project TraceFish (#00164), the Framework Programme 6 projects Seafood Plus (#506359) and TRACE (#006942), the Framework Programme 7 projects WhiteFish (#286141) and FoodIntegrity (#613688), and the Horizon 2020 project Authent-Net (#696371).

I want to thank my co-authors and colleagues; especially those involved in the projects we had in the early years when we did not really know or agree on what traceability was or what it entailed, and we had lengthy arguments about it which eventually led to some degree of consensus, and even some papers.

When I first started looking into the then obscure field of food traceability in the mid-1990s, I was lucky enough to get to know and work with two other pioneers who knew roughly as much, or as little as I did. Together we developed the field (at least our understanding of it) more or less from scratch, we travelled to numerous meetings and conferences trying to explain to everybody how fascinating and useful this new concept was, we had some very late nights, and quite soon we were in bunch of projects together. Thanks to the other two food traceability musketeers; Tina Moe and Jostein Storøy.

In recent years, Melania Borit in particular has been extremely helpful, as she seems to read everything that is being published on food traceability, and then she points me towards the most relevant articles; a service I am very grateful for, and one I hope will continue in the future.

The biggest thanks goes to my partner Michaela Aschan who has many roles in my life; three of the least important ones are vice-dean at the faculty I am submitting this thesis to, project collaborator, and article co-author. It is fair to say that it is unlikely that this thesis would have been written without her constant encouragement (there are also other words I could use here) over a very long time.

Finally, I want to thank my parents, Gro Harlem Brundtland, and Kåre Willoch. Not because I have a close relationship with any of these two political leaders, but because I want to emphasize the importance of the Oxford comma when it comes to reducing ambiguity in written text.

Paper list

The following papers are included in this Dr. philos thesis:

I: Olsen, P.; Borit, M.; (2013): "How to define traceability". Trends in Food Science & Technology, volume 29, issue 2, pp 142-150. doi:10.1016/j.tifs.2012.10.003.

II: Olsen, P.; Borit, M.; (2017): "The components of a food traceability system". Submitted to Trends in Food Science & Technology June 2017.

III: Olsen, P.; Aschan, M.; (2010): "Reference method for analyzing material flow, information flow and information loss in food supply chains". Trends in Food Science & Technology, volume 21, issue 6, pp 313-320. doi:10.1016/j.tifs.2010.03.002.

IV: Karlsen, K. M.; Dreyer, B.; Olsen, P.; Elvevoll, E.; (2012): "Granularity and its role in implementation of seafood traceability". Journal of Food Engineering, volume 112, issues 1-2, pp 78-85. doi:10.1016/j.jfoodeng.2012.03.025.

V: Storøy, J.; Thakur, M.; Olsen, P.; (2013): "The TraceFood Framework – Principles and guidelines for implementing traceability in food value chains". Journal of Food Engineering, volume 115, issue 1, pp 41-48. doi:10.1016/j.jfoodeng.2012.09.018.

Co-author table

Contribution to respective papers, in order of importance:

	Paper I	**Paper II**	**Paper III**	**Paper IV**	**Paper V**
Idea and initiative	PO	PO	PO	KMK	JS
Literature study and references	MB	MB	MA	KMK	MT
Development of concepts, methods or definitions	PO	PO	PO	PO, KMK	PO, JS
Application of concepts, methods or definitions, data collection and analysis	PO, MB	PO, MB	PO	KMK	PO, JS, MT
Manuscript preparation	PO, MB	PO, MB	PO, MA	KMK, PO, BD, EE	MT, JS, PO

All the co-authors have signed co-author statements agreeing to the indicated breakdown of contributions, and also agreeing to have the respective paper used as part of this thesis.

Other relevant papers

In addition to the papers included in this thesis, outlined above, the following scientific publications on food traceability which I have contributed to give additional details on the concept, and in particular on various implementations of it.

a) Karlsen, K. M.; Dreyer, B.; Olsen, P.; Elvevoll, E.; (2013): "Literature review: Does a common theoretical framework to implement food traceability exist?". Food Control, volume 32, issue 2, pp 409-417. doi: 10.1016/j.foodcont.2012.12.011.
b) Borit, M.; Olsen, P.; (2012): "Evaluation framework for regulatory requirements related to data recording and traceability designed to prevent illegal, unreported and unregulated fishing". Marine Policy, volume 36, issue 1, pp 96-102. doi:10.1016/j.marpol.2011.03.012.
c) Donnelly, K. A.-M.; Olsen, P.; (2012): "Catch to landing traceability and the effects of implementation – A case study from the Norwegian white fish sector". Food Control, volume 27, issue 1, pp 228-233. doi:10.1016/j.foodcont.2012.03.021.
d) Donnelly, K. A.-M.; Thakur, M.; Forås, E.; Sakai, J.; Olsen, P.; Storøy, J.; (2012): "Mackerel supply chain from Norway to Japan - Preliminary results from an international traceability project". Økonomisk fiskeriforskning, volume 22, issue 1, pp 11-21.
e) Donnelly, K. A.-M.; van der Roest, J.; Höskuldsson, S. T.; Karlsen, K. M.; Olsen, P.; (2011):"Food industry information exchange and the role of meta–data and data lists". International Journal of Metadata, Semantics and Ontologies, volume 6, issue 2, pp 146-153. doi:10.1504/IJMSO.2011.046596.
f) Karlsen, K. M.; Sørensen, C.-F.; Forås, E.; Olsen, P.; (2011): "Critical criteria when implementing electronic chain traceability in a fish supply chain". Food Control, volume 22, issue 8, pp 1339-1347. doi:10.1016/j.foodcont.2011.02.010.
g) Karlsen, K. M.; Olsen, P.; (2011): "Validity of method for analysing critical traceability points". Food Control, volume 22, issue 8, pp 1209-1215. doi:10.1016/j.foodcont.2011.01.020.
h) Karlsen, K. M.; Olsen, P.; Donnelly, K. A.-M.; (2010): "Implementing traceability: Practical challenges at a mineral water bottling plant". British Food Journal, volume 112, issue 2, pp 187-197.
i) Donnelly, K. A.-M.; Karlsen, K. M.; Olsen, P.; (2009): "The importance of transformations for traceability – A case study of lamb and lamb products". Meat Science, volume 83, issue 1, pp 68-73.
j) Donnelly, K. A.-M.; Karlsen, K. M.; Olsen, P.; van der Roest, J.; (2008): "Creating standardised data lists for traceability: a study of honey processing". International Journal of Metadata, Semantics and Ontologies, Volume 3, No. 4, 2008, pp 283-291.

This thesis aims to be general in nature, and to focus on traceability concepts and methods generally applicable in the food industry. Most of the papers listed above are specific for one chain or one sector, whereas the ones selected for inclusion in the thesis are more general and conceptual in nature. Nevertheless, the papers listed above are relevant, and they can serve to illustrate that the concepts and methods outlined in the papers selected for the thesis have been tried and tested in practice.

Other relevant documents, reports, and standards

Food traceability is to a large degree an applied research field with focus on how to achieve traceability in practice, and a lot of knowledge is documented in project reports, organization reports, and international standards. Below are some of the most important ones that I have contributed to through the years.

k) Borit, M.; Olsen, P.; (2016): "Seafood Traceability Systems: Gap Analysis of Inconsistencies in Standards and Norms". FAO Circular FIAM/C1123, ISSN 2070-6065, available at www.fao.org.
l) Karlsen, K. M.; Olsen, P; (2016): "Problems and Implementation Hurdles in Food Traceability". In: Espiñeira, M.; Santaclara, F. J.; (ed) "Advances in Food Traceability Techniques and Technologies: Improving Quality Throughout the Food Chain", Woodhead Publishing Series in Food Science, Technology and Nutrition, ISBN 978-0-08-100310-7.
m) CWA 16960:2015, Batch-based Calculation of Sustainability Impact for Captured Fish Products, CEN Workshop Agreement.
n) Bhatt T.; Blaha, F.; Boyle, M.; DiMento, B.; Kuruc, M.; Matern, H. J.; Olsen, P.; Trent, S.; (2014): "Recommendations for a Global Framework to Ensure the Legality and Traceability of Wild-Caught Fish Products. Expert Panel on Legal and traceable Wild Fish Products". WWF report.
o) ISO 12875:2011, Traceability of finfish products – Specification on the information to be recorded in captured finfish distribution chains, ISO standard.
p) ISO 12877:2011, Traceability of finfish products – Specification on the information to be recorded in farmed finfish distribution chains, ISO standard.
q) Donnelly, K. A.-M.; van der Roest, J.; Höskuldsson, S. T.; Olsen, P.; Karlsen, K. M.; (2009): "Improving Information Exchange in the Chicken Processing Sector Using Standardised Data Lists". In: Sartori, F.; Sicilia, M. A.; Manouselis, N.; (eds.) "Metadata and Semantic Research, Communications in Computer and Information Science", Volume 46, 2009, pp 312-321. Doi: 10.1007/978-3-642-04590-5_30.
r) Storøy, J.; Senneset, G.; Forås, E.; Olsen, P.; Karlsen, K. M.; Frederiksen, M. T.; (2008): "Improving traceability in seafood production". In: Børresen, T.; (ed.) Improving seafood products for the consumer, Part VI Seafood traceability to regain consumer confidence, Chapter 25, pp 516-538. Woodhead Publishing Limited ISBN 978-1-84569-019-9 (book). Woodhead Publishing Limited ISBN 978-1-84569-458-6 (e-book). CRC Press ISBN 978-1-4200-7434-5. CRC Press order number: WP7434.
s) Dreyer, H. C.; Wahl, R.; Storøy, J.; Forås, E.; Olsen, P.; (2004): "Traceability Standards and Supply Chain Relationships". In: Aronsson, H. (ed.) Proceedings of the 16th Annual Conference for Nordic Researchers in Logistics, NOFOMA 2004, Challenging Boundaries with Logistics, 2004, pp 155-170. Linköping, Sweden.
t) CWA 14659:2003, Traceability of fishery products. Specification on the information to be recorded in farmed fish distribution chains, CEN Workshop Agreement.
u) CWA 14660:2003, Traceability of fishery products. Specification on the information to be recorded in captured fish distribution chains, CEN Workshop Agreement.

I was convener / leader / main writer for the three CWA standards and the two ISO standards, and the strong dependency of traceability systems on standards will be discussed in a later chapter, and the content of the standards will be shown in more detail.

Terms and abbreviations

AIDC	Automatic Identification and Data Capture
CEN	European Committee for Standardization
CoC	Chain of Custody; a way of ensuring that the information you are interested in is not lost
CTP	Critical Traceability Point; a point where information is systematically lost
CWA	CEN Workshop Agreement, a low-level, voluntary European standard
EC	European Commission
EDI	Electronic Data Interchange
EPC	Electronic Product Code; a unique code carried by an RFID tag
FAO	Food and Agriculture Organization of the United Nations
FBO	Food Business Operator, a generic name for an organization in the supply chain that handles food products
FP	Framework Programme; EC research programmes that last for roughly 7 years
GMP	Good Manufacturing Practice, guidelines issued by various organizations, including regulatory agencies, to ensure low risk and high quality when producing
GTP	Good Traceability Practice, guidelines developed as part of the TraceFood Framework, based on GMP guidelines, to ensure that relevant information was recorded, and not lost
GS1	GS1 is a non-profit organisation that develops and maintains global standards for business communication, including for number series, and for various types of bar codes
H2020	Horizon 2020, the EC Framework Programme running from 2014 to 2020
IoT	Internet of Things; inter-networking of physical devices
ISO	International Organization for Standardization
IUU	Illegal, Unreported, and Unregulated (fishing)
LCA	Life Cycle Assessment; a technique to assess environmental impacts
RFID	Radio-frequency identification (tag); a tag that uses radio waves to communicate
RTD	Research and Technical Development
SGTIN	Serialized Global Trade Item Number; a type of EPC used for identification of TRUs
TI	Trade Item, a quantity of material that is sold by one trading partner to another trading partner
TRU	Traceable Resource Unit, a generic name for the object or unit that we are tracing
TU	Trade Unit, same as Trade Item, alternative term used in some papers
WP	Work Package, a sub-project within a (large) RTD project

On "Value chain" versus "Supply chain":

The concept of value chain was introduced by Michael Porter (1985) and can be defined as the process or activities by which a company adds value to an article, including production, marketing, and the provision of after-sales service. Value chain is a business management term, and it includes links in the chain that add value to the product without physically handling the product. Supply chain is a term from logistics and operations management, and refers to the material and informational interchanges in the logistical process stretching from acquisition of raw materials to delivery of finished products to the end user (Council of Supply Chain Management Professionals, 2013). The objective of supply chain management is to manage the flow of products from suppliers to consumers. While the value chain is important, traceability is a term more closely related to logistics, and in particular information logistics, so in this synopsis the term supply chain will be used to refer to the interlinked food businesses with supplier-customer relationships where the food items we want to trace originate and flow.

Writing style

The five papers included in this thesis are not in the list of references, and will in this synopsis be referred to as "**Paper I/II/III/IV/V**". The other papers, documents, reports, and standards listed above are in the list of references if they are explicitly referred to.

The papers included in this thesis use the third person voice ("we"), indirect reference ("the authors"), or passive voice ("the analysis shows …"). The first person voice ("I") is often avoided in scientific writing, as to many it comes across as subjective and unprofessional. However, in this synopsis I have frequently chosen to use the first person voice when I refer to myself. This is not to detract from the efforts and contributions of my colleagues and co-authors; it is an attempt to take responsibility for the assumptions and the decisions that I made in the field of food traceability, and the actions that I took. In addition, using the first person voice has the advantage that the text flows better, it is simpler to write, and it is easier to read. The objective of this synopsis is to provide a narrative to explain how all this came about, what the starting point was, what decisions were made underway and why, and for this purpose the first person voice seems a better and more honest choice.

When it comes to defining terms and concepts, there are frequent references to industry standards and glossaries in this synopsis, to a larger degree than to scientific articles. This is not because these terms and concepts have not been defined in scientific literature; rather it is because there are too many conflicting definitions there. There are fewer conflicting definitions in the industry standards and glossaries, these definitions typically have backing from industry organizations, and they are more practical in nature, and therefore more applicable in this thesis.

A final point to note is that the objective of this synopsis is not to cover and refer to a significant part of the extensive literature that exists on food traceability. Where references seem to be needed I have included them, but I have not referred to all papers that says something on a given issue, nor do I cover all the different points of view that exist. The research field on traceability is fairly new, and there is no common agreement on terms and definitions, so trying to cover everything that has been published can be more confusing than enlightening. In this synopsis, I have given priority to explaining and exemplifying what my view of traceability is, rather than attempting to cover all the views that exist, and this means that this synopsis has a lower density of references than what a scientific paper normally would have.

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1 Introduction

On a wine amphorae found in Tutankhamun's grave it says "Year 5. Wine of the House of Tutankhamun Ruler of the Southern On, l.p.h the Western River. By the chief vintner Khaa" (Cerny, 1965). These amphorae were buried more than 3300 years ago, and the inscription is one of the earliest examples of product labelling that has survived. It gives the vintage and the vintner, and it shows that for several millennia there has been an interest in additional information about the food (or in this case wine) that we consume. While this inscription would not normally be referred to as traceability, it is a recorded identification and it does give us access to information relating to "that which is under consideration" which in this thesis I will refer to as a Traceable Resource Unit (TRU). Food product labelling was voluntary (and often potentially misleading or directly false) for a long time until laws and regulations appeared that established labelling requirements and penalties for violating these. The full history of food labelling requirements is beyond the scope of this thesis, but one of the first instances of a law that dealt with the issue of food labelling and misbranding was the US "Pure Food and Drug Act". It was passed in 1906 where seizure and destruction was the penalty for food that was found to be mislabelled (Wilson, 2008). Food safety and consumer protection was the background for this act, and it specified 10 potentially dangerous ingredients (including alcohol, cannabis, and morphine / opium) that if present had to be declared on the label of the food or drug.

This very brief historical summary has highlighted two drivers for traceability (or product labelling) through the centuries:

- Product information in general, to inform the consumer, to establish a brand, and hopefully to build loyalty to that brand
- Food safety and consumer protection relating to declaring the presence or absence of potentially dangerous ingredients

Roughly 20-25 years ago quite a few things happened that significantly influenced the technological possibilities and the drivers for traceability and food labelling. Some of the most important of these were:

- The widespread use of cheap and more advanced label printing technologies
- The widespread use of bar codes on products, and the corresponding widespread use of bar code readers in the business sector
- The advent of the computer with the possibility to record, transmit, and receive large volumes of information electronically
- The development and widespread use of standardised globally unique number series for company identification, product type identification, and gradually also TRU identification
- Numerous large and well published food scandals affecting various sectors in the food industry
- Increasing consumer awareness on issues relating to the environment, sustainability, ethics, fair trade, animal welfare, etc.

Up until about 25 years ago, product documentation was facilitated by writing information directly on the product, on the product label or on the packaging, and there was a practical limit to how much could be recorded (Opara, 2003). After the technological advances indicated above this limit largely disappeared, and the food scandals and the increasing consumer awareness meant that a significant demand for more information about the food product was created; a demand which the new technologies could be used to satisfy.

These technological advances led to challenges within the field of information logistics. While "logistics" is "the process of planning, implementing, and controlling procedures for the efficient and effective transportation and storage of goods including services" (Council of Supply Chain Management Professionals, 2013), "information logistics" is much the same thing, but for data and recordings rather than for goods and services. The product information was no longer physically associated with the product; the information instead resided in a ledger or in a computer somewhere, and it was sent to the next link in the supply chain through other channels, often electronically. These developments to a large degree led to the importance of traceability in the food industry. As the product information developed channels, movement patterns, and a supply chain of its own, an organizing principle was needed to keep track of the information and the exchange of it. Traceability is that principle; if you have good traceability, information once recorded should never be lost, whereas if your traceability is imperfect, you are likely to suffer from systematic information loss somewhere in your supply chain (a more formal definition follows later).

In recent times, traceability has become an obvious necessity in the food industry (and in many other industries), and there are laws, regulations, businesses, guidelines, standards, and a burgeoning research field associated with the concept. Scholarly interest in food traceability came a bit later than industry interest, but nowadays there are well over 300 scientific articles published on the subject each year; see Figure 1.

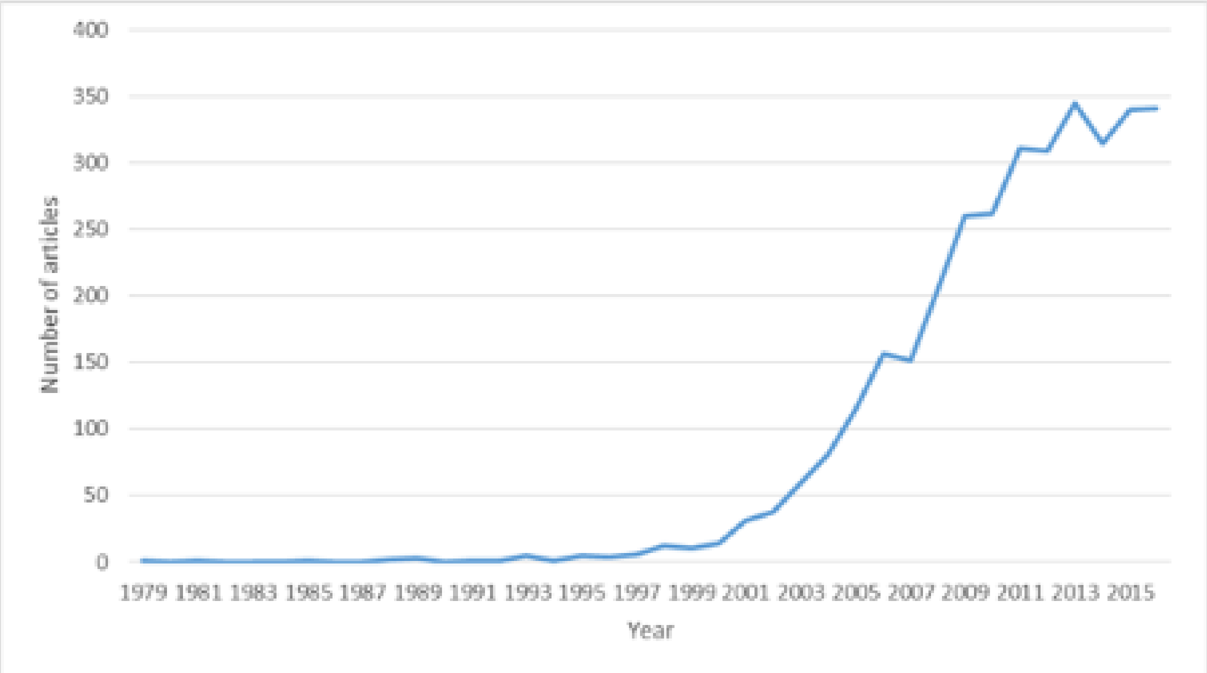

Figure 1. Scientific articles on food traceability published in the Scopus database in the period 1979-2016 (search term: "food traceability"; search date: 23.06.2017). ***From Paper 2****.*

This thesis outlines some of the overall and general developments in the field of traceability over the last years. While the oldest paper in this thesis is from 2010, the work that it reports on started before 2000, and it is still ongoing.

2 Research question and aim of the thesis

The overall aim of this thesis is to outline the theoretical background for food traceability, including how to define terms and concepts, as well as the practical application of traceability in the food industry. The thesis is based on five papers relating to different aspects of food traceability in theory and in practice, and the synopsis puts the papers into context, and provides additional information.

The papers have been selected to be as generally applicable in the food industry as possible, and they go into some detail when it comes to defining what traceability is, and what the overall components of a traceability system are. Based on these concepts, a method for analysing traceability in food supply chains is defined, and applications of this method and interpretation of the results is exemplified in a number of cases. The final paper outlines a framework for successful and efficient implementation of traceability in food chains, and to some degree summarizes the lessons learned in the work that led to the papers.

The aim of the synopsis is twofold:

1. To outline the 20+ years of work that led to this thesis and these papers, to indicate why and in which context the papers were written, and to highlight key findings, milestones and decisions along the way.
2. To serve as an introduction, or as a primer to the field of food traceability. It should be possible to read and understand this synopsis with only a minimum of pre-existing knowledge, and hopefully anyone who does so will gain insight into what food traceability is and how it works.

I have been giving university courses on food traceability since 2001; this thesis can be considered to be the extremely long and detailed version of those courses.

The associated research question underlying this thesis, loosely formulated, is "What is this thing called traceability, and how do I get it?", which logically leads to discussions of food traceability in theory and in practice. I have also worked a lot on the associated research question of "Why should I care about traceability, and what can it be used for?", but I have not attempted to answer this question in any detail here; that will be the subject of future scientific papers.

3 Personal background – From a failed PhD to a new research field

In 1993, I started working as a scientist at Fiskeriforskning in Tromsoe, which later became part of Nofima where I am now a senior scientist. My background was in computer science, systems analysis, programming, and applied mathematics. Initially I worked on projects that other people had initiated, but we were all encouraged to come up with our own ideas and to write our own applications for funding. In one of the projects, I visited numerous Norwegian fish processing plants, collecting data on production and yield. This was just a few years after electronic weighing was introduced, and there was great interest in studying factors that influenced yield, and in optimizing the production.

In the 1990s in Norway, the vessels normally delivered gutted, headless cod to the processing plants. To produce fillets the following process steps had to be undertaken:

1. Machine step – Remove the ear bone
2. Machine step – Remove the main bone, and split the fish into two fillets
3. Machine step – Remove the skin from each fillet
4. Manual step – Cut and trim the fillets, remove small bones

The project I was involved in tried to establish a benchmark for yield in the various process steps, and companies would once or twice per day select 10 or 20 fish that they weighed before and after each process step so that we could quantify the yield. Figure 2 outlines the production line for cod, with average yield numbers:

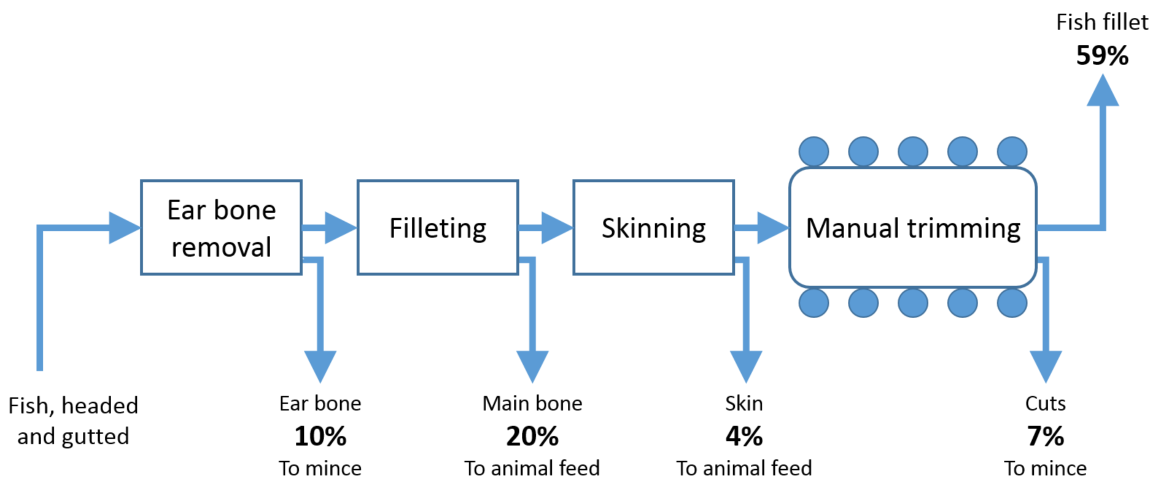

Figure 2. Material flow and yield when processing cod. From my 1995 PhD project description.

Unfortunately, the variation in these numbers was significant, and it depended on the gear used to catch the fish, time elapsed from catch to processing, the heading and gutting process, the storage and handling during this time, the weight, length and shape of the fish, the texture of the fish, the time of year, the type of machine, the time elapsed since the knives on the machine were sharpened, the experience of the machine operators, the experience of the people on the trimming line, etc.

With my background in applied mathematics and computer science, I got what I thought was an excellent idea for a project. I would use actual industry data from electronic weights in a number of processing plants and use multivariate statistics to develop a model that predicted yield in each process step based on the values of the parameters outlined above. Then I would write a computer program to simulate cod production, where the users could input the characteristics of the catch of the day, and play around with different options, e.g. what product to make, what machine to use, how many people to employ in the trimming process, etc.

In 1995, I submitted an application for a PhD project based on this idea to the Norwegian Research Council, and despite a lot of competition my application was funded. The PhD project would run from 1996 to 1999, and I was very happy. That did not last long. As I gradually discovered, there is a major flaw in the reasoning outlined above. I had assumed that the characteristics of the fish would be available to me both as the fish entered the processing plant and after each processing step. This was not the case. We knew, for instance, that gear type had significant influence on yield, and that fish caught in nets normally had lower yield than fish caught in trawls or on lines (Akse et al., 2012). However, the normal practice was that processing plants that received fish from net, trawl and line on the same day would grade (sort) the fish received according to size, and mix fish caught using different gear types, so there was no way to identify which gear type was used to catch a given fish after this process. Even if I focused on the properties of the fish that I could measure as they went into the first process, like weight, length or shape, there was no way to know what the original weight, length, or shape of fish (fillet) coming out of the system had been. Either the production management system did not keep track of this through the machine processes, or even if it did, the information was lost during the manual trimming process.

I had data on several thousand fish going into processing, and data on several thousand fillets coming out of processing, but the data was not connected, so I could not develop a relevant mathematical model. I could sum all the data going in and compare it with the sum of all data going out, but that would not be specific enough to enable me to do production simulation.

I did develop a computer program that simulated cod production, but as the underlying mathematical model was missing, the program was only used for education and training; not as a production planning and optimization tool as intended.

I had discovered a fundamental problem of traceability; the systematic information loss in a process in a supply chain. I came to realize that I had implicitly assumed that each fish had some sort of unique identifier associated with it, and that this identifier would be accessible to me after each process stage. This assumption is obviously wrong, but it was interesting that none of the experts that I had presented the idea to had spotted this. I got interested in traceability, which was a fairly new concept in the 1990s, and my colleagues and I submitted and got funded a number of national and international research projects; one of which was the TraceFish EU project, which is described later in this synopsis.

In 2000, I submitted the final project report to the Norwegian Research Council outlining my failure to obtain a PhD, and the closing paragraph reads as follows:

"Extensive data gathering from 6 processing plants in northern Norway and subsequent analysis showed that it was not possible to make a predictive model, and that most of the variation in yield (80% or so) are due to non-quantifiable factors or noise. … It is worth mentioning that [my] objective of obtaining a PhD within this field remains, even though the PhD as defined in this project could not be completed. The work undertaken in the projects [that were initiated as a spin-off from this project] is novel also on international level, and may provide the basis for future publications and a PhD title."

I am admittedly very late in delivering on the intention that I expressed more than 17 years ago.

4 Terms and concepts

The following constitutes a short, and by no means exhaustive, primer on traceability terms and concepts. On some of these terms where there are conflicting or ambiguous views or descriptions, the definitions most consistent with normal practice in the food industry, as indicated in key industry documents and standards, has been selected. There is some overlap between the terms and concepts defined in this synopsis and some of the papers and reports I have contributed to, including some of the papers included in this thesis. The purpose of this overlap is to increase readability, and to ensure that the synopsis can be read as a stand-alone document.

4.1 Batch

A relevant dictionary definition of batch (or lot) is "the quantity of material prepared or required for one operation" (Farlex, 2017). In supply chains for food products, we commonly refer to raw material batches, ingredient batches, and production batches (see Figure 3), but this distinction is not always applicable. Batch is an internal term in the company (or Food Business Operator (FBO), which is the general term for an actor or a process in the supply chain that handles food products). A production batch in the food industry is typically everything produced of one product type in one unit of time, e.g. a day or a shift. Batch identifiers are often locally generated in the FBO, and do not normally adhere to any external standards. Batches are not necessarily physically labelled in the FBO as long as the FBO knows what constitutes a given batch.

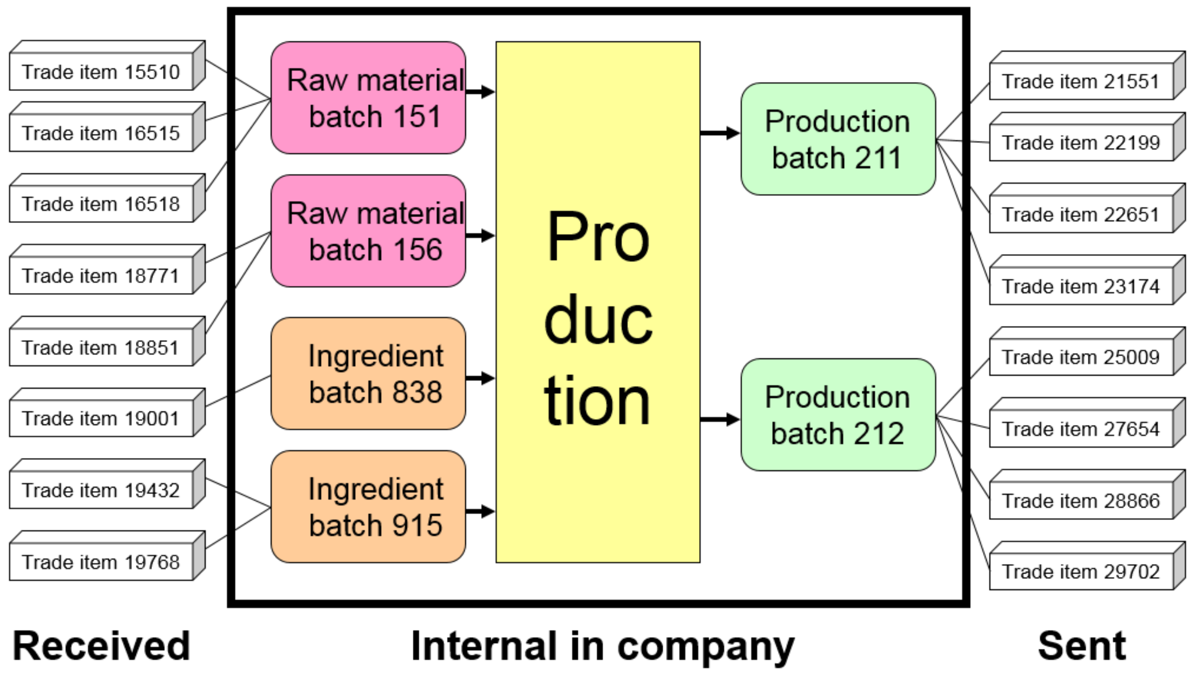

Figure 3. Example of batches and trade items seen from the perspective of a Food Business Operator (FBO). Modified from ***Paper III****.*

There is a whole research sub-field relating to traceability of continuous batches, and there are some special implementation and data recording considerations in sectors where batches are not discrete and clearly separated. I have not elaborated on this special case; for more information on this issue see the thesis of Kvarnström (2008) or Thakur (2010).

4.2 Trade item

A Trade item (TI), also referred to as Trade Unit (TU), is a quantity of material (e.g. a food product) that is sold by one trading partner to another trading partner. GS1 defines trade items as products or services that are priced, ordered or invoiced at any point in the supply chain (GS1, 2017a). Trade items received by a FBO are often merged or mixed into raw material or ingredient batches, e.g. when captured fish is sorted by size and quality before processing. Production batches are normally large, and they are often split into numerous trade items before shipping; see Figure 3 for the relationship between batches and trade items. Trade items have to be explicitly labelled and identified by the producing / selling FBO so that the receiving / buying FBO can identify them. It is not uncommon for trade items to be identified by the (production) batch number they belong to. This makes traceability more difficult and less precise, as numerous trade items will then have the same identifier. See discussion on one-to-one relationships between TRUs and TRU identifiers in section 4.7.

4.3 Traceable Resource Unit (TRU)

As indicated, batches are internal in a company, whereas trade items are exchanged between trading partners in the supply chain. A traceability system needs to keep track of both batches and trade units, and the common term for "the unit that we want to trace" or "the unit that we record information on in our traceability system" is Traceable Resource Unit (TRU) (Kim, Fox, & Grüninger, 1995) (Moe, 1998). In this synopsis, unless the internal or external nature of the food item is of importance for the discussion, the term TRU will be used, and it encompasses both internal batches and items traded in the supply chain.

4.4 TRU attributes or properties

In a traceability system, an important functionality is to keep track of are the attributes or properties of the TRU in question; see **Paper II**. TRU attributes or properties represent "that which we know about the TRU in question", which might be the TRU identification number, the product type, the product condition, the production date, the net weight, the raw material used, and so on. Different papers and documents us different words for this concept, but for the purpose of the discussion in this synopsis, "TRU attribute" is synonymous with "TRU property", and the words are used interchangeably. For a given TRU, the attributes have names and values, e.g. the attribute name might be "Fat", and the value for that attribute might be "12%". See Figure 14 in the section on "Traceability and standards" for detailed examples of attributes with name, description, example values, and categorization.

4.5 Granularity

A relevant dictionary definition of granularity is "having a high level of detail, as in a set of data" (Farlex, 2017). When the level of detail is high, we refer to "granular data", "high granularity", or "fine granularity". Granularity depends on the physical size of the TRU; the smaller the TRU, the more TRUs we have, and the higher or finer the granularity. When implementing a traceability system, companies have to make a decision on the granularity they want. A FBO typically chooses whether to assign a new production batch number every day, every shift (e.g. 2-3 times per day) or every time they change raw materials (e.g. 1-20 times per day) (Riden & Bollen, 2007). The higher the granularity, the more TRUs they will have, the more work will be involved, and the more accurate the traceability system will be. Granularity can be a particularly important consideration when planning for potential product recalls; the coarser the granularity, the more products will have to be recalled if anything goes wrong (Dabbene, Gay, & Tortia, 2014). Granularity is discussed in more detail in **Paper IV**.

4.6 TRU identifiers and uniqueness

TRUs are given identifiers in the form of numeric or alphanumeric codes. These identifiers are either assigned by the company that generates the TRU, or they are mutually agreed between trading partners, often with reference to standards. The identifiers must be unique in their context so that there is no risk of the same identifier accidently being assigned twice (Bertolini, Bevilacqua, & Massini, 2006). Ensuring uniqueness internally in a company is not too difficult; most companies have defined a coding scheme (normally used on batches) that ensures that within that company the same identifier is not used twice. Ensuring uniqueness when many trading partners are involved (typically for trade items) is more difficult, and the most common solution is to use globally unique identifiers. These are typically constructed by combining country codes with company codes that are unique within the country in question, and using this number as a prefix for TRU codes generated by the company. GS1 is the organization that keeps track of globally unique number series, and makes sure that numbers are not accidentally used again. GS1 has published a number of documents, standards, and good practice recommendations relating to this (GS1, 2007, 2017b). Se **Paper II** for a detailed description of how GS1 codes may appear.

4.7 One-to-one relationships between TRUs and TRU identifiers

While the TRU identifier must be unique within its context, practice differs in relation to whether this unique identifier can only be assigned to one TRU, or whether the same unique identifier can be applied to multiple TRUs. The first practice is referred to as the licence plate (or person number) principle. If there is a one-to-one relationship between TRUs and TRU identifiers, then each TRU will have its own unique identifier, not to be shared with any other TRUs; see Figure 5.

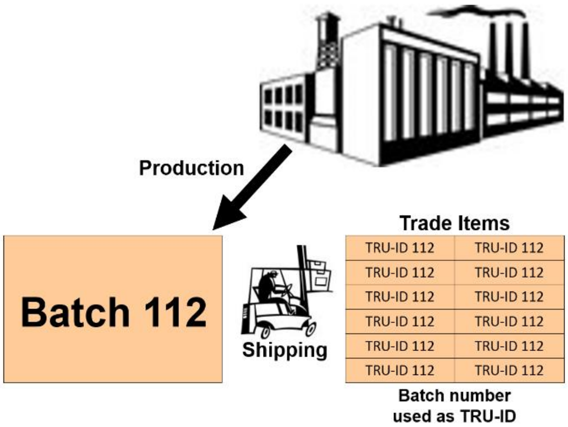

Figure 4. Batch number as TRU identifier

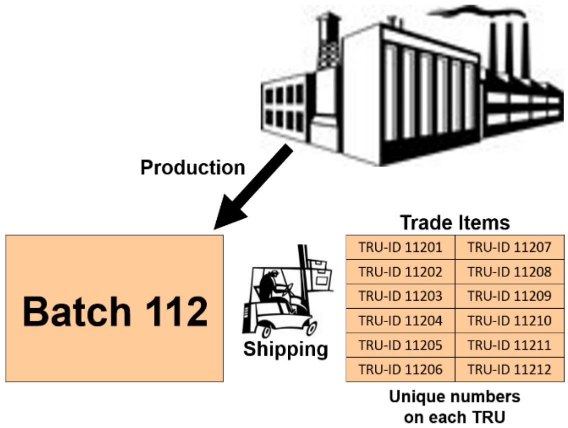

Figure 5. One-to-one relationship between TRU and TRU identifier

If the same TRU identifier is present on multiple TRUs this will limit the effectiveness of the traceability system; see Figure 4. Even if the identifier “112” is unique in a given context and has a number of properties associated with it (e.g. producer, production date, product type, raw material used, etc.) it is not possible to use the identifier to find one particular TRU. While all the TRUs that share an identifier will have the original set of properties in common (e.g. they all come from the same farm and were produced on the same dates), it is not possible to distinguish between individual TRUs. In addition, it is not possible to record further properties related to each TRU (e.g. date/time and location for that particular TRU, date/time and temperature for that particular TRU, etc.). It is not uncommon in the food industry to use the internal production batch number as identifier for each trade item that is generated and sold; this does not provide a one-to-one relationship between TRU and TRU identifier. Traceability systems that are not based on one-to-one relationships may be simpler (shorter codes) and cheaper (less generation of codes, less reading of codes), but they will inherently suffer from the limitations indicated, and there will be numerous potentially relevant TRU properties that these systems can never keep track of.

In some papers (including some papers in this thesis), a one-to-one relationship between TRUs and TRU identifiers is referred to as “referential integrity”, but after some consideration we no longer use this term, because it has a slightly different meaning in the field of computer science / database design, and this might cause confusion.

4.8 Transformations

New TRUs are created at specific times, typically when the raw material is harvested, when processes generate products in a given time period, or when existing TRUs are split up or joined together. When new TRUs are generated based on existing ones this is called a transformation; typical transformation types are joins, splits and mixes; see Figure 6.

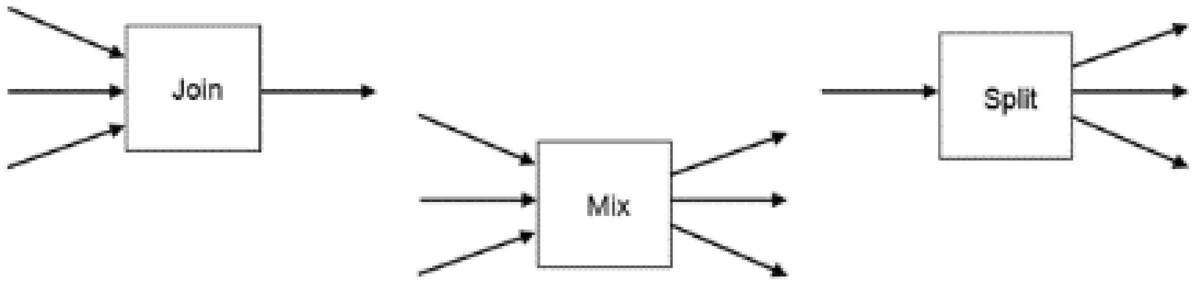

Figure 6. TRU transformation types

To document a transformation one needs to document exactly which existing TRUs were used to create a new batch or trade item; often it is also relevant to record the amounts or percentages used.

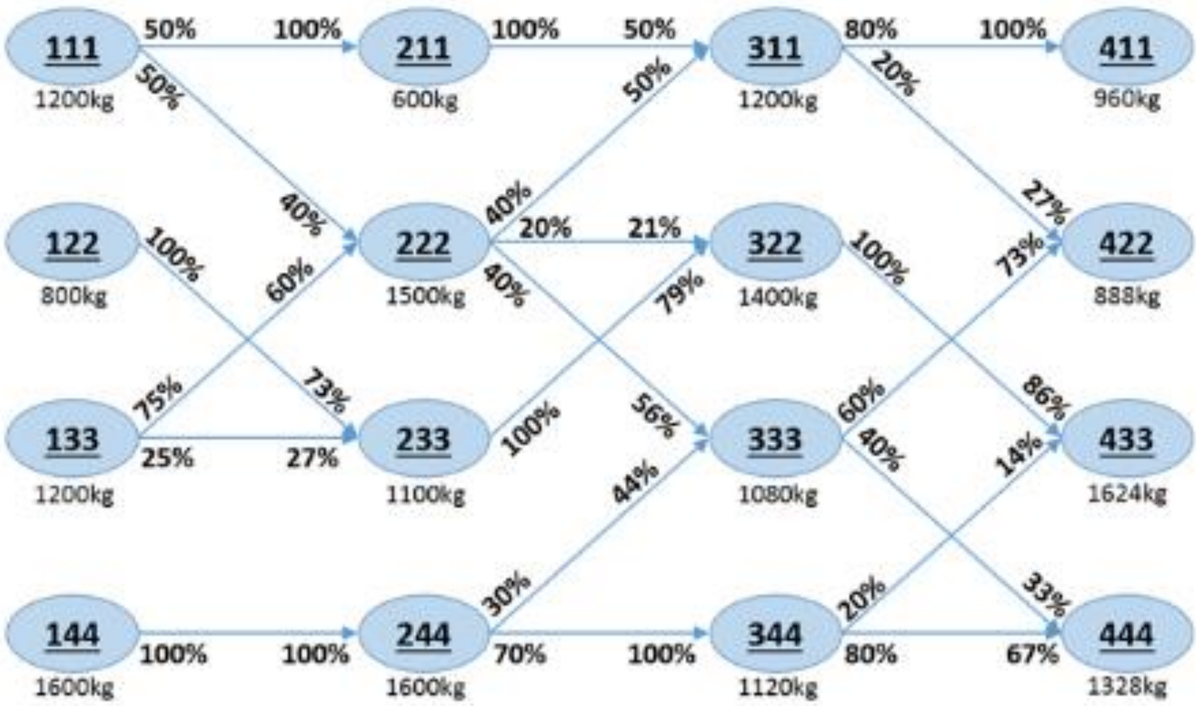

*Figure 7. An example of a traceability tree with four processing stages. From **Paper II**.*

In Figure 7, the circles are TRUs, and the underlined numbers in the circles are TRU identifiers. The arrows indicate transformations; e.g. TRU 111 is split into TRU 211 and TRU 222, and TRU 211 is joined with part of TRU 222 to make TRU 311. TRU weights, and transformation percentages are also indicated. A diagram of this type is called a "traceability tree", and while this might look complex, it only shows 4 process steps and 16 TRUs; a real life chain would have many times that number.

Normally trade items are smaller than the internal batches, which means that received trade items are often joined together to make raw material batches, and production batches are split into smaller trade units before they are sold. The overall supply chain with numerous TRUs being created, split up, and joined together can be very complex.

4.9 Traceability

There are numerous definitions of traceability (Jansen-Vullers, van Dorp, & Beulens, 2003), most of them recursive in that they define traceability as "the ability to trace" without defining exactly what "trace" means in this context. An attempt to merge the best parts of various existing definitions while avoiding recursion and ambiguity is made in **Paper I**, where we define traceability as "The ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications". This emphasises that any information can be traced, that traceability applies to any sort of object or item in any part of the life cycle, and that recorded identifications need to be involved. The latter requirement is important when it comes to differentiating between traceability and traceability control mechanisms; i.e. methods and instruments that measure biochemical properties of the food product. These are used for authentication and testing whether what is claimed in the traceability system correspond with the actual TRU attribute; see further discussion on this in chapter 5.

Traceability depends on recording all transformations in the chain, explicitly or implicitly. If all transformations are recorded, one can always trace back or forward from any given TRU to any other one that comes from (or may have come from) the same origin or process. In addition, traceability requires relevant information to be recorded and associated with every TRU in the supply chain. This makes it possible to find the origin of a given TRU (the "parents"), the application of the TRU ("the children"), and also all properties of every TRUs (when and where was it created, weight or volume, what form is it in, what species, fat content, salt content, etc.).

4.10 Chain of Custody

Traceability is related to, and sometimes confused with another term in the realm of information logistics, which is Chain of Custody (CoC). In the context of fisheries FAO defines CoC as "*The set of measures which is designed to guarantee that the product put on the market and bearing the ecolabel logo is really a product coming from the certified fishery concerned. These measures should thus cover both the tracking/traceability of the product all along the processing, distribution and marketing chain, as well as the proper tracking of the documentation (and control of the quantity concerned)*." (FAO, 2009a). Hence, while traceability and CoC to some degree have the same goal (well-documented products), the approach is rather different (Borit & Olsen, 2012) (Borit & Olsen, 2016).

Traceability is generic and non-discriminatory; the company receives trade units, splits, joins or merges trade units into raw material batches, makes production batches based on the raw material batches, and finally splits the production batches into outgoing trade units. At each stage, a spilt, join or merge can take place, which will be recorded in the traceability system so that all transformations and dependencies are documented. The golden rule in a traceability system is that "you can do 'anything' (as far as the traceability system is concerned), but you must document what you are doing".

With CoC, there is one particular set of attributes that it is desired to protect, retain, and document (e.g. fair trade, organic production, or a particular origin) while other attributes are considered to be less important. A CoC identifier will be assigned to all products produced by the FBO with the given attribute, and the same CoC number may be assigned to many different production batches, even from different suppliers. The golden rule in a CoC system is that "you can only mix units that have the same CoC number, and if you do so, the CoC number is retained".

CoC is often used when producing according to eco-label requirements; then the attributes associated with the CoC number are those which are required for certification in accordance with the eco-lablel in question. CoC can be a relevant and useful approach in some circumstances, but it is not the same as traceability. The ISO Technical Committee ISO/PC 308 was established in 2017 to standardise the definition of Chain of Custody for food products in general, and the yet unpublished ISO 22095 "Chain of custody -- Transparency and traceability -- Generic requirements for supply chain actors" is under development where the relationship between CoC and traceability will be clearly defined.

4.11 Internal traceability

Internal traceability is the traceability within a link or a company (Moe, 1998), see Figure 8. On a farm or fishing vessel the first step is recording information related to the harvest or catch; in the other links the first step is recording information related to the received trade items. Subsequently, information on all the other internal steps needs to be recorded, including all transformations that take place and all relevant properties related to internally generated batches or trade items. Internal traceability is the backbone of traceability in general; everything else depends on each company in the chain having good systems and good practices when it comes to recording all the relevant internal information. Internal traceability mainly deals with batches, but the relationship between incoming trade items and raw material (or ingredient) batches needs to be recorded, and also the relationship between production batches and outgoing trade items. Internal traceability is the domain and responsibility of a single company, data confidentiality or access is not a big issue, and several good systems, solutions, practices and standards have been developed in this area.

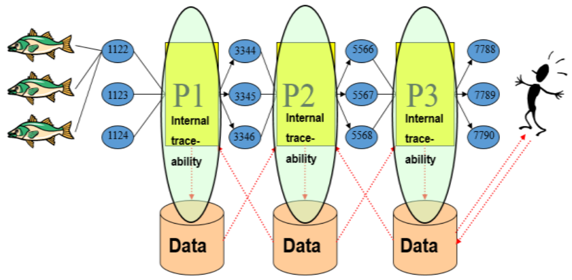

Figure 8. Internal traceability

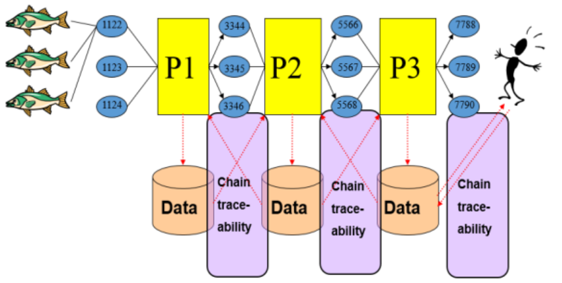

Figure 9. Chain traceability

4.12 Chain traceability

Chain traceability is the traceability between links and companies, and it depends on the data recorded in the internal traceability system being transmitted, and then read and understood in the next link in the chain (Moe, 1998), see Figure 9. Data can be transmitted in various ways; the simplest being by physically (on the label) or logically (in accompanying documentation) attaching the information to the product when you send it. A more flexible way of implementing chain traceability is for trading partners to agree on a way of identifying the trade items, and then to send the required information through another channel (fax, mail, electronically integrated systems, etc.) while referring to the trade item in question. This is commonly referred to as “information push”; as the amount of data grows ever larger, “information pull” has also gained popularity as a way of implementing chain traceability. This is when the trading partners agree that the seller should retain and make available information about the trade item in question on request (Lehr, 2013). This could be a request submitted by telephone or fax, but in modern electronic systems this functionality is typically accomplished by trading partners sharing an intranet where the supplier provides detailed data on all trade items, and the buyer can extract whatever data is needed. Chain traceability is more complex to achieve than internal traceability, because it requires the cooperation and agreement between at least two (in practice more) FBOs, and data confidentiality and levels of access are a big issues. Chain traceability is often closely related to Electronic Data Interchange (EDI), which in turn depends heavily on the agreement on -, and adoption of standards both when it comes to media, identifiers, content and structure of the data that are to be exchanged. See discussion in “Traceability and standards” section.

4.13 Traceability systems

Traceability systems are constructions that enable traceability; they can be paper-based, but more and more commonly they are computer-based. Several detailed descriptions of traceability systems in various food sectors have been published, and there is general agreement on what requirements a traceability system should fulfil (Moe, 1998) (Mgonja, Luning, & Van der Vorst, 2013).

- It should provide access to all properties of a food product, not only biochemical properties that can be verified analytically.
- It should provide access to the properties of a food product or ingredient in all its forms, in all the links in the supply chain, not only on production batch level.
- It should facilitate traceability both backwards (where did the food product come from?) and forwards (where did it go?).

As indicated in **Paper I**, this means that the following activities must be carried out:

1. Ingredients and raw materials must be grouped into units with similar and defined properties, commonly referred to as TRUs (Moe, 1998) (Kim et al., 1995).
2. Identifiers / keys must be assigned to these units. Ideally these identifiers should be globally unique and never reused, but in practice traceability in the food industry depends on identifiers that are only unique within a given context (typically they are unique for a given day's production of a given product type for a given company).
3. Product and process properties must be recorded and either directly or indirectly (for instance through a time stamp) linked to these identifiers.
4. A mechanism must be established to facilitate access to the recorded properties.

In practically all FBOs we have an internal traceability system; often software with ample opportunity for browsing data, visualizing dependencies (which TRUs were based on which TRUs), and creating reports related to what happens within the company. Implementing similar functionality for a whole supply chain, where we can examine the whole chain of transformations from raw material source to consumer, is a (and probably "the") major challenge, and requires effort, motivation and cooperation, in addition to the presence of technical solutions that build on well-proven and widely adopted standards. Verification and validation of the data in the traceability system is of course also very important, but these are external processes and not part of the traceability system itself.

The terms and concepts outlined in this chapter forms the basis for the theoretical approach that my colleagues and I have developed in the field of food traceability.

5 Food traceability in theory

The theoretical work that I have been involved in has largely been based on practical project work, followed by discussions and generalizations, and only later on production of standards and publications. The theory was based on the practical implementation experience, not the other way round. Traceability was a new field in the mid / late 1990s, and although reports and publications existed, there was no widespread agreement on what terms meant, what traceability entailed, what components a traceability system should have, or how to implement it. Some other disciplines existed where the term traceability was used, or where some underlying concepts were similar. This chapter outlines some of these other disciplines which influenced our initial approach to traceability, and gives some background for the theoretical approach that my colleagues and I eventually chose, which is part of the basis for this thesis, and which led to the publication of the two papers included in this chapter.

5.1 Traceability in relation to other scientific disciplines and research areas

This section examines some of the other disciplines that influenced our way of thinking, especially in the early years. Food safety was a strong driver for traceability, and it took some time before we could convince our colleagues that traceability was not in fact a sub-field under food safety. A number of analytical methods existed, and some scientists in this field referred to what they did as "traceability", or "analytical traceability" (Peres, Barlet, Loiseau, & Montet, 2007). It was important to draw a distinction between what these scientists were doing, in contrast with those of us who were working with traceability as outlined above, where "recorded identifications" was the basis, rather than analytical measurements. Laws and regulations also referred to traceability, especially after a number of large food contamination incidents around 2000; one of which was the Belgian dioxin incident (Bernard et al., 2002) which is examined in more detail in the "Traceability and food safety" section. My background in computer science and programming also influenced my approach to traceability; especially the Object Oriented Programming (OOP) paradigm, where there are many parallels to traceability, TRUs, chains, and transformations.

5.1.1 Traceability and object oriented design

As a systems analyst and programmer, I was trained in Object Oriented Programming (OOP). This is a programming paradigm based on the concept of so-called objects, which may contain data as well as methods / procedures that do something to the object in question. If the data has several parts it is referred to as a record, and each named part of the record is referred to as a field or an attribute. For instance, the data in a given object might refer to a person, and each of the data elements we record about that person ("first name", "last name", "date of birth", etc.) is a field / attribute. An important principle is that of inheritance, so that if object B is created from object A, object B inherits all the fields that object A has. Thus, if we created an object type to represent employees, and we based this object type on the person object, the employee object would inherit the fields "first name", "last name" and "date of birth", and in addition we could add more fields (like "department" or "salary") which only applied to the employee objects, but not to the person objects. In programming terms, the original object (person) is called a "parent", and the new object created (employee) is called a "child".

For me, this way of thinking was the starting point when trying to model TRUs and traceability. Each TRU is an object, and it has many attributes; e.g. an identification number or code, a creation date, where it was created, who the owner is, the product type, the net weight, and many more depending on what type of TRU it is. Inheritance also applies to TRUs; if you use one TRU to create another TRU (for instance through a split or a join), the newly created TRU will inherit many of the attributes of the parent TRU, and also some of the attribute values. This might sound complicated, but it simply means that if you have a production batch of 1000 kg of ground beef, and you split it up into 1000 trade units of 1 kg each, then each of the created TRUs will inherit many attributes, and also some attribute values from the parent TRU (Dupuy, Botta-Genoulaz, & Guinet, 2005). For instance, the attribute value of "slaughter date" will be inherited, because the slaughter date has not changed when we created the new TRUs, but the attribute "net weight" will not be inherited, because the net weight of the created TRU is not the same as the net weight of the parent TRU. Obviously, the "parent" / "child" concepts are also immediately applicable to TRUs; we call the TRU that is split or joined "parent", and we call each TRU that is created "child".

A background in OOP is in no way required to understand traceability, but it did provide me with a very useful starting point and an approach that I believe has made it easier to think about traceability in a structured manner. This has been particularly important when formulating traceability standards, which are structured in a way that closely matches the object / record / attribute name / attribute value paradigm; see section on "Traceability and standards". These terms are also widely used in the rest of this thesis.

5.1.2 Traceability and food safety

Traceability is a principle (or tool, when implemented in a traceability system) that has very important applications in the field of food safety (J. K. Porter, Baker, & Agrawal, 2011). As the supply chains have become longer and more complex, traceability has become more and more important when it comes to ensuring food safety. However, it is worth pointing out that not only is food safety and traceability not the same thing, but they are not even the same type of concepts. Traceability in its nature is descriptive; a traceability system does not care about the values of any attributes; the objective in a traceability system is that data once recorded should never be lost. When it comes to food safety on the other hand, some TRU attribute values are very important, and will determine whether there is or might be a food safety issue or not. Seen from a traceability perspective, the attributes that are related to food safety (like "production date" or "temperature log") are very few, and most TRU attributes recorded in a traceability system have little to do with food safety. However, the main overlap between traceability and food safety is the focus on documenting transformations, which is essential in both contexts. Recording of transformations is essential in a traceability system, because when TRUs are split or joined, we need to preserve a link from TRU child to TRU parent, otherwise information is lost. Recording of transformations is essential also for food safety purposes, because if a TRU is contaminated, it may have come from the parent TRU, and it is very likely to affect all the child (and grandchild, and so on) TRUs. If contamination is discovered, one of the most important first steps is to try to identify the source of the contamination, and that means tracing backwards, from child to parent (Jansen-Vullers et al., 2003). Once the source of the contamination has been discovered, it is crucial to issue a recall, and preferably a targeted recall, which only focuses on actually contaminated food items. This means tracing forwards (also called tracking in some contexts), from parent to child (Jansen-Vullers et al., 2003).

To illustrate how traceability and food safety are connected, we can examine the so-called dioxin scandal that affected the chicken industry in Belgium and in the rest of Europe in 1999. The following is a brief summary of the sequence of events that happened (Lok & Powell, 2000) (Bernard et al., 2002) (Buzby & Chandran, 2003):

1. In January 1999 a car demolition company in Wallonia, Belgium delivered oil from a transformer to a municipal oil recycling plant. The oil contained polychlorinated biphenyls (PCBs) contaminated with about 1 gram dioxin. By accident, the oil ended up in a vegetable oil storage tank.
2. A company that produced vegetable oil collected oil from the tank, and produced contaminated oil.
3. A company that produced vegetable fat bought the oil, and produced contaminated fat.

4. A company that produced feed bought the fat, and produced contaminated feed, mainly chicken feed.
5. Egg producers noticed chicken sickness and reduced egg quality, there were numerous complaints, and the government and insurance companies got involved.
6. The “feed” company stopped selling feed, and reported the “fat” company to the police.
7. PCB / dioxin was identified as the contaminant, all feed production in Belgium was stopped, and the neighbouring countries were informed.
8. On May 27th the first public press statement was issued, and the press accused the government of attempting to cover up the case.
9. The management of the “fat” company was arrested, the management of the “oil” company was arrested, and the Belgian minister of agriculture and the minister of health were forced to resign.
10. The Belgian government estimated the direct economic loss as a result of these events at least to be 465 million Euro in Belgium alone; the European Commission estimated the total loss to be close to 1500 million Euro (Buzby & Chandran, 2003).

Now this case was obviously mainly about food safety, but as such, there have been many worse cases. The enormous costs associated with this event was not mainly because of the effect in itself; there were no human deaths associated with this, and only a limited number of animals were affected. The problem here, and the enormous cost, was related to the scope of this incident, and the fact that it was almost impossible to contain it, and this in turn relates to traceability, or lack of it. Firstly, it took a long time from when contamination was discovered until the source of the contamination was found. Secondly, after the original contamination had been identified, it turned out to be impossible in practice to recall only the contaminated feed and the contaminated food items. There was no legal requirement in the EU in 1999 to keep track of those you received food items from or those you sold food items to; that law came three years later, as a direct result of this incident (European Commission, 2002). Farmers in Belgium in 1999 bought and used feed, and when the incident was discovered a few months later, the farmers had no record of what feed they had bought (certainly not the details, like production date or batch number), and the feed producing company had no record of exactly who they had sold the contaminated feed to. In traceability terms, the transformation was not recorded, and there was no link between parent TRU and child TRU. This, coupled with the fact that the number of potentially contaminated farms and products was so large, led to the widespread recall and destruction of Belgian egg and poultry products (including Belgian chocolate, which could contain egg yolk) across Europe.

This is only one out of hundreds of food safety cases where a large part of the problem was closely related to traceability, or lack of it. Two years earlier, in 1997, the largest US recall ever (over 11.000 tons) had been issued on hamburgers originating from Hudson Foods in Arkansas, and as a result of this the value of the company was reduced so much that it was bought by a competitor shortly afterwards (Walsh, 1997). The federal report after the incident indicated “*the reason for the addition recall is that Hudson took leftover raw materials from one day’s production and used them in the next day’s production*” (CNN, 1997), which in traceability terms means that there was no separation of batches.

Today, there is still a very strong link between traceability and food safety, but it is clear that if you want a good food safety system, you need to include many other aspects and considerations in addition to traceability (hygiene, for one), and it is also clear that traceability has many other applications than food safety.

5.1.3 Traceability and methods for analysing biochemical food item properties

There are a number of methods used for analysing the biochemical properties of food items (Peres et al., 2007). These include DNA-based analyses, stable isotope and trace element analyses, analysis of lipid profiles, high-performance liquid chromatography (HPLC), gas chromatography–mass spectrometry (GC-MS), nuclear magnetic resonance (NMR) spectroscopy, near-infrared (NIR) spectroscopy, metabolite profiling, chemical profiling, proteomics, and many more. Collectively these methods are referred to as "analytical methods", and what they have in common is that they analyse a food item sample, and conclude with respect to the value of one, or set of biochemical food item properties. Properties that to some degree can be verified by analytical methods include species, geographical origin (broadly), process status (e.g. fresh or frozen), presence of additives, some aspects of organic production, remaining shelf life, and some others, depending on the type of food item (Peres et al., 2007). While the list of food item properties that can be verified analytically is extensive and growing as the methods and technologies improve, it is worth noting that this is only a small sub-set of the properties recorded in a traceability system. Analytical methods cannot tell you who the owner of the TRU is, or the name of the farm or farmer, or the route the TRU took in the supply chain, or whether the production was ethical of fair trade, or similar. While practitioners and publications sometimes refer to these types of methods as "methods for traceability" that is inaccurate, at least in relation to most definitions of traceability (including the one chosen here), because they do not deal with "recorded identifications". What these methods can be used for is to verify some of the claims in the traceability system. It is important to keep in mind that a traceability system is made up of statements that are claimed to be true, but we do not know for sure that they actually are true, so that is something we need to check.

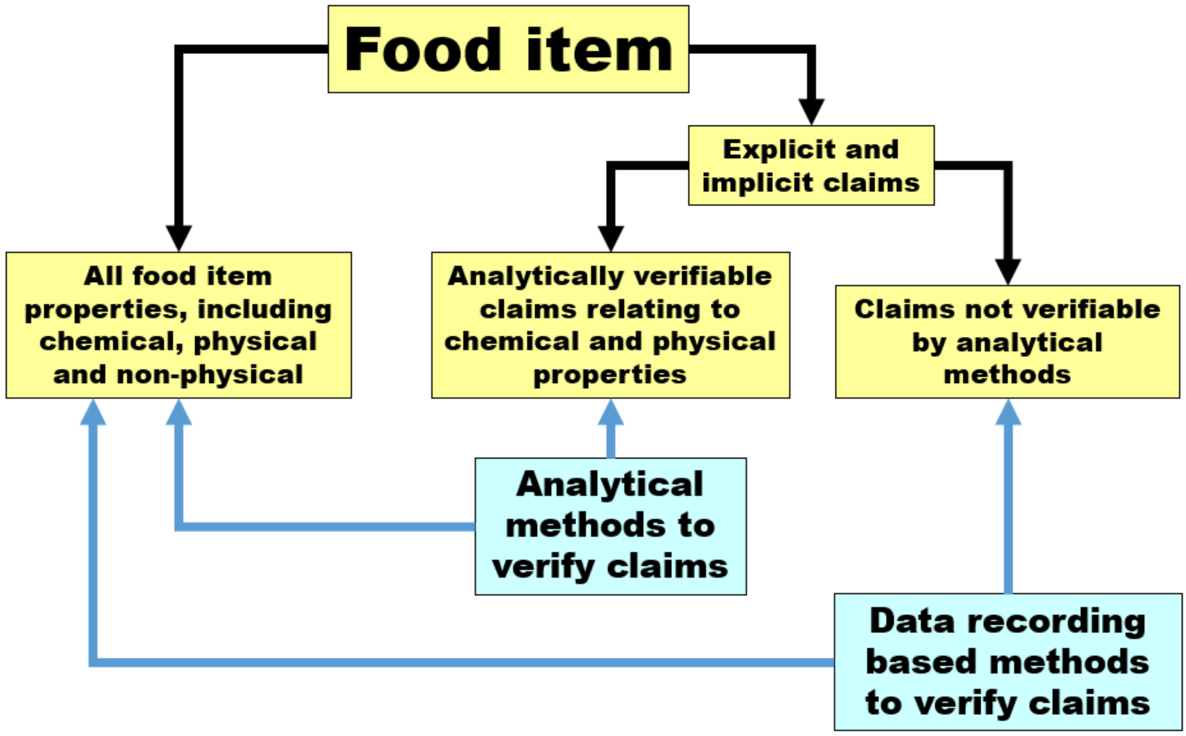

Figure 10. Relationships between claims and methods to verify them

Figure 10 illustrates the relationship between food item properties on one hand, and the claims in a traceability system on the other. Claims may be explicitly stated in the traceability system, or they may be implicit in that if the food item had that property (contained nuts, was made from genetically modified material), it should have been declared. The claims, whether implicit or explicit, fall into two categories; those that can be verified by analytical methods, and those that cannot. If we want to verify a claim in the first category ("this product is made from cod"), we can utilize analytical methods and get a true/untrue answer, or sometimes a likely/unlikely answer. If we want to verify a claim that is not related to a biochemical property ("this TRU came from the farm of Jim Jones") we need to look into the data recordings in the system, especially the transformations ("Did Jim Jones deliver to the FBO that made this TRU?"). Using methods based on analysing data recordings cannot actually verify the claim, but they can often indicate if the claim might be true or not ("No, according to the records, Jim Jones has never delivered anything to the FBO that made the food item in question").

This means that analytical methods are very important when we are dealing with traceability, but they do not in themselves provide traceability. What they do provide is a way of verifying most of the claims relating to biochemical attributes of the food item in question. While these claims are only a subset of the total number of claims in a traceability system, they are among the most important ones, because if there is a food safety problem related to a food item, it will be detectable through application of analytical methods, and food safety, as we have seen, is strongly linked to traceability.

5.1.4 Traceability, laws and regulations

In some areas laws and regulations constitute important drivers for traceability, and in some food sectors there are extensive and detailed regulations specifying exactly what information must be recorded and shared. One example of such a sector is the captured fish sector, where both the EU, the US, and other countries have regulations in place (European Commission, 2008) (European Commission, 2009) (National Ocean Council Committee on IUU Fishing and Seafood Fraud, 2014) with extensive traceability requirements designed to prevent the introduction of Illegal, Unregulated and Unreported (IUU) fish into the legal supply chain (Borit & Olsen, 2012). In this thesis, I have chosen to focus on traceability in general, so I will not go into detail on the existence of this type of national or sector-specific laws and regulations around the world, and what requirements for traceability are inherent in them. For more details on this issue, see (Charlebois, Sterling, Haratifar, & Naing, 2014) or the thesis of my colleague Kathryn Anne-Marie Donnelly (2010).

In general, the most common legal requirement for food traceability is "one up, one down" traceability. As an example, Article 18, part 2 of EU regulation 178/2002 (European Commission, 2002) commonly referred to as the Common Food Law says "*Food and feed business operators shall be able to identify any person from whom they have been supplied with a food, a feed, a food-producing animal, or any substance intended to be, or expected to be, incorporated into a food or feed*." Article 18, part 3 of the same regulation says "*Food and feed business operators shall have in place systems and procedures to identify the other businesses to which their products have been supplied*." This general requirement is fairly weak, and these days most FBOs have systems in place for recording and documenting who they buy from, and who they sell to anyway, regardless of regulations. With that said, laws and regulations containing traceability requirements for food products can be important for two reasons. Firstly, they clearly define what the minimum requirements are, and they outline penalties for violating these requirements. Secondly, they can act as drivers for implementation of traceability for small producers, and in some regions of the world. Even if these regulations do not apply in the exporting country, they have to be met if an FBO wants to sell to a market where such requirements do apply. This means that the traceability system used by the FBO, and the information the FBO provides about the product, must be more extensive than what is locally required. This has led to an interesting situation, in that often food producers in developing countries are more motivated, and have better traceability systems than in industrialised countries (personal observation in Vietnam, South Africa, and China). In some developing countries, they want market access for their products, and they are willing to do what it takes. In industrialised countries, food producers already have market access (to their home market at least), and so traceability might be less of a priority.

5.2 Theoretical approach

As indicated, the theoretical approach that my colleagues and I initially chose was partly based on the fields that were closely related to traceability (food safety, analytical methods, laws and regulations, and in my case, object oriented design) and partly on practical experience in numerous implementation projects. Our goal was to get traceability and traceability systems to work in practice, and to a large degree, we employed a trial and error approach. We did the best we could in one project, learned from our mistakes, and tried to do a better job in the next project. This worked reasonably well; with our knowledge from -, and background in the other related research fields we didn't make too many initial mistakes, and when something didn't work as intended, we improved on it the next time. Our goal was not to establish a theoretical framework; when my colleague and friend Tina Moe, who I worked closely with in various traceability projects in the late 1990s, asked if I would be interested in collaborating on a scientific paper with her (Moe, 1998), I declined, as I could not really see the point. However, my opinion changed a few years later when I got involved in some large European traceability projects, and it turned out that the people we worked with there had completely different (and in my opinion, misguided) notions of what traceability was, and what it entailed. I found that I had to explain and argue with one scientist at a time about traceability and what it was, and it would have been so much easier if I had a paper to refer to. In the TRACE project (see section on "International food traceability projects") we had to establish an internal glossary to reduce miscommunication between project participants, and several years later a part of that led to **Paper I**, outlined below. The other theoretical paper included in this thesis is **Paper II**, which names and defines the components of a traceability system. When working with applications of traceability and drivers for traceability it is relevant to examine the different components separately, because they have different purposes and constraints, and some are connected to costs, and some are connected to benefits. These two papers together outline the theoretical basis for implementing food traceability as I see it after many years of research and development. I believe that traceability should be defined as outlined in **Paper I**, and I believe it is important to distinguish between the components in a traceability system as outlined in **Paper II**.

5.3 Paper I: How to define traceability

The background for this paper was numerous discussions with colleagues on what traceability is and what it entails, in particular in some of the large EU projects on traceability. There were two misunderstandings in particular that were prevalent, and that had to be cleared up before the projects in question could progress in a constructive way:

1. Misunderstanding – "Traceability is a means of finding origin or provenance". While it is true that a common application of a traceability system is to find origin or provenance, that is not all that traceability is (Opara & Mazaud, 2001). Some FBOs claim "we have perfect traceability" when they mean "we can document the origin of our products". This misses out on two things; firstly that information relating to origin is only one attribute of the TRU; there are numerous other attributes that we want to keep track of. Secondly, that a traceability system should provide information not only on where the TRU came from, but also where it went. In some contexts, and also in some scientific articles, the word "trace" is used specifically to identify origin (looking backward), whereas the word "track" is used to identify where the TRU went (looking forward). However, this distinction is not consistently applied and can be more confusing than enlightening; e.g. traceability would then have to be defined as "the ability to trace and track". In the "GS1 Global Traceability Standard" (GS1, 2017b) GS1 writes "For

practical reasons, 'trace' or 'track and trace' may be used as equivalent terms to designate the action of ensuring the traceability", which is a view and a practice I agree with.

2. Misunderstanding – "For traceability, we need to analyse the biochemical properties of the food item in question". This was a common misunderstanding, especially among scientists that used laboratory methods and equipment to analyse and document food item properties. The problem was compounded by the fact that some of these scientists called what they did "traceability", and had made scientific publications using the word in this context. The key question here was whether traceability was necessarily based on recorded identifications or not. ISO 8402 (1994) had "by means of recorded identifications" as part of the traceability definition, and industry practice was also to use the word traceability in relation to historically recorded information rather than in relation to immediate measurements. It was clear that analytical methods were relevant and useful when implementing traceability, but it was not clear what the demarcation between the different research fields were, or how these fields related to the definitions of traceability.

In **Paper I**, my co-author and I listed and analysed all the traceability definitions we could find that were relevant for food products. We also examined how frequently each of these existing definitions were referred to in 101 selected scientific articles, and outlined developments over time for this frequency. Our original intention was to write only a descriptive article, ending with a recommendation for which the "best" definition was, or at least what the disadvantages and limitations of each of them were. However, every single definition had obvious weaknesses; the two most common ones were defining traceability as "ability to trace" without defining what "trace" meant, or unnecessarily limiting what and where you could or should trace. In the end, we combined the good parts of several existing definitions, and came up with the following:

> **Traceability (n)**
> **The ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications**

In our opinion, this is at least a less bad definition than the other existing ones, and it has been referred to a few times in scientific publications. However, the use and relevance of it obviously suffers from the fact that it has no official status or backing.

For the full paper, see appendix.

5.4 Paper II: The components of a food traceability system

This is the newest paper that I have initiated the writing of, and it contains terms and concepts that it was useful to formulate explicitly before writing this synopsis. There are now literally hundreds of food traceability papers, but many of them (including several I have contributed to) focus only on individual companies, chains or systems, or they focus only on one aspect or one application of food traceability. A generic and robust model of traceability, where the overall components are named and identified, is not present in most of these papers, and terminology use in this area is often inconsistent and confusing. As **Paper I** highlights, traceability is about record-keeping, and you can keep records relating to any type or number of attributes of the TRU in question. Many papers on traceability focus mostly on particular attribute types, like the biochemical food item properties, or the attributes relating to food safety or food quality. However, this is not really what traceability is about; these attributes are simply carried by the traceability system, and once we have the traceability system in place we can carry anything. When teaching courses on traceability, I use Figure 11 to try to explain this concept.

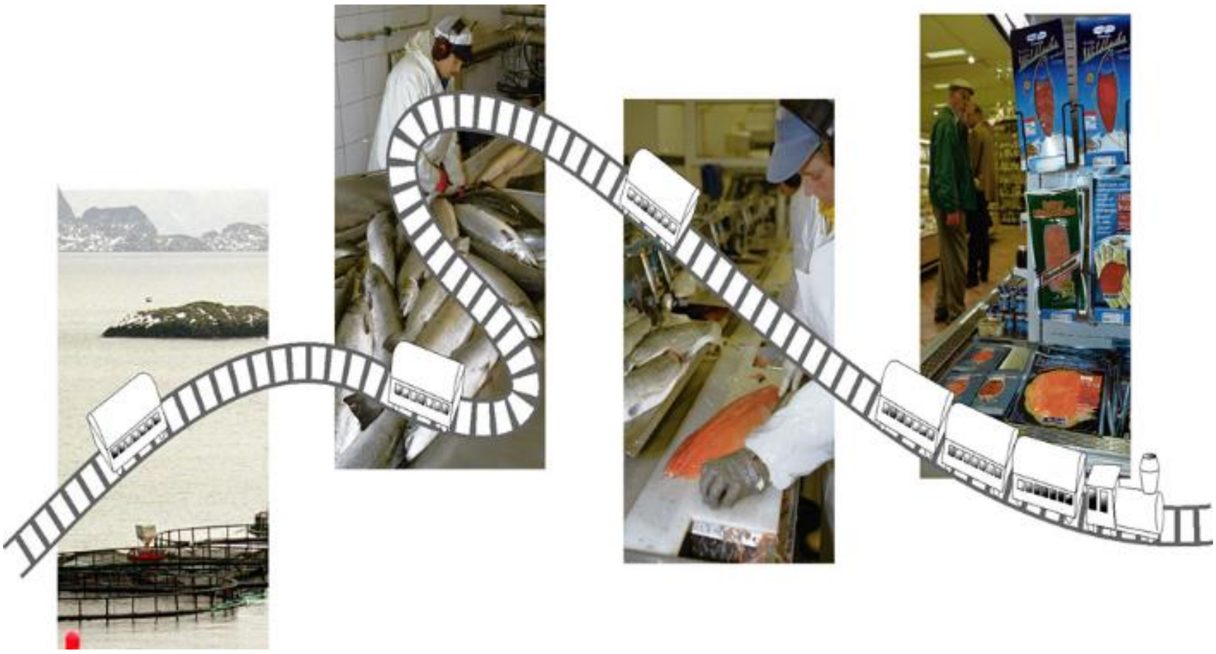

Figure 11. Visualizing traceability as a railroad track. Graphics by Oddvar Dahl, Nofima.

The background shows some links in a supply chain for food (farmed fish), and the carriages represent the data that is recorded in each link of the chain, i.e. the TRU attributes. However, for traceability, we want to "access any or all information relating to that which is under consideration", so this means that the information recorded in the first link of the chain must somehow be made available in (or transported to) the next link of the chain. This is what the traceability system does; it makes sure that the recorded information is made available elsewhere, and not lost. In Figure 11, the traceability system is the railroad track itself, and the implementation of it consists of assigning identifiers to the TRUs, and recording the transformations. This means that if we want to describe or analyse the properties of a traceability system, we need to distinguish clearly between the following component types:

- The systems and processes that relate to the identification of the TRUs, which includes choosing a code, deciding on uniqueness and granularity, and associating the identifier with the TRU
- The systems and processes that relate to the documentation of the transformations in the chain, which includes recording of the TRU transformations, the weights or percentages, and the related metadata
- The recording of the attributes of the TRU, which can basically be anything that describes the TRU

Paper II describes each of these components in more detail, as illustrated in Figure 12, and also discusses how each of these component types can be improved, and what the overall effect of this improvement might be.

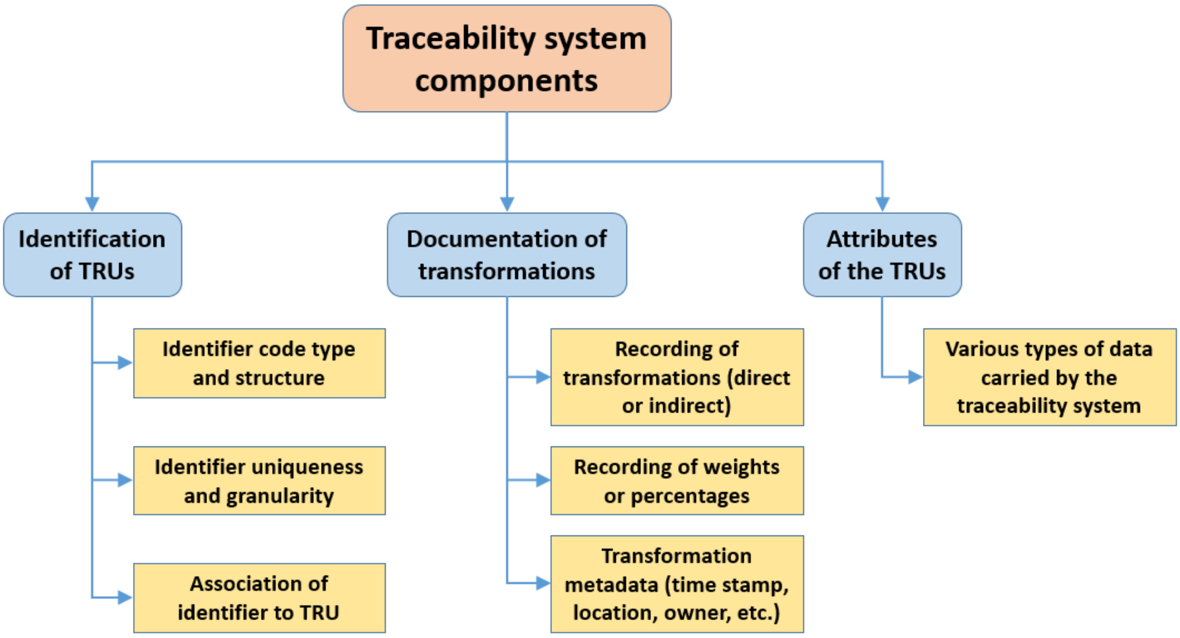

*Figure 12. The components of a traceability system, from **Paper II***

For a holistic view of how a traceability system works, this distinction is crucial, especially if you want to examine costs, benefits, drivers, or constraints. The components are there for different reasons, and to a large degree TRU identification and documentation of transformations is a cost, whereas the ability to access TRU attributes gives us benefits. It is difficult to find scientific publications on food traceability that makes this distinction clearly and consistently, and it is difficult to write coherently about traceability without referring to this overall classification. For this reason, **Paper II** is the most general of the papers included in this thesis, and the classification that it makes underlies all the other papers on traceability included here.

For the full paper, see appendix.

6 Food traceability in practice

Food traceability in practice starts with implementation projects, and this chapter starts with an overview of some of the most significant international traceability projects I have been involved in. The implementation projects always involved industry partners, so one of the first things we had to learn was how to analyse traceability in existing supply chains. I developed a methodology for this, which was extensively used also by others, and with my co-author I wrote **Paper III** to outline the methodology and explain how it should be applied, and how to interpret the results. After analysing traceability in existing supply chains, the next step was to aid and advice the companies on how to improve their systems. My colleagues and I did this in several dozen supply chains, and **Paper IV** outlines implementations in three different chains, and some lessons we learned. We discovered how important standards were when implementing traceability, especially chain traceability, and this led to many of the projects developing first internal standards and guidelines, and then gradually official international standards on European (CEN) or global (ISO) level. To highlight the dependency of traceability on standards, my co-authors and I wrote **Paper V** where we outlined what we called the TraceFood Framework, which describes what type of standards are needed when implementing traceability, and also outlines what we called "Good Traceability Practice" (GTP) guidelines, inspired by many examples of "Good Manufacturing Practice" (GMP) guidelines that already existed (US Food & Drug Administration, 2004).

6.1 International food traceability projects

Food traceability was, at least initially, an applied research field where projects and implementation was more important than scientific publication. In the mid and late 1990s, my colleagues and I were involved in a number of smaller local, national, and Nordic projects focusing on food traceability. When the European Commission in the 5th Framework Programme under "Quality of life and management of living resources" indicated funding available for a project on "Quality monitoring and traceability throughout the food chain", we decided to apply. The project type was not specified, and we decided to apply for a network project (a so-called Concerted Action) rather than an implementation project. We called the project "Traceability of fish products" (short name TraceFish), and in the project application we wrote:

> *The overall objective of this concerted action is to go some way towards establishing a broad consensus for what traceability data should be recorded and transmitted for fish products, and how these data should be coded. To accomplish this, we will establish a forum where representatives from various parts of the fish/product industries and research institutes can meet to discuss traceability related issues.*

In retrospect, I am glad we went for a network project which focused on standardization, rather than on yet another implementation project. Not only because we got the application funded, but mostly because our experience from the implementation projects we had already been involved in indicated that we could not keep solving the problems in one chain at a time; we needed a broader approach, and we needed to come up with more generically applicable solutions.

As project coordinator, I am biased, so it is difficult for me to objectively evaluate TraceFish, but it is clear that:

- We delivered the two European standards (CEN Workshop Agreements or CWAs), CWA 14659:2003 "Traceability of fishery products. Specification on the information to be recorded in farmed fish distribution chains" (CEN, 2003a) and CWA 14660:2003 "Traceability of fishery products. Specification on the information to be recorded in captured fish distribution chains" (CEN, 2003b).

- The standards were used by the industry, also outside Europe. CWAs last for three years, and after that they can be renewed if they are still used and seen as relevant, which the TraceFish CWAs were. In 2007, ISO established a Fisheries and Aquaculture (TC234) working group on traceability (WG1), and the first task of this working group was to make ISO standards based on CWA 14659 and CWA 14660. ISO standards are global, and do not expire unless they are retracted, so to a large degree the TraceFish CWAs from 2003 still live on today as part of ISO 12875 (ISO, 2011a) and ISO 12877 (ISO, 2011b).
- The TraceFish network was valuable to us, and the discussions we had there led to greater insights, a broader view, and a better understanding of traceability.
- The competence that we acquired from this project and the network also led to several other projects, many on European level.

Table 1: List of EU food traceability projects, my role, and what came out of them

Project full name	Short info	My role	Traceability relevance
Traceability of fish products	EU 5FP TraceFish 2000-2002	Coordinator, overall responsibility for constructing project and writing proposal	Defined some terms and concepts Produced the CWA 14659 and 14660 traceability standards which is the basis for the ISO 12875 / 12877 standards
Health promoting, safe seafood of high eating quality in a consumer driven fork-to-farm concept	EU 6FP Seafood Plus 2004-2008	WP leader, assisted with constructing project and writing proposal, responsible for methodology development	Produced and applied first version of the "Reference method" (**Paper III**) to analyze traceability in supply chains
Tracing Food Commodities in Europe	EU 6FP TRACE 2005-2009	WP leader, significant responsibility for constructing project, writing proposal, as well as concept and methodology development	Applied the "Reference method" (**Paper III**) in several chains Numerous discussions on how to define traceability which resulted in **Paper I** Developed sector-specific ontologies Produced the "TraceFood Framework" (**Paper V**)
Automated and differentiated calculation of sustainability for cod and haddock products	EU 7FP WhiteFish 2012-2014	Coordinator, overall responsibility for constructing project, writing proposal, concept and methodology development	Produced the CWA 16960 sustainability standard which builds on the traceability standards
Ensuring the Integrity of the European food chain	EU 7FP FoodIntegrity 2014-2018	WP leader, significant responsibility for constructing project, writing proposal, concept and methodology development	Using traceability to document food authenticity and to detect food fraud Linking claims in a traceability system to analytical methods that can be used to verify them

AUTHENT-NET – Food Authenticity Research Network	EU H2020 Authent-Net 2016-2018	WP leader, significant responsibility for constructing project, writing proposal, concept and methodology development	Using traceability to document food authenticity and to detect food fraud Producing CWA standard on food authenticity, and how it relates to traceability

A summary of the most important EU food traceability RTD projects that I have been part of is shown in Table 1.

I would especially like to emphasize the importance of the TRACE project which finished in 2009, and the FoodIntegrity project which finishes in 2018. In these projects my colleagues and I applied the methods and principles that we had largely developed in the seafood industry on several other foodstuffs, including mineral water (K. M. Karlsen, Donnelly, & Olsen, 2010), honey (Donnelly, Karlsen, & Olsen, 2008), chicken, (Donnelly, van der Roest, Höskuldsson, Karlsen, & Olsen, 2012) and meat (Donnelly, Karlsen, & Olsen, 2009). We were happy to find that while there were particular considerations in some sectors, the challenges were largely the same, and the principles and methods we had developed were generally relevant and applicable.

6.2 Analysing traceability in supply chains

To properly understand food traceability you need to engage with the industry and investigate what systems and needs they have, and how these match. This requires detailed study and analysis of various supply chains, using a number of techniques for gathering and representing data. If you do this a number of times, it makes sense to develop and gradually refine a robust methodology to ensure that you ask the same questions and gather the same type of data in the same way each time so that the results are comparable. **Paper III** outlines the development, application, and refinement of such a methodology.

6.3 Paper III: Reference method for analyzing material flow, information flow and information loss in food supply chains

A lot of the early work on traceability was in individual companies or chains. There was significant food industry investment in traceability systems in the 1990s and early 2000s, and expertise in this area was sought after. My colleagues and I initiated numerous projects where we would visit a single company or a supply chain for a given product, collect data and conduct interviews, describe and analyse material flow, information flow, and information loss, and identify weaknesses and potential for improvement. I developed a set of forms that we used when interviewing the companies, and also some instructions for how to use these forms, how to plan and carry out the interview overall, and how to represent and interpret the results. This worked well, the forms were used in practically all our projects, and I released several new and improved versions of the forms. When I distributed version 10 of the forms and the accompanying guidelines to my colleagues, I took the initiative to publish the methodology. Scientific publication had not been a priority for me up to that point; the industry was more interested in specific recommendations, and some of the reports that we produced and some of the analyses that we did were confidential. There were three main reasons why I nevertheless decided to initiate the writing of a scientific article outlining the methodology and the accompanying guidelines:

- The method was robust and well proven to work, and had been applied by numerous scientists in a variety of food chains

- My colleagues who had applied the method urged me to publish it so that that they had a proper reference to give to it when they wrote reports and publications
- Hopefully the method could be of use to other scientists and food industry professionals who wanted to analyse material flow and information flow, and in particular to anyone who wanted to identify systematic information loss

The method was based on breaking each process down into an alternating sequence of durations and transformations, and assigning one set of questions and a form to be filled out for each of them. Duration was defined as "the time between transformations when nothing happens to the integrity of the unit; that is it is not split up, joined, or grouped with other units". The transformations were typically reception of ingredients and raw materials, application of them, batch production, and splitting of batches into trade items before shipping. Before and between each of these transformations there was a duration as illustrated in Figure 13, so there were nine sets of questions and nine forms to be filled in for each process we analysed.

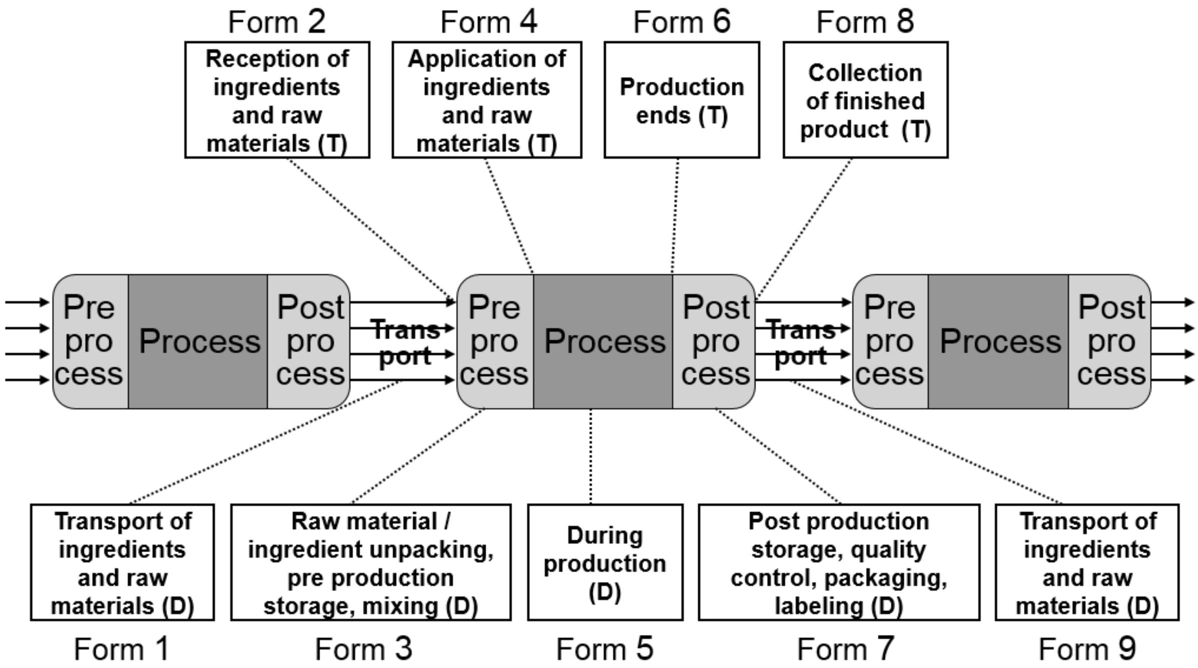

*Figure 13. Transformations (T), durations (D), and forms for each process. From **Paper III**.*

Description of the whole mapping process, examples of the forms, and an indication of how to interpret the results can be found in **Paper III**. An interesting fact that we discovered was that the method was most efficient if we went against the flow, both internally in each process (starting with the questions on form 9 and ending with form 1) and in the supply chain where we started downstream (near the consumer) and then gradually mapped the processes further upstream (closer to the original raw material). The reason was that we normally knew what end product we wanted to analyse, but we did not necessarily know all the ingredients it contained or all the processes it had been through. When we first started using the method, we started upstream, but then we found that we often had to revisit links that we had mapped before, because there were ingredients or processes we did not know about, and relevant questions we had not asked. When we went against the material flow, starting with product questions and ending with raw material questions, this was less of an issue.

For the full paper, see appendix.

6.4 Implementing and improving traceability in supply chains

Using the method outlined in **Paper III**, my colleagues and I analysed a large number of chains. We found systematic information loss in every chain we analysed; this could of course be related to the fact that our pilot companies were interested in traceability and considered investing in better traceability systems, which meant that their existing systems and practices were less than perfect. In general, we found that:

- Our pilot companies had good practices when it came to systematic and extensive recording of relevant data
- Our pilot companies varied when it came to how much of this recorded data they sent or made available to their customers
- Our pilot companies had significant potential for improvement when it came to how they treated data that was sent to them, and how they integrated received data into their own systems

We found, for instance, that information-rich labels with many data elements were produced, but that these labels were largely ignored when the TRU arrived at the next link in the chain. We also found that the companies that received TRUs normally recorded (a very limited number of) TRU attributes, rather than the TRU identifier. This meant, for instance, that in their own system they could find out, for a received TRU, who had produced it, and the production date, but not the identifier on it. In addition, the identifier on the received TRU was normally the production batch number which was an internal number meaningless to anyone outside the producing FBO, and it was used on all trade items that came from that batch, so there was no one-to-one relationship between TRU and TRU identifier. All this led to systematic information loss, and for all the chains that we analysed we could outline potential for improvement, and indicate what the benefits of this improvement might be.

What became clear however, especially as technology and standards improved over time, was that the main reason for systematic information loss was lack of motivation in the company (McEntire, Arens, Bernstein, & Ohlhorst, 2010). Most of the technical problems were solvable, but a combination of financial investment and change of internal practices would be required. In the view of many companies, their traceability was good enough, and they could not see tangible benefits of investing in improved systems, or of changing their established practices (Banterle & Stranieri, 2008). It is worth pointing out that this observation is not meant as criticism of the FBOs in question; it is reasonable for a company to avoid spending time and money on something that they do not think that they need. The question remained, however, whether the companies knew what benefits an improved traceability system could bring, or what risks and limitations were connected to their existing systems. This issue is discussed further in the "Discussion and conclusions" chapter.

My colleagues and I produced numerous papers and reports outlining the analysis we had done, and the recommendations we had made in various FBOs and chains; see sections on "Other relevant papers" and "Other relevant documents, reports, and standards". To exemplify the implementation efforts we were involved in, I have included **Paper IV** in this thesis, where existing and improved traceability systems in three seafood chains are outlined, together with some observations and conclusions regarding how the selected granularity influences the traceability. For more details on this last issue, see the thesis of my colleague Kine Mari Karlsen (2011).

6.5 Paper IV: Granularity and its role in implementation of seafood traceability

This paper illustrates how my colleagues and I worked in implementation projects in specific chains. It was selected for inclusion in this thesis for the following reasons:

- It describes three implementations, not only one, so it is more representative, and it is easier to generalise from
- The reference method outlined in **Paper III** was used to analyse several of the chains
- The principles from the TraceFood Framework outlined in **Paper V** was used as basis for the traceability implementations and the recommended improvements in the supply chains
- There are relevant overall conclusions to draw from this paper and the implementations it outlines, relating to Critical Traceability Points (CTPs, points where systematic information loss occurs (A. F. Bollen, Ridena, & Cox, 2007) (Kine Mari Karlsen & Olsen, 2011)) and in particular to granularity

The three supply chains were:

1. Three suppliers of salmon feed ingredients -> One salmon feed producer -> One salmon farm
2. Fishing vessels -> Wet salted cod producer -> Dried salted cod producer
3. Fishing vessels -> Landing and filleting link -> Packing and distributing link -> Supermarket

The conclusions from the analysis were:

- There was systematic information loss in all chains because the same TRU identifier was used on many TRUs; there was no one-to-one relationship
- There was systematic information loss in all chains because transformations were not explicitly recorded
- Granularity was largely decided by production preferences, not by information preferences. This means that even if the sales department or the customers would prefer to be able to distinguish between fish from different vessels, or geographical areas, or fish caught with different gear types, they could not, because in the batch size chosen, fish with different attributes were mixed. Even though changing to a smaller batch size and finer granularity was technically possible, and might even be quick, simple, and practically without cost, many FBOs are reluctant to do so. Partly because they prefer not to change established practice, but also because the connection between granularity and potential for profiling product characteristics is not clear to them. If the batch size is large, and everything is mixed together, all you can sell is “fish”. If the batch size is smaller, and traceability is present, there is a potential to sell “line caught fish”, or “fish from vessel ABC”; either of which may fetch a higher price than the generic product in some markets.

These conclusions are in line with the conclusions from many other implementations based on similar principles. As a consequence, **Paper IV** highlights the need for cost-benefit analysis related to implementation of improved traceability in general, and finer granularity in particular. As in many other implementations and as mentioned above, the limiting factor was not the technology; it was the motivation of the company that was lacking.

For the full paper, see appendix.

6.6 Traceability and standards

Standards are often useful to ensure unnecessary duplication of effort, to establish and represent consensus, and to facilitate error-free communication (Bechini, Cimino, Marcelloni, & Tomasi, 2008). For traceability, standards play a particularly important role, because the recorded identifications need to be shared in the supply chain, and often this sharing is done electronically (Dupuy, Botta-Genoulaz, & Guinet, 2002). Before the advent of computers, when product information was physically attached to the food item, standards were less important. The information was sent physically along with the TRU, and the recipient and intended reader was human. When product information is recorded and sent electronically, standards are essential, for two reasons:

1. As both the sender and the receiver are computer programs, and it is not necessarily the same computer program, we need a clear specification of a protocol for Electronic Data Interchange (EDI). We need to define exactly, without room for misinterpretation, how the messages are to be coded so that the sender can construct a message and the receiver can understand it. If there are only two trading partners, these could agree on some way of coding messages that suited them, but the supply chain is very complex, and there are many-to-many relationships between suppliers and customers. The most practical way of communicating is to decide on a standard for EDI that everyone supports. A parallel here is fax machines, which became popular in the 1980s. If each fax machine producer had insisted on their own standard, faxes could only have been sent to other machines from the same producer, which would have significantly limited their utility. Instead, all fax machine producers agreed on a common standard, buyers knew that regardless of what brand of fax machine they bought they could send faxes to anyone, and fax machines became very popular. This is similar to the standard for EDI that is needed to facilitate electronic exchange of product information. There are a number of to some degree competing standards in this area. Some of the most prominent are the EDIFACT standards (UNECE, 1987) and the ebXML standards (OASIS & CEFACT, 1999) developed by the United Nations, the Universal Business Language (UBL) (OASIS, 2006) which is based on ISO/IEC 19845:2015, and EPCIS (GS1, 2016) which is supported by GS1. These are standards with different functionality, maturity and intended areas of application, but it is beyond the scope of this thesis to go into more detail on this issue.
2. To facilitate EDI, we also to some degree need standards for the contents of the messages; we need to agree on what the words mean (Folinas, Manikas, & Manos, 2006). If trading partner A uses an EDI standard and sends the message “TRU 1234 has 12% fat” (or more formally, “TRU 1234 has an attribute called “Fat”, and the value of that attribute is “12%”), this might not be unambiguous to trading partner B. Fat may be measured in different places, in different processes, and using different methods. Communication and understanding requires not only the exchange of electronic messages, but also a clear agreement on what the words and values in these messages mean. A standard for content is needed, where the meaning of words are defined (the TRU attributes in particular), and also the meaning of the attribute values. This type of standard is commonly referred to as an ontology (Pizzuti, Mirabelli, Sanz-Bobi, & Goméz-Gonzaléz, 2014), and there are some broad international efforts in this area. The UN organization FAO has developed the structured, hierarchical vocabulary AGROVOC (FAO, 2009b) where more than 32000 words and concepts related to food, nutrition, agriculture, fisheries, forestry, environment, etc. have been defined. Smaller, sector specific standards for content and meaning has also been developed, e.g. ISO 12875:2011 “Traceability of finfish products - Specification on the information to be recorded in captured finfish distribution chains” (ISO, 2011a) and “ISO 12877:2011 “Traceability of finfish products - Specification on the information to be recorded in farmed finfish distribution chains” (ISO, 2011b).

Data element		Description	Examples	Categorization		
				Shall	Should	May
Source						
CLA203	Previous food business ID	Country prefix plus unique national identification number for the organization, as well as name and address of the food business from whom the unit was received (vessel or transporter, etc.)	GB – 123467890 Humber Trawlers, Albert Dock, Hull, HU1 7AR, UK		x	
CLA204	Date and time of reception	Date and time of transfer from previous food business, ISO 8601 format	2010-06-28T04:00		x	
Control checks (related to the logistic or separate trade units, as appropriate)						
CLA205	Temperature of unit when received	Temperature of unit °C	1,0 °C		x	
CLA206	Unit temperature record	Temperature/time log (manual/automatic) (if there is a recording device affixed to the unit)	Series of temperature (°C)/date and time points in ISO 8601 format		x	
Transformation information (for each trade unit that is transformed by landing business or auction)						
CLA207	Related created trade unit IDs	List of the UTUIs of the created trade units that may incorporate part of the received trade unit	978817525.0766.00001 0123 978817525.0766.00001 0131 978817525.0766.00001 0272	x		

Figure 14. A page from the ISO 12875 standard

As an example of a content standard, see Figure 14 from ISO 12875 intended for use by landing businesses and auction markets. Each row defines a data element that can be recorded and transmitted, and there is a unique identifier for each data element, a name, a description, and an example or a specification of the content. In addition, each data element is categorized as "shall" (mandatory to record), "should" (recommended, according to good practice guidelines), or "may" (optional). Using a standard like this, trading partners can agree on exactly how data elements should be named and measured, and how messages should be constructed and understood.

The work we did on standards, in particular in the TRACE project, resulted in a paper where we attempted to outline good traceability practice guidelines based on extensive use of standards.

6.7 Paper V: The TraceFood Framework – Principles and guidelines for implementing traceability in food value chains

After having analysed a number of chains and recommended system improvements, we attempted to generalise our recommendations, and to outline what constituted good practice in relation to implementing traceability. We called our recommendation "The TraceFood Framework", and we illustrated it as follows; see Figure 15.

The TraceFood Framework has six components, as follows:

- Unique identification; one-to-one relationship between TRUs and TRU identifiers. This issue has been discussed above, and the advantages of this approach has been described.
- Documenting transformations. This issue has been discussed above, and the advantages (or even necessity) of doing this has been described.

- Use of an EDI standard for exchanging messages, as outlined above. In the TRACE project we developed our own standard called TraceCore XML and demonstrated that the approach was viable. In practice, it does not matter much what EDI standard is used, as long as it supports the required functionality, and as long as enough FBOs (trading partners in particular) use it.
- Development and use of a sector-specific standard for defining the meaning of terms, and to establish how to measure them. In the TRACE project, we made such standards for mineral water, honey, and chicken; for seafood we used the existing CWA 14659 (CEN, 2003a) and CWA 14660 (CEN, 2003b) standards.
- Generic guidelines for Good Traceability Practice (GTP). We split the recommendations into how to implement internal traceability, how to implement chain traceability, and how to implement electronic data interchange.
- Sector-specific guidelines for implementation where we dealt with issues that were unique for the commodity in question, for instance parameters or production methods that influenced traceability, or the presence of commodity-specific regulations.

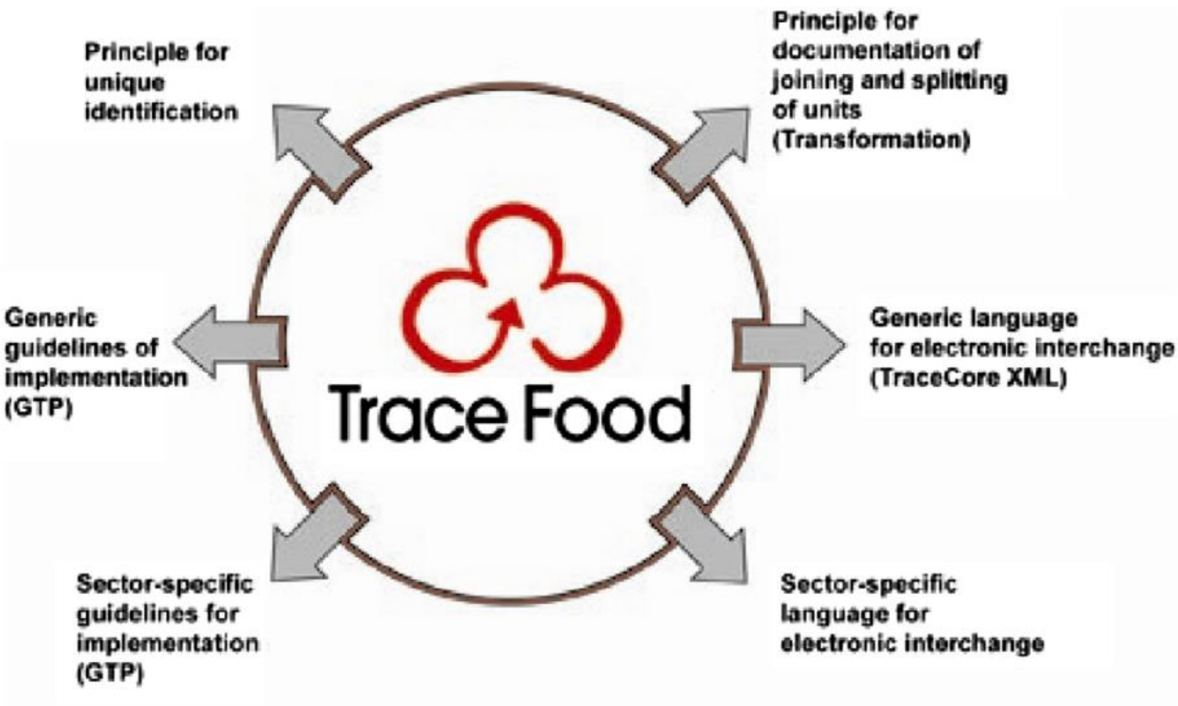

*Figure 15. The TraceFood framework components, from **Paper V***

To formulate, implement, and test the TraceFood framework was for us a very useful exercise. The TraceCore XML was hardly used after the project finished, but by then the publicly available standards for EDI had improved, so companies used these instead. The sector-specific standards for mineral water, honey, and chicken were not used after the project finished; mainly because there were no follow-up projects in these sectors, and the standards had been made with input from only a small number of companies. For the seafood standard we had input from a large number of companies, and the fact that ISO initiated a process to get the original European CWA standards upgraded to ISO level shows that the concept is sound, and seen as relevant by the industry.

For the full paper, see appendix.

7 Discussion and conclusions

To summarize the thesis, I want to first examine the current situation, and then look a bit into the future. While food traceability has come a long way in the last 20 years, there are still gaps in various areas, which I will identify and discuss. There are also new and exciting developments and technologies emerging that will influence and most likely improve traceability, and I will present and discuss some of these. Finally, I will indicate the most important lessons learned, and attempt to give useful advice to scientists and food industry professionals who may be involved in future traceability implementation projects.

7.1 Status on implementation of food traceability, gaps identified

Although there is improvement in the implementation of chain traceability in recent years, we still face some mayor challenges (Forås, Thakur, Solem, & Svarva, 2015) (Bai et al., 2017). Based on the research outlined in this thesis, it is useful to examine where we are now with respect to food traceability, and where the gaps and unsolved problems are. It is possible to identify traceability-related gaps both when it comes to awareness, implementation, technology and standards; the most important are indicated below. These gaps mainly apply to the food industry, but some of the awareness gaps also seem to apply to the scientific community.

7.1.1 Awareness gaps

- There is a lack of understanding of what traceability is, and how it differs from other concepts that are viewed to be similar, e.g. Chain of Custody, or methods for analysing biochemical food item properties. Hopefully **Paper I**, **Paper II**, and some of the standards developed can go some way towards reducing this gap.

- There is a lack of understanding of what the difference between internal and chain traceability is, and why this distinction is important. Many of the potential benefits of having traceability in place comes from chain traceability, but the focus of many implementation projects is on single FBO, internal traceability improvements. Improving the internal traceability is fine and relevant, but it only gives you some of the benefits. To get the benefits from chain traceability implementation, the focus must be on the communication between the trading partners, not only on the data recording in each of them (**Paper IV** and **Paper V**).

- There is a lack of understanding of the fact that a traceability system can cover the entire food chain, from farming or catch through all types of processing and transport all the way to the retailer and the consumer, and also that any attribute may be recorded in the system. The legal requirement is often one-up, one-down traceability, but the commercial requirements, and some of the benefits depend on the ability to trace all the way back to the original source of the raw material, and all the way forward to the eventual application or sale of the finished product. Some proposed definitions of traceability limit the scope of traceability, or they limit the type of data that may be recorded, see **Paper I**. It is difficult to see why, in a definition, it should be desirable to limit what can be traced or where tracing can occur; once the traceability components are in place, any TRU attributes or transformations can be recorded in the system.

- There is a lack of understanding of the importance of having a one-to-one relationship between TRUs and TRU identifiers. If many TRUs have the same identifier, it is impossible to record further information in the chain relating to one particular TRU. We have asked many FBOs about why they put the same identifier on each TRU when it is comparatively simple and cheap to generate unique identifiers. The answer is normally that for the FBO in question, the

TRUs are indistinguishable when they are generated; they are trade units coming from the same production batch, and they share all the same attributes and most of the attribute values. This is true initially, but this reasoning only applies as long as the TRUs are kept together. In practice, they will be transported and stored apart from each other, and they will be sent to different destinations using different means of transport. The fact that there is no unique code on each TRU significantly limits the possibility to record more information related to it (**Paper IV** and **Paper V**).

- There is a lack of understanding of the importance of documenting transformations, and how the chain of transformations is essential if we want to trace back or forward to or through companies (Badia-Melis, Mishra, & Ruiz-García, 2015). There is a significant difference between recording "I used 1000 kg meat from supplier ABC and DEF with the following attributes (and then a list of attributes and values) to make my hamburger batch 1234" as opposed to "I used raw material batch 111 and 112 to make my hamburger batch 1234". Even though more information is recorded in the first case, it will lead to systematic information loss, because the input TRU IDs were not recorded. In the second case the transformation is explicitly recorded, which means that as long as the attributes of raw material batch 111 and 112 are also somehow available, no information will be lost. If something happens (a complaint or a food safety incident), the recorded transformation will make it possible to trace back to the supplier (who hopefully also recorded the transformations that made the produced batches, and so can trace to the previous link in the chain).

- There is a lack of understanding of the fact that many of the main obstacles for adoption of traceability in food chains are cultural and organizational rather than technical. Some FBOs have been under the impression that an improved traceability system can be installed and used without changing the existing manual procedures and processes. In general this is not true; the efficiency, accuracy, and granularity of the traceability system depends on the production processes, and if these are not changed (e.g. if the batch size remains "everything produced of a product type on one day") then this will seriously limit the utility of the traceability system. Successful adoption of a new traceability system requires motivation both in management and among the operators, and this in turn requires training, and explanation and demonstration of what the new system can do, and what the advantages are.

- There is a lack of understanding of how traceability can streamline internal company processes and improve financial performance. This is probably the biggest awareness gap, and it represents the biggest obstacle for widespread implementation of better traceability systems. The FBOs are aware of the costs of improved traceability, but they do not see sufficiently large benefits to justify these costs (Mattevi & Jones, 2016). When it comes to chain traceability, this relates to the fax machine parallel outlined in the "Traceability and standards" section; there is little benefit from buying a fax machine if hardly anyone else owns one. When it comes to internal traceability, there is evidence both from confidential industry reports and from scientific literature (Alfaro & Rábade, 2009) that an improved traceability system pays for itself in less than two years, mainly due to the streamlining of internal processes which result in better industrial statistics, faster turnover of ingredients, raw materials and products, and reduced amount of goods on storage. However, either the food industry does not believe that it is profitable to invest in an improved traceability system, or they do not know it. Either way, more case studies, more data, and more research in this area is needed to establish exactly what the expected benefits of an improved traceability system are, and to what degree, and under what circumstances, investment in such a system is profitable.

These awareness gaps are significant, and they serve to prevent more widespread implementation of improved traceability systems in general, and the uptake of new technologies in particular.

7.1.2 Implementation gaps

- There is a significant gap related to lack of implementation of (improved) food traceability systems, and to a large degree this is a consequence of the awareness gaps. While there are still challenges related to availability of technology, solutions, and standards, it is clear that most companies have less traceability than they could have. They also probably have less traceability than they should have, given their strategy, their priorities and their own economic interests. There is increasing documentation of the fact that not only can a good traceability system reduce operating costs and fulfil legislative and commercial requirements; it can also underpin company branding and marketing strategies, and give the company a competitive advantage.

- There is an implementation gap related to the use of standards, or rather to the fact that too many solutions and implementations rely on proprietary data recording and communication protocols rather on the standards that exist. This is connected to the awareness gap related to the lack of understanding of what the difference between internal and chain traceability is. If the focus is on a single company, standards are less relevant. If the focus is on having traceability in the whole chain, between all the interconnected actors, standards are needed both for EDI and for content.

- There is an implementation gap related to the lack of integration of received data into own system. As indicated above, the biggest systematic information loss in the existing systems happens when data is recorded and sent, but more or less ignored by the recipient. FBOs need to consider the data they receive about a TRU to be a valuable aspect of the TRU; one that they pay for, and must take care of upon reception, the same way they take care of the food item itself.

- There is a gap related to the lack of widespread implementation and use of new technologies for automatic identification. Both for TRU identification and for representation of attribute values, bar codes still dominate in the food sector. Bar codes have significant limitations compared to e.g. RFID tags; they need to be read physically with a scanner, they can only store a limited amount of information, and they are not well suited to support one-to-one relationships between TRUs and TRU identifiers. The time and work involved in reading a number of bar codes is significant, whereas RFID tags can be read instantaneously and from a distance. The cost of reading is a very important factor which to some degree prevents the introduction of finer granularity, and in particular it makes it difficult to implement one-to-one relationships between TRUs and TRU identifiers. RFID tags inherently provide this functionality; no two tags ever have the same identifier, and the efficiency of the traceability systems will be significantly improved when the bulk of the industry adopts RFID tags as common practice. Nevertheless, use of bar codes is still the dominating technology; a fact that is connected to several of the awareness gaps outlined above.

- There is a gap related to the lack of widespread implementation and use of new technologies for automatic data capture. Automatic Identification and Data Capture (AIDC) is the common term and abbreviation for these last two technology types, and it refers to methods for automatically identifying objects, collecting data about them, and entering them directly into computer systems, without human involvement. A significant cost related to the running of a traceability system is associated with initial data entry that is frequently performed manually.

It would simplify and speed up the process, and reduce the number of errors, if technologies existed that could automatically extract the relevant data, enter them into the traceability system, and associate them with the TRU in question. Electronic weights on the processing line can be considered AIDC technology when they record the weight of a TRU and associate this weight with the TRU identifier in the system. More advanced sensor types (for temperature, location, pressure, humidity, etc.) exist, but they are still not widely used. See section on "New technologies" for more information on some of these.

The food industry would argue that many AIDC technologies are too expensive, not robust enough, and not value-adding enough. This is not completely untrue, and it brings us to some technology gaps.

7.1.3 Technology gaps

- There is a lack of cheap, functional and robust radio-frequency identification (RFID) tags and technologies (Regattieri, Gamberi, & Manzini, 2007) (Aung & Chang, 2014). Price is probably the main constraint preventing more widespread use of RFID tags, but there have also been issues related to reading distance, reading problems when the tags have the wrong orientation, and reading problems in some environments (cold or frozen products).

- There is a lack of cheap, functional, robust, and integrated technologies for automated data capture. Price is again a major constraint, but another problem is that for the data captured to be associated with the TRU in question, the TRU needs to have an identifier that is known to the sensor. Also, if the TRU identifier is not unique for that TRU (if we do not have a one-to-one relationship), it is difficult to attach sensor data to the TRU. If the TRU identifier is on a bar code (which is still common), it is difficult to read it in real time, as the sensor operates. The widespread introduction of RFID codes would solve most of these problems, which means that automatic data capture technologies will become more common when RFID is more widely implemented.

- There is a lack of instruments and technologies that can verify claims in the traceability system related to the biochemical properties of the food items. As indicated, a traceability system consists largely of claims in relation to food item properties, but mistakes or fraud might cause erroneous claims to be entered into the system. Ideally, for the most important biochemical attributes, we would like to be able to verify the claim in question, but currently it is difficult, expensive, and time-consuming to do so.

As indicated, even if we narrowed the technology gaps and the implementation gaps, if we wanted chain traceability we would have to make extensive use of standards to make sure that information was communicated and shared, and that it was understood by all in the same way. While standards do exist, there are still some gaps also in this domain.

7.1.4 Standards gaps

- The "Traceability and standards" section outlines a number of EDI standards that can be used for data communication and integration. One problem is that there are several of these standards, and that to some degree they are competing. A bigger problem is that they do not enforce or even encourage "good traceability practice". The EDI standards are like enormous menus with numerous choices; they can support whatever type of EDI the user wants. This flexibility might seem like an advantage, but it means that not only do the trading partners need to use the same EDI standard if they want to communicate; they also need to use the standard in the same way. There are no uniform requirements for how to use the standards in a way that supports good practice when it comes to chain traceability (Bosona & Gebresenbet, 2013). This gap to some degree inhibits interoperability of technology systems along the supply chain, increasing business risks and costs when choosing and adopting traceability and information systems.

- While there are a number of ontologies developed for various food sectors (Pizzuti et al., 2014), they cannot be said to be widely used, and most of them do not have official status or significant backing. Once EDI becomes more prevalent, the need for sector-specific ontologies that clearly define what attribute names and values mean (see Figure 14 for an example) will become more acute. Even for some animal species there is confusion; different countries may use different names to refer to the same species, or different countries may use the same name to refer to what is two different species (e.g. an anchovy in Peru is not the same species as an anchovy in Sweden).

Some of the gaps identified will be narrowed when some novel technologies become more widespread in the food industry.

7.2 New technologies and future developments

Paper II describes the components of a traceability system to be identification of TRUs, documentation of transformations, and recording of TRU attributes. There are emerging technologies in each of these fields; some of the most relevant are outlined below.

7.2.1 New technologies for identification of TRUs

The main gap in relation to identification of TRUs is to go from one-to-many relationships between TRU identifier and TRU to one-to-one relationships; the unique license plate principle outlined earlier. The GS1 Electronic Product Code (EPC) is designed as a universal identifier that provides a unique identity for every physical object anywhere in the world, for all time. EPC can be used to carry information about locations, shipments or assets, but for traceability purposes it is most relevant to use it to carry information about TRUs, and that is what the 96 bit Serialized Global Trade Identification (SGTIN) code is for. SGTIN is designed for globally unique identification of trade units in general, not only of food items. For a detailed description of SGTIN with examples, see **Paper II**. One-to-one relationships between TRUs and TRU identifiers already exist in some sectors (for instance when tracking parcels online); there is significant potential for value adding when this principle becomes widespread for food items in general. If you scan the barcode of a food item now, all it will tell you is what product type it is. If you scan or read a unique code, it can link to any relevant information pertaining to the uniquely identified TRU in question, e.g. the best before date, or the transaction in the chain that produced the TRU. This will simplify storage and handling both for the industry and for consumers, and intelligent cold storage rooms or refrigerators can scan or read codes automatically, and tell you when the best before date is approaching.

7.2.2 New technologies for documentation of transformations

Blockchain technology in its current form has been around since 2008; it is what underlies the digital currency called Bitcoin, and it can be used to document transformations in the supply chain in a secure and transparent manner. Blockchain technology is best described as one that enables records to be shared by all network nodes, updated by miners (system users who, for a fee, keep track of transaction records), monitored by everyone, and owned and controlled by no one (Swan, 2015). A significant problem in traceability is that it is difficult to verify that the stated transformations actually took place. If a FBO claims “we split TRU 111 into TRU 222 and TRU 223”, this is difficult to check, because we do not have access to the internal recordings of the FBO, and even if we did, the records might not be accurate or complete. Using blockchain technology, the record of all transformations would be in the public domain, openly visible to anyone (although most of the TRU attributes would not be visible)

(Tian, 2016). If a buyer received a TRU where the transactions were documented using blockchain technology, every single transaction from the TRU in question back to the original farming or harvesting would be available for inspection, also for the other TRUs that came from the same source. This to some degree prevents FBOs from introducing undocumented raw materials or products into the supply chain; if they did, the mass-balance accounting would not add up (you cannot produce 1200 kg fillet from 1000 kg meat or fish). It also prevents anyone from overwriting the transaction once it has been recorded, which means that if the original data recorded is correct (and it is normally in the interest of high quality producers to record the initial data correctly, to protect their brand and to justify the higher price they get) it becomes very difficult for FBOs later on in the chain to counterfeit or dilute the product. Blockchain technology will not guarantee accurate recordings, but it will certainly remedy some weaknesses that currently exist, and it will be interesting to see what happens when the technology becomes prevalent.

7.2.3 New technologies and trends for recording of TRU attributes

There are two significant developments in this area; one is related to technologies for Automatic Identification and Data Capture (AIDC) and the Internet of Things (IoT), and the other is related to the interest in recording new attribute types.

AIDC is by no means a new concept, but use of AIDC is increasing, the technology is becoming simpler, cheaper, and more accurate, and there is increasing interest in the attributes that AIDC can record (Trappey, Trappey, Hareesh Govindarajan, Chuang, & Sun, 2016). AIDC covers a broad range of technologies; what they have in common is that data is generated and recorded without the need for human effort. Various types of sensors in the production plant can be examples of AIDC, and they can record weight, location, speed (if on a conveyor belt), room temperature, process temperature, other process parameters, pressure, humidity, or other attributes that it is relevant to associate with the TRU in question. A more recent, and more advanced version of AIDC technology is when the sensor is not in the production plant, but embedded in the TRU itself. Embedded time/temperature loggers have existed for many years, but more advanced embedded sensors can also measure e.g. pressure, humidity, or exact GPS coordinates (Bai et al., 2017).

The Internet of Things (IoT) is the inter-networking of physical devices and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to collect and exchange data (Trappey et al., 2016). The advent of IoT can significantly increase the utility of AIDC technologies. We can envisage, for example, a TRU with an RFID chip embedded, travelling on a conveyor belt in a production facility. On the conveyor belt there is an electronic weight that the TRU passes over, and nearby there is a time-temperature sensor that monitors the environment. If these three sensors are connected through IoT, the traceability system can automatically, without human intervention, assign the recorded weight and temperature at the given place and time to the TRU in question by linking the data to the unique TRU identifier. Interoperability and connectivity is unproblematic; all these sensors communicate through a predefined protocol. This functionality is achievable today, but it will become cheaper and more widely used as more devices are IoT-enabled. As with traceability, the limiting factor is not the technology, it is the utility, and the degree these technologies add value to the product (Pang, Chen, Han, & Zheng, 2015).

Another significant development the recording of new attribute types; especially so-called secondary attributes that are not related to the biochemical properties of the food item. This is largely a consumer driven development, where a small, but increasing part of the consumers show interest and willingness to pay for information relating to various aspects of sustainability or ethics (Miller et al., 2017). Examples of attributes that it might be relevant to record include:

- Exact origin, name of farmer or fisherman, documented local production
- Organic production status, organic certification
- Alternative production methods, like biodynamic production, no additives, special recipes
- Religious attributes, halal or kosher production
- Social sustainability attributes, like absence of child labour or slave labour, freedom to join a union, fair trade principles in place
- Environmental sustainability attributes, like resource use, emissions, or transport distance

A particularly relevant application of improved traceability is in relation to environmental accounting where the principle is that based on Life Cycle Assessment (LCA) principles, the emissions and resource use related to all the processes and ingredients that went into making and transporting the final product will be quantified. This means that the buyer, whether a FBO or a consumer, can see, on a specific product, how much emission (measured in carbon dioxide equivalents, or CO_2e) went into the production and transport of that product. Widespread environmental accounting would require the CO_2e of each TRU to be recorded in the traceability system, and for an updated CO_2e to be calculated in each process that generated new TRUs. The European standard CWA 16960:2015 "Batch-based Calculation of Sustainability Impact for Captured Fish Products" outlines the principles of environmental accounting in the captured fish sector based on recordings of resource use in the traceability system (CEN, 2015).

7.3 Summary and lessons learned

To conclude, I will attempt to briefly summarise what I believe to be the most important lessons learned after working for many years in the field of food traceability. I have focused on what I hope constitutes useful advice to scientists and food industry professionals who might get involved in future traceability implementation projects.

- In any project or endeavour related to implementation of food traceability, you should clearly define the terms and concepts so that everybody involved has the same understanding, and uses the same definitions. In some of our early traceability projects, a lot of time was wasted on misunderstandings, and sometimes when we seemed to disagree, it turned out that we were just using the same word in different ways. Hopefully **Paper I**, **Paper II**, and some of the standards developed have helped bring clarity, rather than confusion, in relation to this.
- Unique identification of TRUs, and one-to-one relationships between TRUs and TRU identifiers is very important. If several TRUs have the same identifier, you are not making a traceability system for the future. Many of the emerging technologies, and many of the value-adding applications depend on the ability to associate data with one particular TRU. If you are not assigning unique identifiers to each TRU, you are building a system where the focus is on a single FBO rather than on the chain, and it is a system where you cannot avoid systematic and significant information loss.
- In implementation projects, you should focus on chain traceability, and you should involve more than one partner. Chain traceability is the real challenge; improving internal traceability does not necessarily improve chain traceability. Firstly, it is important to know what chain traceability and internal traceability is, and what the difference is. Secondly, it is important to

realise that in general, you cannot implement good systems for chain traceability by yourself; you need to collaborate closely with your trading partners. Many of our first traceability projects were based on single companies that were interested, motivated, and willing to invest in improved traceability, including hardware and software. In these projects, we managed to improve their internal traceability, but many of the benefits generally associated with traceability were not achieved. We had numerous examples of companies implementing excellent procedures and systems for traceability, but when the TRU was sent, often with a product label overflowing with information, including a code that could give access to more, it was largely ignored by the trading partner. This obviously yielded frustration and the investment in improved traceability seemed to some degree to be wasted. After experiencing this situation a number of times, we established the requirement that in industry implementation projects, we would require (or at least strongly prefer) the involvement of at least two FBOs who had an existing supplier-customer relationship. A related piece of advice is to be aware that it is not enough to record and send relevant information; it is necessary that the receiver actually reads and processes the information, and incorporates it into their own systems.

- If they exist; use standards. If they do not exist; develop standards. There is a strong dependency between standards and traceability, and some of the challenges of traceability can only be solved through the development and widespread use of standards. In addition to defining what the terms and concepts related to food traceability means, we need standards on different levels to operationalise traceability in an efficient manner. For Electronic Data Interchange (EDI), there are a number of standards to choose from, many with backing and support from major corporations. For efficient and widespread implementation of chain traceability, we need these standards to be used extensively. Above, the exchange of data in a traceability system was likened to a fax machine. An interesting rhetorical question is, who was stupid enough to buy the very first fax machine? That person or company had no one to send to and no one to receive from, and the first fax machine was basically useless. The same is true for EDI standards, both in general, and in relation to traceability. The more FBOs start using EDI standards for exchanging information on TRUs and transformations, the larger part of the chain we can cover, and the more valuable the information will become. The same is true for content standards where attributes are named and defined. When use of EDI becomes more widespread, the availability of information that was received electronically will increase, and the need for standards that define what the attribute name and values mean will increase. In some form, it is likely that standards similar to the content standards developed for seafood (ISO, 2011a) (ISO, 2011b) will have to be developed, at least for the other major food sectors, as outlined in **Paper V**.
- When you are doing supply chain mapping and analysis, go against the product flow. Start by defining where in the supply chain your mapping will end, and what food item or items you will look at there. Interview the last link first, find out about suppliers, raw materials, and ingredients, and gradually move against the product flow. This was not obvious to us when we started, but the mapping going with the product flow (which intuitively seemed to be the way to do it) turned out to be inefficient, and we often had to revisit already mapped FBOs with supplementary questions, because of something we discovered further downstream in the supply chain. Also, the buyer of a product normally has more power in the trading relationship than the seller has, so when we went with the product flow, the seller had to introduce us to the buyers and ask them to spend time answering our questions, which wasn't always popular. When we went against the product flow, the buyer had to ask the supplier to spend time

answering our questions, and as the suppliers wanted to accommodate their customers, this was far less of a problem. For more details on this, see **Paper III**.

- Be aware that improving the traceability system will improve the internal logistics significantly, even for companies that thought that they already had optimised this area (F. P. Bollen, Riden, & Opara, 2006). Practically every company that we worked with that did an *ex post* evaluation of costs and benefits related to the investment in a new traceability system reported benefits related to better control, better industrial statistics, better ability to optimise production, faster through-put, less raw material storage, and less product storage. It is difficult to document this scientifically; partly because *ex post* cost-benefit calculations may be biased so that they defend the investment decision.
- Be aware that the main bottleneck for successful and widespread implementation of food traceability is economics and motivation. Although there are some gaps, such as missing standards and unresolved technical issues, these are not what prevents investments and implementation. The problem is that most FBOs see the costs associated with investing in improved traceability, but they do not see the benefits (Mattevi & Jones, 2016). Cost-benefit analysis of investment in improvement in traceability systems is normally performed by the companies themselves, and the reports are confidential. Through the years, my colleagues and I have been allowed to see a few of these confidential reports with *ex-post* analysis of the investment, and they all indicated that the traceability system paid for itself in less than two years; a timeframe that is confirmed by other observations (Alfaro & Rábade, 2009).

In my view, we are now in the third implementation wave of food traceability systems. The first wave was driven by the advent of computers and other related technologies, and resulted in data being recorded electronically rather than in ledgers; the focus was on improving data recording and internal traceability. The second wave was driven by the advent of the internet and communication technology, and resulted in systems, procedures, and standards for sharing data electronically, mainly through point-to-point messaging. In the third wave where we are now, the main obstacle is no longer lack of technology or lack of standards. Networked, interoperable food traceability systems are viable, and technologies are emerging for cheap and efficient globally unique identification of TRUs, automated data entry from external and embedded sensors, and publicly available and validated records of TRU transformations. The focus now is on using all this functionality and this data to add value to the food product, either for the food business or for the consumer. It is an exciting time to work in this still developing field, but my guess is that the food traceability scientists of the future to a larger degree will come from the fields of economics, marketing, and even psychology, although there will hopefully still be some use for those with a background in computer science and applied mathematics.

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9 Appendix – The papers

9.1 Full text version of Paper I

Paper I

Olsen, P.; Borit, M.; (2013): “How to define traceability”. Trends in Food Science & Technology, volume 29, issue 2, pp 142-150. doi:10.1016/j.tifs.2012.10.003.

9.2 Full text version of Paper II

Paper II

Olsen, P.; Borit, M.; (2017): “The components of a food traceability system”. Submitted to Trends in Food Science & Technology June 2017.

9.3 Full text version of Paper III

Paper III

Olsen, P.; Aschan, M.; (2010): "Reference method for analyzing material flow, information flow and information loss in food supply chains". Trends in Food Science & Technology, volume 21, issue 6, pp 313-320. doi:10.1016/j.tifs.2010.03.002.

9.4 Full text version of Paper IV

Paper IV

Karlsen, K. M.; Dreyer, B.; Olsen, P.; Elvevoll, E.; (2012): "Granularity and its role in implementation of seafood traceability". Journal of Food Engineering, volume 112, issues 1-2, pp 78-85. doi:10.1016/j.jfoodeng.2012.03.025.

9.5 Full text version of Paper V

Paper V

Storøy, J.; Thakur, M.; Olsen, P.; (2013): "The TraceFood Framework – Principles and guidelines for implementing traceability in food value chains". Journal of Food Engineering, volume 115, issue 1, pp 41-48. doi:10.1016/j.jfoodeng.2012.09.018.