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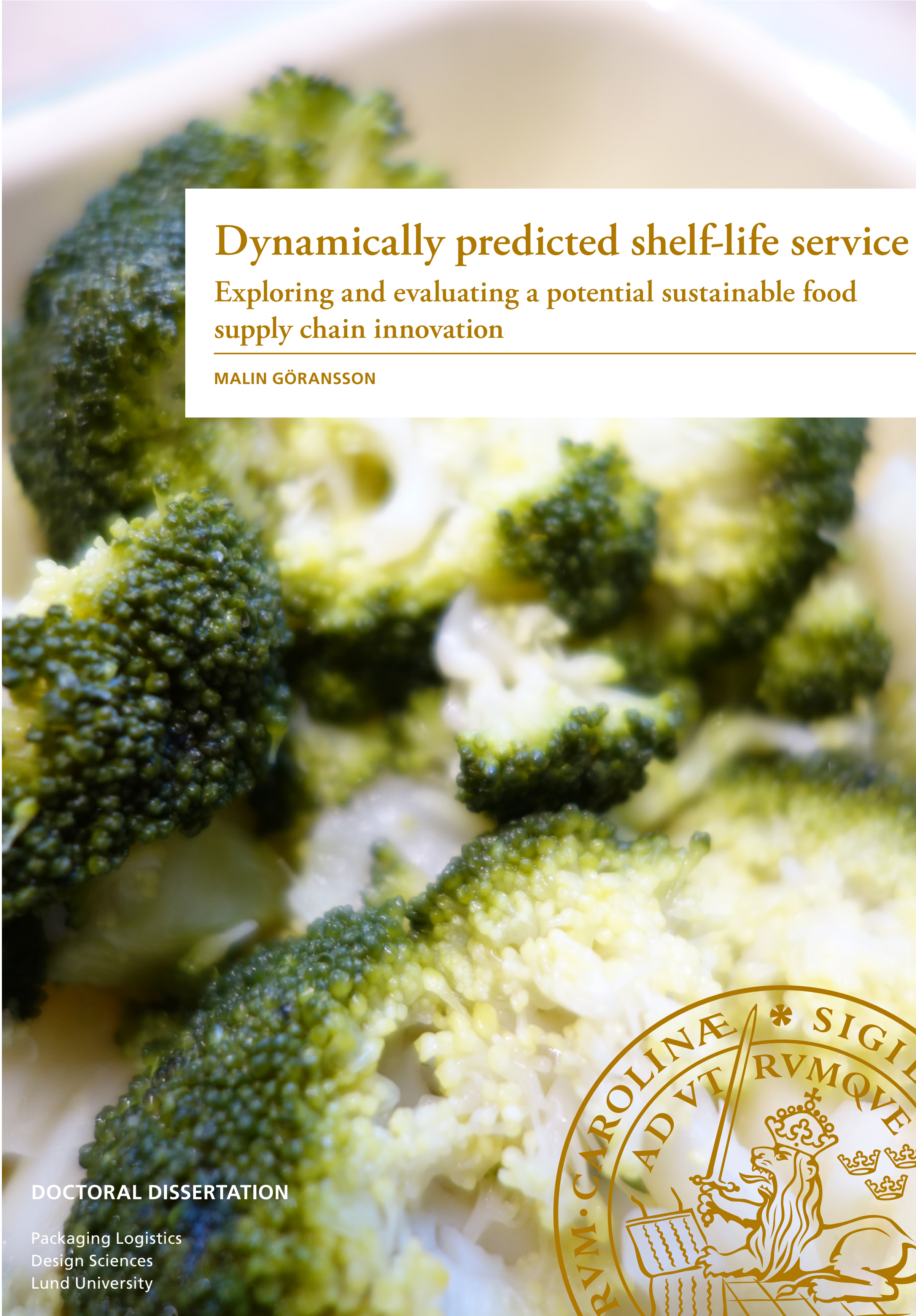

Dynamically predicted shelf-life service

Exploring and evaluating a potential sustainable food supply chain innovation

MALIN GÖRANSSON

DOCTORAL DISSERTATION

Packaging Logistics
Design Sciences
Lund University

Dynamically predicted shelf-life service

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Exploring and evaluating a potential sustainable food supply chain innovation

Malin Göransson

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Abstract

Roughly one third of all the food produced worldwide goes to waste. The global goals for sustainable development set by the United Nations in 2015 call for a 50% reduction of food waste per capita by 2030. We thus face several major food waste challenges that need academic and practical attention. Food loss and waste occur throughout the entire food supply chain, from primary production to consumption. The shelf-life information printed on the package along with the temperature fluctuations (which are linked to consumer behavior, food safety assurance and food quality control) are some of the central aspects related to food waste in developed countries. There is a need for improved shelf-life labeling/communication systems that continuously convey the actual quality of food products and their shelf life in a clear and credible way.

The research presented in this dissertation sets out to explore and evaluate the concept and requirements of a dynamically predicted shelf-life service and to provide understanding and guidance for actors involved in sustainable supply chain ventures. The dynamically predicted shelf-life service investigated is a conceptual supply chain information service system for the monitoring and communication of food quality and supply chain operational process quality. Sensors attached to packed food products continuously measure and provide data (time, temperature, position, etc.) to a cloud-based communication system as the food products are distributed along the food supply chain. The data is cataloged and used in microbiological prediction models to determine the actual shelf life of a food product at any given time.

The research presented in this dissertation is based on abductive reasoning and a systematic combining approach that uses both qualitative and quantitative data collection methods, such as field tests, experimental work, systematic literature reviews, interviews, workshops and observations. The dissertation includes three research studies and five appended papers, the results of which are analyzed to provide overall key findings.

Four key findings/challenges facing food supply chain practice and the foundation of the related academic knowledge are: 1) Lack of accessible and accurate data and information sharing cause food supply chain inefficiency and food waste (in both FSCs and in households); 2) Continuous temperature monitoring close to the food products is essential to providing accurate operational and food quality data; 3) Opportunities for realizing a dynamically predicted shelf-life service; 4) Realization of sustainable food supply chain innovations is needed to reach the United Nations' global sustainability goals.

Interdisciplinary and transdisciplinary research is needed to approach the challenges that these findings illuminate. The interdisciplinary research presented takes on the challenge of sustainable development and contributes to sustainable supply chain research and practice by identifying and categorizing critical factors to realize sustainable supply chain innovations. It also proposes a process model for sustainable supply chain innovation creation that includes the fourteen critical factors identified.

The research in this dissertation contributes to academia by generating new knowledge in the interdisciplinary intersection between the areas of food quality and shelf life, packaging logistics and supply chain management. Critical factors and food supply chain challenges (from production to retail) that lead to food waste are identified and analyzed to provide new knowledge (both academic and practical) on a detailed level, but mostly on an interdisciplinary and comprehensive systematic level. These findings provides an overall description of food waste challenges in food supply chains and existing knowledge gaps. The research also provides suggestions for further research.

Key words: Supply chain, Packaging logistics, Food quality, Food waste, Sustainable innovation

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MADE IN SWEDEN

“Don't limit your challenges
challenge your limits”

Table of Contents

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Popular science summary in Swedish

Har du någon gång slängt mat för att du varit osäker på dess faktiska kvalitet? Kanske har bäst-före-datumet passerat? Vi slänger alla mat och tänker sällan på att det bidrar till klimatförändringar, ekonomiska förluster och felaktiga sociala beteendemönster. Tidigare forskning visar att omkring en tredjedel av alla livsmedel som produceras i världen inte når sitt slutgiltiga mål – att bli uppätet. Det är så mycket som 1,3 miljarder ton livsmedel som hade kunnat mätta jordens undernärda befolkning fyra gånger om.

Men det är inte bara vi konsumenter som slänger mat. Faktum är att mycket livsmedel går till spillo långt innan den når oss. Mat slängs genom hela livsmedelskedjan – i jordbruket, hos livsmedels-producenter, under transport, distribution, lagring och i livsmedelsaffärer. Tidigare studier visar att de största problemen är kopplade till kylvaror, så som färskt kött, fisk, fågel, mejeriprodukter, frukt och grönt. Kylvaror har hög vatten- och näringshalt vilket skapar en perfekt miljö för mikroorganismer att föröka sig i. Därför är en skyddande förpackning och låga förvaringstemperaturer A och O för att bevara livsmedlets kvalitet. Trots detta leder bristfälliga förpackningslösningar, förhöjda eller okända temperaturer samt stela regelverk och praxis till svinn.

Matsvinn är en stor utmaning i dagens samhälle och det finns många anledningar till varför mat slängs. Resultat från denna avhandling visar att en hel del livsmedel går till spillo på grund av att det saknas korrekt information som påvisar matens kvalitet och hur den har förvarats. Därför behöver vi bättre system för datummärkning som beskriver livsmedlets faktiska kvalitet och hållbarhet på ett tydligt och trovärdigt sätt.

Denna avhandling visar att tillämpning av ny teknik med intelligenta och innovativa förpacknings-, och logistiklösningar kan bidra till ett minskat matsvinn. Konceptet för en dynamisk hållberhetsservice har utforskats, utvecklats och utvärderats genom tvärvetenskaplig forskning som kombinerar främst teknisk livsmedelsmikrobiologi, förpackningslogistik, supply chain management och innovation. Den dynamiska hållbarhetsservicen är uppbyggd av små temperatursensorer som placeras på livsmedelsförpackningar och mäter tid, temperatur och positionsdata under produktens resa genom livsmedelskedjan. Data skickas till servrar där den sorteras, kategoriseras och matas in i så kallade mikrobiologiska prediktionsmodeller som beräknar den aktuella kvaliteten på livsmedlet. Livsmedlets aktuella kvalitet, också kallat dynamisk hållbarhet, samt övrig registrerad information skickas sedan tillbaka till alla aktörerna i livsmedelskedjan.

Servicen har testats och utvärderats i laboratoriemiljöer, men också ute i flera livsmedelskedjor för att studera funktionaliteten av den dynamiska hållbarhetsservicen och kvaliteten på de svenska livsmedelskedjorna för kylda varor. Studien visar att svenska livsmedelskedjor håller produkterna väl kylda fram till butik. Studien visar också hur viktig en dynamisk hållbarhetsservice innehållande en kontinuerlig temperaturmätning genom hela livsmedelskedjan är. Både för att påvisa om kylkedjan brutits och livsmedlets kvalitet påverkats, men också för att visa att produktens kvalitet och hållbarhet kan vara avsevärt bättre än det tryckta bästföredatumet. En dynamisk hållbarhetsservice och en kontinuerlig temperaturmätning genom hela livsmedelskedjan kan därmed leda till en ökad livsmedelssäkerhet och att mat med god kvalitet inte slängs i onödan. Denna studie visar också att de största utmaningarna för temperaturhållning hittades i livsmedelsbutiker, där många kylar inte klarade av att hålla tillräckligt låg temperatur i hela kylen. Detta uppmärksammas sällan då företagen i livsmedelskedjan oftast övervakar temperaturen i sina utrymmen med hjälp av temperaturmätare som är placerade nära utrymmets kylaggregat. Däremot är själva livsmedelsprodukternas temperaturer sällan övervakade.

En dynamisk hållbarhetsservice har flera fördelar utöver kontinuerlig temperaturmätning. Hållbarhetsservicen minskar personalens handläggning för temperaturprover av produkter och medför att alla aktörer i kedjan har ett gemensamt sätt att mäta och registrera temperaturdata. Detta minskar risken för produktreturer och långdragna dispyter gällande temperaturavvikelser då alla aktörer kan ta del av samma temperaturdata som är uppmätt på samma sätt genom hela kedjan. Vid temperaturavvikelser kan systemet varna aktörerna som snabbt kan ingripa. Aktörerna kan med hjälpa av temperaturdata hitta svaga punkter i kedjan och minska risken för framtida temperaturavvikelser. En dynamisk hållbarhetsservice kan också användas av livsmedelsproducenter för att bestämma livslängden (bäst före-datum) på livsmedel med bättre precision. Är temperaturen i kylkedjan alltid låg och stabil kan hållbarheten på produkten förlängas. Hållbarhetsservicen ger också ett ökat informationsflöde mellan aktörerna. Detta kan i sin tur leda till ökat samarbete mellan aktörerna och att de inte enbart ser till sin egen verksamhets bästa, utan även till hela kylkedjans. Detta är speciellt viktigt när det gäller att lösa stora samhällsproblem så som matsvinn.

Aktörerna i livsmedelskedjan står inför stora utmaningar om en dynamisk hållbarhetsservice ska införas. Alla aktörer måste vara villiga att arbeta över företagsgränserna och dela mål och visioner där resurseffektivisering i hela försörjningskedjan står framför de enskilda företagens prioriteringar. Det finns många kritiska faktorer som måste ha setts över innan en så pass stort innovations system kan realiseras. Denna avhandling bidrar med en processmodell som kan användas i vidare forskning samt hjälpa till att vägleda företag och försörjningskedjor att realisera en dynamisk hållbarhetsservice och andra så skallade ’hållbara innovationer i försörjningskedjan’. Processmodellen bygger på kritiska faktorer funna i vetenskaplig litteratur som fokuserar på hållbara innovationer. Skapandet av hållbara innovationer i komplexa system så som försörjningskedjor är ytterst viktigt för att minska den totala resursanvändningen och bidra till en global hållbar utveckling.

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Many years of learning, personal development and positive challenges are coming to an end with this dissertation. The journey towards becoming a Ph.D. can sometimes be lonely, but I have been fortunate to be surrounded by many people that have supported, inspired, pushed and encouraged me, both in and outside of my academic work. I would like to take the opportunity to show my gratitude.

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List of appended papers

The research presented in this dissertation is comprised of five academic papers. They are listed here, accompanied by brief descriptions of the authors' contributions.

Paper I

Göransson, M., & Nilsson, F. 2013. The Role of Biosensors in Future Food Supply Chains. *The 25th Nordic Logistics Research Network (NOFOMA) Conference Proceedings*, Gothenburg, Sweden.

Paper I is a blind peer-reviewed conference paper. Göransson was the primary contributor regarding the structure and content. Nilsson was the main contributor to the narrative literature review on supply chain challenges. Both authors conducted the workshops and interviews together. Göransson wrote most of the manuscript with guidance from Nilsson, who critically revised the manuscript.

Paper II

Jevinger, Å., Göransson M., & Båth, K. 2014. A Field Test Study on a Dynamic Shelf Life Service for Perishables. *The 26th Nordic Logistics Research Network (NOFOMA) Conference Proceedings*, Copenhagen, Denmark.

Paper II is a blind peer-reviewed conference paper. Jevinger and Göransson equally shared authorship. Jevinger and Göransson performed the field test data collection, observations and interviews. Jevinger and Göransson also performed the narrative literature review and contributed equally to arranging and making sense of the results, and writing the discussion and conclusions. Göransson was the main contributor to writing the introduction, supply chain information sharing, and methodology sections, and Jevinger was the main contributor to writing the cold chain monitoring, remaining shelf-life prediction, results and analysis sections. Båth contributed with mathematical models for shelf-life calculations based on microbial growth.

Paper III

Göransson, M., Jevinger, Å., & Nilsson, J. 2018. Shelf-life Variations in Pallet Unit Loads During Perishable Food Supply Chain Distribution. *Food Control*, 84, 552-560.

Göransson and Jevinger mainly performed the ideation and design process of Paper III with experienced advice and guidance from Nilsson. Göransson and Jevinger together performed the experimental study, data collection, results evaluation and analysis. Göransson was the main contributor to writing the introduction, conclusion and methodology with the exception of 'Calibration of tags', 'Heat transfer', 'Thermal time constants' and 'Compensation for sensor tag dynamics', which were investigated and written by Nilsson. Jevinger mainly wrote the results and analysis and simulated the temperature scenarios in GNU Octave.

Paper IV

Göransson, M., Nilsson, F., Jevinger, Å. 2018. Temperature Performance and Food Shelf-life Accuracy in Cold Food Supply Chains – Insights from Multiple Field Studies. *Food Control*, 86, 332-341.

The three authors were all involved in the ideation, design and data collection. Göransson and Jevinger performed the analysis of the results together. Göransson wrote the main part of the manuscript. However, Nilsson was a large contributor to the introduction and 'Cold food supply chain management and monitoring'. Jevinger contributed to the results, analysis and discussion sections of the paper. All authors revised the paper. An earlier version of this paper was presented at *The 29th Nordic Logistics Research Network (NOFOMA) Conference Proceedings*, Lund, Sweden, in 2017. Göransson and Jevinger mainly wrote this version of the paper.

Paper V

Nilsson, F. & Göransson, M. 2019. Critical Factors for the Realization of Sustainable Supply Chain Innovations - Model Development Based on a Systematic Literature Review. Under third review in *Journal of Cleaner Production*.

Paper V has been submitted the *Journal of Cleaner Production* and is in the third round of review. Nilsson and Göransson were both involved in the design, data collection and analysis. Nilsson was the main contributor to the development of the process model. Nilsson was the main contributor to the introduction, 'Innovation, sustainability, and supply chains', discussion and 'A process model for sustainable supply chain innovations' sections of the manuscript. Göransson was the main contributor to the methodology and findings sections. Nilsson was the main contributor to the second and third revision of the paper. An earlier version was presented at *The 27th Nordic Logistics Research Network (NOFOMA) Conference Proceedings*, Molde, Norway, 2015. Göransson mainly performed the research in this earlier version and wrote most of the paper.

Publication not included in this dissertation

Göransson, M., & Nilsson, F. 2015. Enablers and Hinders for Eco-innovations in Supply Chains – Evidence from Literature. *The 27th Nordic Logistics Research Network (NOFOMA) Conference Proceedings*, Molde, Norway.

Göransson, M., Nilsson, F. & Jevinger, Å. 2017. Food Supply Chain Improvement – Evaluation of Shelf Life Accuracy. *The 29th Nordic Logistics Research Network (NOFOMA) Conference Proceedings*, Lund, Sweden.

Nilsson, F., Göransson, M. & Båth, K. 2019. Chapter 15 – Models and Technologies for the Enhancement of Transparency and Visibility in Food Supply Chains. In: Accorsi, R. & Manzini, R. (eds.) *Sustainable Food Supply Chains*, London, UK, Academic Press.

List of central abbreviations

DPSL	Dynamically predicted shelf life
FSC	Food supply chain
IoT	Internet of Things
SFSCI	Sustainable food supply chain innovation (SFSCI)
SSCI	Sustainable supply chain innovation (SSCI)

1. Introduction

1.1. Food waste

We live in a time with increasing global change (UN 2019a, IPCC 2014). A growing global population, urbanization, emerging economies, and increasing environmental burdens call for environmentally friendly solutions (Myers et al. 2017, IVA 2016, UN General Assembly 2015, WWF 2014a, FAO 2011). Currently, rising societies do not develop as rapidly as emerging economies, leaving us with obsolete economic, environmental and social solutions. Amended living standards and growing consumption place alarming restraints on natural resources and the environment (UN 2019a, FAO 2011). At the same time, roughly one third of all the food produced worldwide goes to waste (UN 2019b, FAO 2011). According to FAO (2011), this is equivalent to 1.3 billion tons of food waste annually. Simultaneously, the energy, greenhouse gas emissions and the water needed for cultivation and distribution are also lost. In the past decade, food waste has been recognized as a comprehensive environmental and social problem and is ranked as one of the largest global emitters of greenhouse gases (FAO 2019, Heller et al. 2019, IPCC 2019, FAO 2013). The global goals for sustainable development set by the UN in 2015 call for a 50% reduction of food waste per capita by 2030 (Target 12.3) (UN General Assembly 2015). Hence, there are several major challenges resulting in food waste that need academic and practical attention because the loss and waste of food occur throughout the entire food supply chain (FSC), all the way from primary production to consumption (HLPE 2014). The High Level Panel of Experts on Food Security and Nutrition states that, "*The distribution of FLW* [food loss and waste] *along the food chain varies greatly by region and product. In middle and high-income countries, most of the FLW occur at distribution and consumption*" (HLPE 2014, p. 11). The EU funded FUSION project estimated European food waste to be 88 million tons per year, where primary production accounts for approximately 10% of the waste, processing 19%, wholesale and retail 5%, food service 12%, and households 53% (FUSION 2016). However, as with many other reports on food waste, these figures are mainly based on secondary data. Xue et al. (2017, p. 6618) state that, "*There has been a growing body of literature on FLW quantification in the past years; however, significant challenges remain, such as data inconsistency and a narrow temporal, geographical, and food supply chain coverage*". Defining a methodology for food waste quantification is one key aspect to monitor the progress of food waste reduction (Corrado et al. 2019).

Central food waste challenges are related to consumer behavior, food safety assurance and food quality control from production to consumption. Scientific reports show that mismanaged temperature in the logistics of perishable food can result in up to 35% of the product loss (Zöller et al. 2013), and that over 50% of all food waste in industry derives from expired best before dates (Lindbom et al.2014). This is because substantial underlying factors for food waste in developed countries are connected to the printed shelf life on packages and to temperature fluctuations (Göbel et al. 2015, HLPE 2014, Fox & Fimeche 2013, WRAP 2007, WRAP 2011, Rahelu 2009). Issues relating to temperature fluctuations and food waste are in general fragmented in FSC silos. For example, Moureh and Flick (2004) report temperature differences of up to 12°C inside trucks, and Lundén et al. (2014) observed temperature violations in retail outlets for over 50% of the monitored products. There has been a growing body of literature addressing the problems of cold chains, such as Hafliðason et al. (2012), Kuo and Chen (2010), and Abad et al. (2009); however, literature that examines cold chains from production to retail and households exists but is scarce (e.g., Derens-Bertheau et al. 2015, Derens et al. 2006).

Other underlying factors that indirectly contribute to food waste is the lack of FSC collaboration, communication and transparency (Doorey 2011, Storøy et al. 2013, Kamath 2018). Eden et al. (2010) report that the inter-organizational information exchange of product-related data is not applied effectively in FSC management. Hence, researchers has emphasized the need for extensive studies on issues that result in food waste on a more holistic level (e.g., Heller et al. 2019, Verghese et al. 2013, Fredriksson & Liljestrand 2014), especially in the areas of innovation, packaging, and logistics. Fredriksson and Liljestrand (2014) state the need for a summarized view of the specific logistical issues for each segment of actors in the FSC. "*Many papers focus on the actors in food logistics, so the characteristics of the food products are not as thoroughly described. A first consequence of this present focus on the actor rather than on the product is a lack of knowledge about how to handle food products within logistics.*" (Fredriksson & Liljestrand 2014, p. 15). Furthermore, Verghese et al. (2013, p. 6) state that "*There has been very little research into the role of packaging in protecting fresh and processed foods at every stage of the supply chain, and in extending product shelf life. These important functions are often overlooked in debates about food security and waste*". Food quality and safety assurance, which mainly originate from microbiological contamination and growth, are also critical aspects in the food waste challenge (HLPE 2014, Labuza & Fu 1993).

Consequently, in order to address the food waste challenge from a holistic FSC perspective, there is a need for interdisciplinary research that integrates food quality (food microbiology), packaging and logistics. Sanders et al. (2013) has emphasized the need for more interdisciplinary research in supply chain and logistics management and Nilsson (2019) too in the era of sustainability. According to Sanders and Wagner (2011), the complexity of supply chain phenomena is not fully considered as of yet in supply chain management (SCM) and logistics research because there is a disconnection between siloed research across a range of disciplines. Multidisciplinary and transdisciplinary (Lawrence 2010) research and cross-functional collaboration may be of even greater importance in FSC research because the FSC setup and the perishability of food products add additional levels of complexity.

1.2. Food quality and packaging logistics challenges

Every chilled FSC is unique in its emphasis on product characteristics, quality, freshness, timeliness and low margins (Gustafsson et al. 2006). The FSC design is, in contrast to many other supply chains, highly dependent on the quality and safety requirements of the supplied product (Dani 2015, Göbel et al. 2015), and the targeted end customer (i.e., households, municipal enterprises, restaurants, etc.) (Gustafsson et al. 2006). Each food product has specific quality and safety requirements, but can be divided into three main supply groups: ambient, chilled, and frozen foods (Fredriksson & Liljestrand 2014, Göbel et al. 2015). The quality of all food products is highly dependent on the packaging because the most central function of food packaging is to preserve and protect the product from surrounding impairment and contamination (Gustafsson et al. 2006). The chilled food group is the most perishable. This is due to the food products' high amount of free water molecules in liquid state, which together with the high nutrient content create a perfect environment for microorganisms to propagate (Adams & Moss 2008). The microbial growth rate is reduced by storing food products preferably at +0-4°C (+0-15°C for fruits and vegetables. Each product category has its own optimal storage condition). The shelf life of chilled food products can, however, only be prolonged for a short period of time before the quality and safety are at risk (Adams & Moss 2008). How receptive a food product is to microbial contamination and other safety and quality degrading mechanisms depends on: the foods' physiochemical properties (intrinsic factors), the storage and handling conditions (extrinsic factors), the interactions with the present microflora (implicit factors), and processing hygiene factors.

The strict requirements on chilled food storage conditions together with their short shelf life place high demands on FSCs (Aung & Chang 2014b), particularly the packaging logistics activities in securing safe and high quality food products to consumers. The FSC actors need to execute the distribution time effectively, and with an intact cold chain in order to deliver their products in a state fit for consumption (Dani 2015, Fredriksson & Liljestrand 2014). Mistakes in the FSC can have smaller or more severe implications for the end consumer, and thus also for the company making the mistake, the supply chain and sometimes even the whole business (e.g., food scandals) (Dani 2015, Wognum et al. 2011). Currently, most food products that are distributed to end consumers are delivered in a satisfactory state (in developed countries). However, Wognum et al. (2011, p. 65) state that "*Nowadays, consumers include factors like quality, safety and environmental conformity in their buying decisions*". Hence, FSC actors need to respond to changing consumer demands (Wognum et al. 2011), especially in terms of sustainability factors such as food waste, food quality and sustainability transparency. Increased holistic FSC control and collaboration – including increased levels of alignment, integration, and information sharing – are required to ameliorate the FSC sustainability factors (Aung & Chang 2014b, Dani 2015, Wognum et al. 2011).

Improving FSC sustainability and reducing food waste is challenging. Both business managers and scientific researchers regard product innovation and design as the most essential driving force behind sustainable SC development (Wognum et al. 2011). Hence, there is an increasing need for FSC innovation, especially innovation that provides customer and business value and at the same time focuses on significantly decreasing environmental impacts (James 1997, Wognum et al. 2011): in other words, sustainable supply chain innovation (SSCI) (Gao et al. 2017, Tebaldi et al. 2018).

1.3. Sustainable supply chain innovation creation in food supply chains

One of many examples of inefficient resource usage that calls for sustainable innovations in supply chains is food waste. The food industry has traditionally been conservative and are decades behind many other sectors when it comes to adopting technology innovations (Bigliardi & Galati 2013, Beckeman & Skjöldebrand 2007, World Economic Forum 2018). Sustainable innovation research and practice have gained increased attention due to the sustainability issues, societal changes and technology developments that have been elucidated (Govindan 2018, Bigliardi & Galati 2013, Beckeman & Skjöldebrand 2007). However, innovative measures need to be taken to realize sustainable development and keep up with environmental changes. While companies, authorities, and organizations individually engage in the creation of innovations, it is when they are working together, in a supply chain or network, that they can have the greatest potential impact (De Marchi & Grandinetti 2013, WWF 2014b). Involving several stakeholders, though, can be difficult. It often implies shifting from developing and implementing technologies to developing and implementing new systems or business models (Bocken et al. 2014).

To successfully realize FSC innovations, one must recognize the incentives, enablers, and hinders for each stakeholder (Göransson & Nilsson, 2013). Moreover, working with innovation in the supply chain context places new and more demanding requirements on integration, openness, as well as on trust among the actors involved.

This dissertation emphasizes the interdisciplinary nature of FSC innovation by exploring and evaluating the requirements of an ongoing SSCI creation that enhances food quality control and reduces food waste. It is called a "dynamically predicted shelf-life (DPSL) service" and has not yet been fully implemented in any FSCs. Hence, the research in this dissertation explores and evaluates the concept of a DPSL service.

The DPSL service is a conceptual supply chain information service system for monitoring and communicating food quality and FSC operational process quality (see ***Figure 1***). Sensors attached to packed food products continuously measure and provide data (time, temperature, position, but also, if essential, vibration, pH, etc.) to a cloud-based communication system because the food products are distributed along the FSC. The data is cataloged and used in microbiological prediction models to determine the actual shelf life of a food product at any given time. Data on the DPSL and other relevant product information can be communicated to the FSC actors through different digital interfaces (webpages, mobile apps, business systems).

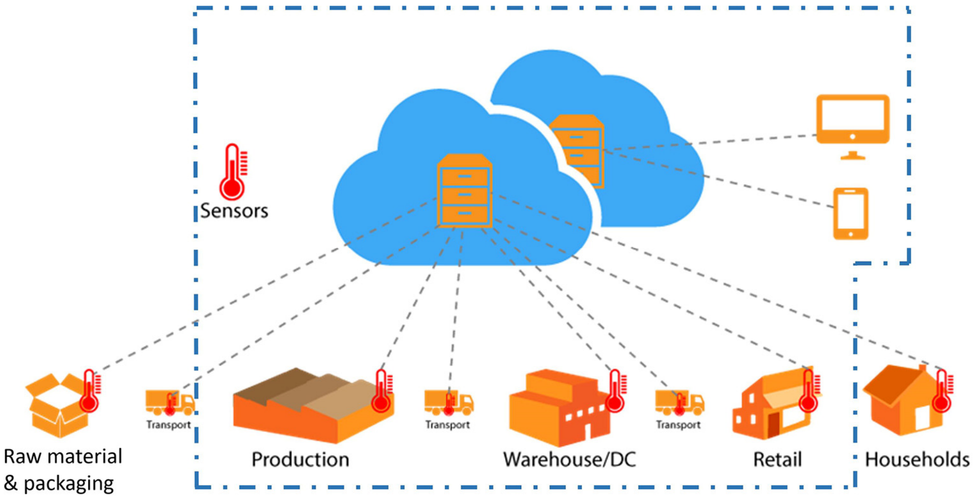

Figure 1. The concept of a dynamically predicted shelf-life (DPSL) service. Sensors placed on food packages continuously communicate the quality of the food throughout FSC distribution. In this dissertation, the chilled FSCs studied starts at the point of packaging in food production and ends when the consumer picks up his/her perishables in the retail store. Issues regarding households and end consumers are discussed to some extent.

1.4. Purpose and research questions

The overall aim of the research presented in this dissertation is to contribute to lowering food waste. The purpose is to explore and evaluate the concept and requirements of a dynamically predicted shelf-life (DPSL) service and to provide understanding and guidance for actors involved in sustainable supply chain innovation (SSCI) ventures.

To achieve the purpose, three research questions (RQ) were defined. They are motivated and stated in the following paragraphs:

The DPSL service was developed to increase food quality control in FSCs and decrease food waste. However, to successfully develop the DPSL service, observations in the field along with insights and reflections on contemporary and future FSC sustainability challenges from the FSC actors (the users), stakeholders and end consumers were needed. This called for a study exploring the operational, business model and strategical opportunities and challenges of a DPSL service. Hence, the first RQ:

RQ1: *What are the opportunities and challenges of a dynamically predicted shelf-life (DPSL) service?*

Several operational requirements and phenomena needed to be evaluated in order to realize the conceptual DPSL service. For instance, how close to the food product should the sensors be placed to generate reliable and accurate temperature data and DPSL? How extensive are the temperature fluctuations that occur in the FSC, and how do these fluctuations affect the food quality and shelf life? Hence, the second RQ:

RQ2. What are the specified operational requirements for realizing a dynamically predicted shelf-life (DPSL) service system in a food supply chain (FSC)?

The DPSL service aims to create and communicate a more accurate and up-to-date food shelf life than today's printed shelf life. The innovation also aims to be a sustainable concept that reduces FSC food waste and FSC costs, and imposes societal changes in terms of food handling, consumption and waste; in other words, a sustainable supply chain innovation (SSCI). However, the implementation and realization process of a DPSL service is complex. The lack of literature supporting such a complex process was evident, not only for the DPSL service but also for SSCIs in general. Thus, frameworks stating the critical factors for SSCIs, and process models supporting the realization of SSCIs were needed. Hence, the third RQ:

RQ3. What are the critical factors for sustainable supply chain innovation (SSCI)?

1.5. Focus and demarcations

The research topic of this dissertation is sustainable food supply chain innovation (SFSCI), which is a fusion of the following research areas: food microbiology, food packaging logistics, food SCM, and innovation. The dissertation approaches the food waste problem by taking a holistic view of FSC systems by connecting the characteristics and interdependencies between the research areas.

Explicitly, this dissertation focuses on finding challenges in the development, design and realization process of a proposed sustainable food supply chain innovation (SFSCI) in the form of a dynamically predicted shelf-life (DPSL) service. Explorative studies, experimental studies field tests, along with systematic literature research studies were designed to determine the opportunities and challenges that actors face when trying to realize SSCIs. Designing and evaluating SSCIs in a FSC requires interdisciplinary research and knowledge in food microbiology, packaging logistics, supply chain management, innovation, intelligent goods, and the Internet of Things (IoT). The studies and papers included in this dissertation cover or discuss all of these research areas. However, because of the cross-disciplinary nature, not all of the studies have an in-depth setup; several are designed instead to produce findings on an overall level.

The studies included were performed in parallel with the innovation project, Dynahmat. Dynahmat was a five-year long innovation project (2012-2017) aimed at creating SSCIs in the food sector. The project involved in total 20 actors, covering three FSCs from packaging and production, via transportation, wholesale, distribution, retail outlets to the end customer. The goal of the project was to develop intelligent packaging and logistics solutions that increased food quality and safety control and thereby decreased food waste (the Dynahmat Project is described in more detail in ***sections 2.4*** and ***3.3.1***).

The project was mainly based on innovation creations but only parts of the work could be used in research. On the other hand, the innovative project environment gave me a platform to explore and find evidence for my research in practice. The project environment also enabled me to expand my knowledge in areas outside of the dissertation's research scope. It enabled me to reflect on my research and results in a wider context, which both directly and indirectly affected the evolution of the research. Some of these reflections will appear as future research suggestions but are not developed further in this dissertation. One example is a business model development for supply chains, especially SSCIs. The progression and evolution of Dynahmat somewhat steered the subject areas of my research and paved the way for a focus leaning more towards FSC management rather than food microbiology.

The empirical area of my research is delimited to study food supply chains in developed countries such as Sweden. The studies mostly focus on the business-to-business part of the supply chain, and the consumer issues are just briefly reflected upon. More specifically, the studies focus on the supply of chilled perishable food, food shelf life, and food quality control. Trackability, traceability and rigidness are also reflected upon.

“Food quality” in this dissertation is referred to from a microbiological perspective (which is most sensitive to the parameters of time and temperature). Shelf-life is the period of time during which a food maintains its acceptable or desirable characteristics (preferably under specified storage and handling conditions). These acceptable or desirable characteristics is related to both food quality and food safety. In this dissertation, the food shelf life is primarily referred and evaluated through the characteristics of microbial growth.

In this dissertation a typical chilled FSC includes: industrial producers that refine, process and pack the food product (food producer); logistics service providers that collects and transport food products (transporter); wholesalers that collects several types of food products at a convenient cite for further distribution (warehouse); logistics service providers that co-distribute several types of foods to retailer, municipal enterprises or restaurants (distributors); and retailers that provide households with various types of food products (retailers) (see ***Figure 1***). A food supply chain starts with a primary producer that grows, harvests or cultivates the raw material. However, primary producers are not included in the FSC studied; nor are packaging producer, sensor producer and waste managers. Households are only mentioned to some extent.

There is currently many existing definitions of “food waste”. In this dissertation, “food waste” is referred to any food lost by deterioration or waste, and encompasses both of Food and Agriculture Organization of the United Nations’ definitions of food loss and food waste, which they refers to as “food wastage” (FAO 2014). FAO (2019, p.5) defines food loss as: “*The decrease in the quantity or quality of food resulting from decisions and actions by food suppliers in the chain, excluding retail, food service providers and consumers”*, and food waste as: “*the decrease in the quantity or quality of food resulting from decisions and actions by retailers, food services and consumers”.*

1.6. Dissertation outline

This dissertation consist of a collection of five appended papers. The dissertation presents an overview of the papers, the theoretical knowledge areas behind them, the methodologies applied and an analysis of the results from the five papers providing overall key findings of the research. The overall contributions are elaborated on as well as how they relate to the aim and the research questions. This dissertation consists of six chapters:

Chapter 1 introduces the problem area addressed. It presents the aim and research questions in relation to the problem area and focus. The dissertation's demarcations are stated.

Chapter 2 presents the theoretical knowledge areas upon which the dissertation is built and the interlinkage between these knowledge areas, namely food quality and shelf life, packaging logistics and SCM.

Chapter 3 presents an outline of the methodology approach of the research. The reasoning behind the research approach is elaborated. The research design explains how the five papers and the three research studies relate to the aim and RQs of the dissertation. The research scope and units of analysis of the research studies and appended papers are explained in relation to the three knowledge areas and the levels of the food supply chain system. This chapter also reflects on the research process and the methods used. It ends with a discussion of the analytical framework, the quality of the work and its limitations.

Chapter 4 presents the results. This chapter includes summaries of the five appended papers (with emphasis on the three journal papers) and how they relate to each other. This chapter presents an overall analysis of the findings of the three research studies (including the five appended papers) resulting in the key findings of this dissertation.

Chapter 5 discusses the key findings of and how they relate to previous published research. This chapter also elaborates on the contributions and limitations of the dissertation.

Chapter 6 concludes by providing answers to the three RQs. The chapter also states the dissertations' contributions to academia and practice and offers suggestions for future research.

2. Food packaging logistics – from microorganisms to innovative supply chain solutions

This chapter presents the theoretical knowledge and application areas upon which the dissertation is based. As stated, the purpose of this dissertation is "to explore and evaluate the concept and requirements of a dynamically predicted shelf-life (DPSL) service and to provide understanding and guidance for actors involved in sustainable supply chain innovation (SSCI) ventures". In order to fulfil the purpose, the fundamental aspects and activities within the FSC system, and how they affect food shelf life and food waste, needed to be assessed. The FSC system is divided into three knowledge areas: 1) food quality and shelf life, 2) packaging logistics, and 3) SCM (see ***Figure 2***). The knowledge area of food quality and shelf life describes the microbiological aspects of food quality, that is, the factors that control microbial growth and how these factors can be monitored. The packaging logistics area describes the packaging system and its interaction with the product and the logistical activities. It also describes the different activities (physical operations and information flow) within and between the actors in a supply chain environment. The SCM area considers the supply chain as an entity in order to describe the possibilities and challenges involved in decreasing the environmental footprint of supply chains and increasing innovative and sustainable development.

Consequently, the dissertation's theoretical framework consists of the overlapping knowledge areas (see ***Figure 2***), namely, intelligent packaging and logistics solutions, and IoT; food supply chain and food packaging logistics; sustainable food supply chains and innovation, and are all interconnected in the central topic of this dissertation: a DPSL service.

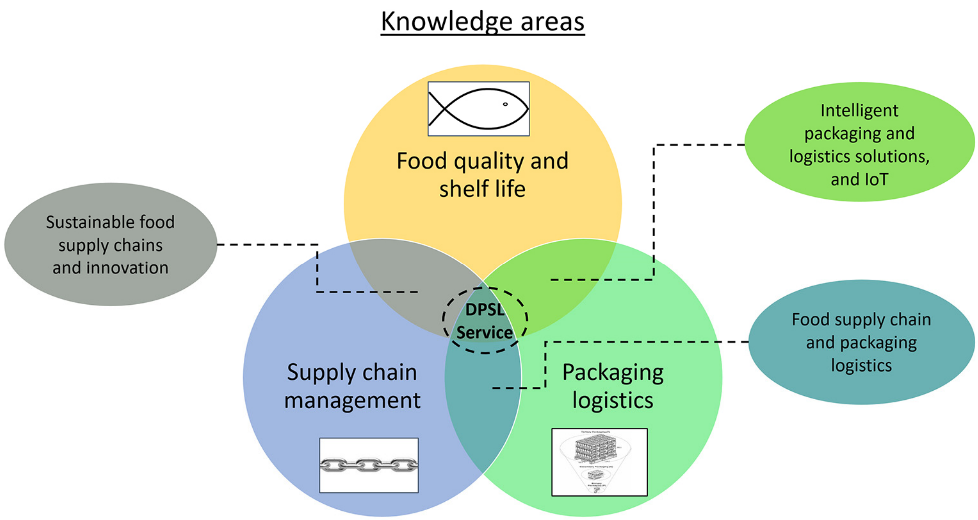

Figure 2. Relevant literature concerning the food supply chain system that frames the dissertation research. The three main knowledge areas of the FSC system are food quality and shelf life, packaging logistics, and supply chain management. In the overlap of the three one finds intelligent packaging and logistics solutions, and IoT; FSC and packaging logistics; sustainable FSCs and innovation. All knowledge areas are interconnected in the central topic of the dissertation: a DPSL service.

2.1. Aspects of food quality and shelf life

The term "food quality" is comprehensive and contains a range of different characteristics such as appearance, color, composition, perishability, safety, smell, suitability, taste and texture (Alli 2003). Food quality can be defined as the totality of inherent characteristics of a product and accompanied service that bear on its ability to satisfy the stated and implied needs and requirements (ISO 9000:2015, American Society for Quality. Food, Drug, Cosmetic Division 1998). Due to the numerous characteristics and their subjective features (especially their organoleptic characteristics), food quality may be perceived differently from person to person. Hence, food quality is difficult to estimate and measure (Alli 2003). A discussion of the organoleptic characteristics is not included here. The following sections instead concentrates on microbiological aspects of food perishability and food safety, which are directly related to shelf life, expiration dates, and food supply chain control, particularly when it comes to fresh food products.

2.1.1. Food perishability and safety

Fresh food is perishable, which means that the food product is likely to spoil or decay quickly. The high water and nutrient content of fresh food creates the perfect environment for microorganisms to grow (Adams & Moss 2008). The food we cultivate, produce and consume will always carry some kind of microbial affiliation. The microflora composition depends on which microorganism gain access, grow, and survive in the substrate (the food product). The composition also depends on how the microorganisms interact with each other and with their substrate over time. Microorganisms can be introduced in the food product from the natural microflora of the raw material or during the course of harvesting, slaughter, processing, distribution, storage, or preparation (Alli 2003, Adams & Moss 2008).

Foodborne microflora can be divided into three groups: good microorganisms, microorganisms that spoils the food, and pathogens (Adams & Moss 2008). The good microorganisms include fermenting bacteria that supports intestinal functions and overall health. Spoiling microflora is the major factor to organoleptic quality changes in food. The microflora and their metabolic byproducts can create off-odor, pigment changes, structural changes or off-flavors (Adams & Moss 2008). This is what microbiologist refers to as “food quality changes” (Alli 2003). Microbial pathogens are microorganisms that can cause disease or illness to the host. Pathogens, in contrast to spoilage microorganisms, do not change any organoleptic properties in the food. This makes it impossible to detect pathogenic microorganisms without growth-based or molecular detection methods. The results from these detection methods take from a few hours up to several days to generate (Bhunia 2008). The reduced risk and control of pathogenic contamination and growth in food products is what microbiologist refers to as “food safety” (Alli 2003). Foodborne illnesses can be caused by the ingestion of either microorganisms or toxins produced by the microorganisms (intoxication). They can also be caused by ingested microorganisms that produce toxins inside the host (toxicoinfection) or through foodborne infection where the microorganisms themselves are toxic (Bhunia 2008).

Food safety is the most important and crucial aspect of food quality. Food may be rejected due to poor food quality even though the level of food safety is acceptable. The food quality, however, will always be rejected if the food safety is rejected (Alli 2003). Both food quality and food safety are dependent on microbial growth. Microbial growth is also one of the main underlying issues causing food waste (HLPE 2014; Labuza & Fu 1993). This is why it is of great importance to recognize the factors controlling microbial growth.

2.1.2. Factors controlling microbial growth

There are four main groups of factors that control microbial growth: intrinsic, extrinsic, implicit, and process hygiene. The environmental conditions (extrinsic factors) and the substrate’s nutritional content (intrinsic factor) affect the type of microorganism that can survive and grow in a food product (Jay et al. 2005). The growth rate of a microorganism can also be affected by the competitive microflora and their metabolic byproducts (implicit factors) (Adams & Moss 2008), and by general food process hygiene such as location, slicing, washing, pre-cooking, packing, pasteurization, and personal hygiene (Adams & Moss 2008, FAO 1998).

Intrinsic factors involve, among others, the food product's level of nutrients and water activity (Adams & Moss 2008, Prescott et al. 2005). Intrinsic factors will set the initial restrictions for the kind of microorganisms that can grow in a specific food product. Water is essential for all microbial growth and exists in large amounts in fresh food (Prescott et al. 2005). Fresh food has high water activity, which also can be described as a high level of available water molecules. Salts and other ions bind to water and can thereby decrease the level of free water molecules, reducing the ability for microorganisms to grow (Adams & Moss 2008). Foodborne microorganisms also require sources of energy, nitrogen, vitamins and minerals in order to grow and function normally (Adam & Moss 2008, Jay et al. 2005).

Extrinsic factors involve the properties of the food's storage environment. These factors have a significant impact on the growth of foodborne microorganisms and include, among others, storage temperature and gas composition (Adam & Moss 2008). The storage temperature has the largest extrinsic impact on microbial growth and is thus especially important to control (Prescott et al. 2005). All microorganisms have a specific optimal temperature span for growth and propagation. Microorganisms can, under optimal conditions, reproduce and multiply in as fast as 20 minutes. Improper storage temperature can thereby have severe consequences on food quality and safety as well as food waste. Lower temperatures change the membrane structure resulting in a decreased uptake of nutrients and reduced growth rate. Hence, it is of great importance to store and distribute fresh food in temperatures that are preferably between 0-4°C. Higher temperatures cause degradation of plasma membranes and denaturation of proteins, which leads to decreased growth rate or cell death. (Adam & Moss 2008, Jay et al. 2005, Prescott et al. 2005). This emphasizes the importance of adequate cooking methods (Hui & Sherkat 2005). Another important extrinsic factor that affects microbial growth rate is the gas composition of the surrounding environment. Oxygen is a strong oxidizing agent and can alter a food product's organoleptic qualities. The characteristics of microbial growth are also thoroughly dependent on the presence or absence of oxygen, depending on the microorganism's respiratory system. A good way to control the effects of the surrounding environment and thereby its influence on microbial growth is to encapsulate the product in proper packaging material (Robertson 2013). The environment inside the package can also be modified to influence microbial growth. A modified atmosphere package includes different gaseous compositions of O_2, CO_2 and N_2 and is used as a preservative method. The packaging method is mostly used on fresh food such as meat, fish and poultry (Tucker 2008). Vacuum (evacuation of air) is another preservative method mostly used on meat, fish and poultry.

Implicit factors are the properties and characteristics of the microorganisms that influence how the microorganisms react and interact with their environment, and with each other and the competing microflora. The microflora of fresh food are often very diverse but in general are dominated by one or a few microorganisms. The intrinsic factors of fresh food are ideal for most microorganisms, which is why the extrinsic and implicit factors are crucial for the characteristics of the microflora. Significant implicit factors for survival are the microorganism's growth rate, affiliation to the substrate, stress tolerance to environmental changes, tolerance to toxic substances produced by competing microflora, and mutualism (enhanced microbial growth due to stimulation from competing microflora). The microorganism's specific growth rate is one of the most crucial implicit factors for survival and dominance (Adam & Moss 2008, Jay et al. 2005).

Process hygiene factors includes all the possible contamination sources in the FSC from farm to fork, which predominantly consist of operations in direct contact with the raw material and unpacked food (Adams & Moss 2008, FAO 1998). Examples of such operations are washing, slicing, pre-cooking, pasteurizing and packing. The sanitation routines of facilities, equipment and personnel hygiene are of central importance to general food process hygiene. The Codex Alimentarius Commission established internationally recognized food standards and programs to ensure food hygiene practice throughout supply chains (FAO/WHO 2019, FAO/WHO 2003, FAO 1998). The Prerequisite Program includes Codex General Principles of Food Hygiene (Good Hygiene Practice, GHP) (FAO/WHO 2003), specific codes of practice for a range of food groups, food processing techniques (FAO/WHO 2019), and guidelines and laws on microbiological criteria (EC 2005b, FAO/WHO 2019). The Prerequisite Program and GHP lay a firm foundation for each company involved in the FSC to establish an effective food safety system. Such a system is required by law to be regularly controlled with a Hazard Analysis and Critical Control Points (HACCP) system or other compatible quality management system such as ISO 9001:2000. The HACCP system is a science-based tool that identifies, evaluates and controls hazards in the food safety system (see the seven principles of HACCP in ***Table 1***). The GHP and HACCP systems focus on the prevention of food contamination rather than relying on end-product testing (FAO/WHO 2003).

Table 1.
The seven principles of a HACCP system (Alli 2003, FAO 1998)

Principle step	Action
1	Conduct hazard analysis
2	Determine critical control points
3	Establish critical limits
4	Establish monitoring procedures
5	Establish corrective action procedures
6	Establish verification procedures
7	Establish recordkeeping and documentation procedures

It is of key importance that each company in direct contact with food establishes its own specific GHP and HACCP for each of its facilities. Each facility possesses a unique local microflora influenced by the surrounding environment, air, soil, foreign objects, raw material, packaging material, staff hygiene, and cleaning techniques (Lelieveld et al. 2005). Specifications regarding the packaging material that comes in direct or indirect contact with food are that it must be clean and free from contaminating material. The packaging material must not transfer unhealthy or harmful compounds to the food. The packaging material cannot excrete aldehydes or amines to mask food spoilage or change other organoleptic properties (EG 1935/2004, Rydén & Lorentzon 2018).

The Prerequisite Program and HACCP system make up the foundation for safe food production. However, no matter how good the systems are, food products will never be free from microbial growth. This section has described numerous factors that control microbial growth. The most important ones for maintaining food quality and prolonging shelf life are temperature and risk of contamination (especially for fresh chilled food product).

2.1.3. Monitoring factors that control microbial growth

It is required by law to measure and register storage temperature for all types of enclosed areas during food distribution (EC 2005a). Generally, analog or infrared temperature thermometers are used to sample momentaneous temperatures. Registration is required at every interconnection between the FSC actors. Additionally, the transporter is responsible for monitoring the temperature in the cargo space. The registered temperature history is used as documentation of operational quality assurance in case of temperature abuse that results in reclamation, returns and discards (FFKM 2016). The instruments used for temperature measurement and registration are regulated by 92/2 /EEC (EC 1992). This regulation does not allow data from temperature indicators (TIs) and time and temperature indicators (TTIs) to be the basis for temperature registration decisions. TIs, also called partial history indicators, only respond to temperatures that have exceeded (over or under) predetermined thresholds (FFKM 2016, Robertson 2013). Since TIs do not include the full temperature history, they can only be used to indicate that temperature abuse has occurred but not the extent. Hence, there is no relation between food quality and the response of TIs (Robertson 2013). TTIs, also called full history indicators, continuously respond to all temperatures (FFKM 2016, Robertson 2013). TTIs are based on physical, chemical, microbiological or enzymatic changes that imitate the shelf life of food. Consequently, denatorative reactions that lead to food quality loss in a specific food product need to be defined, measured, recalculated and expressed as a TTI response. Both TIs and TTIs are most frequently expressed visually by color change or color movement. The indicators, especially TTIs, are used more and more frequently in FSCs, but still to a limited extent. This is primarily due to the technical challenges involved in producing reliable indicators (Robertson 2013).

Moreover, time and temperature tags (TTTs), also called temperature recorders and temperature data loggers, are commonly used in the food sector. The TTT includes a memory and a data transfer connection, usually in the form of a USB. Time and temperature is measured and stored digitally on the TTT (Raab et al. 2011) and the TTT can be used as a tool for operational quality assurance (Verghese et al. 2015, Newsome et al. 2014). However, TTTs are rarely used in the self-monitoring system due to the need for the physical transfer of data. TTTs are more commonly used as sampling instruments to control specific FSCs or critical control points. Temperature monitoring tags can be integrated with radio-frequency identification (RFID) tags. These RFID tags can also be connected to other sensors such as GPS, pH and moisture (read more about RFID tags in ***section 2.2.2***). The ability to connect several features to RFID, expressed as digital signals that can be shared among FSC actors, is an indication that the tags have a good future (Ruiz-Garcia et al. 2009).

Biosensors are indicators of food quality and shelf life. They can rapidly detect microbiological contamination and spoilage in food (Robertson 2013). They consist of bioreceptors that target specific analytes and transducers that convert biological signals into digital responses. However, non-destructive and small biosensors that can be placed on consumer packed food are currently unavailable on the market.

Another way to monitor the quality of food is by using microbiological prediction models. These are mathematical models, mostly developed and based on observations obtained from experiments carried out under controlled conditions (Perez-Rodriguez & Valero 2013). Researchers have developed numerous predictive models over the years, all of which are food product and condition specific. These models can predict the fate of microorganisms when a given food product is stored under specific and known conditions, (i.e., temperature, pH, gaseous atmosphere, etc.). These dynamic models indicate the microorganism's ability to grow, but also provide information about the rate and extent of growth that occurs in a given time period (Man & Jones, 2000). Microbiological prediction models are a commonly used tool to support decisions concerning food safety and quality in the food industry, such as self-monitoring systems and as HACCP. Moreover, prediction models can be used to predict the shelf life of a food product (Perez-Rodriguez & Valero 2013).

By combining digital monitoring systems that continuously measure dynamic extrinsic factors with microbiological predictive modeling, a dynamically predicted shelf-life (DPSL) can be calculated and continuously updated as new extrinsic data are added. Such a combined monitoring system can thus provide a more accurate measurement of shelf life. Monitoring shelf life and relevant extrinsic factors has several clear benefits, which are foreseen to play an important role in future FSCs (Robertson 2013).

2.1.4. Shelf life and printed date labels

The European Parliament and Council define "printed shelf life" or "minimum durability" of food as: "*The 'date of minimum durability of a food' means the date until which the food retains its specific properties when properly stored*" (EC 2011, p.26). As the definition implies, the shelf life of food is a factor-dependent concept, in terms of both the factors that control microbial growth (food safety and quality) and the factors that affect organoleptic properties (food quality). Nevertheless, shelf life is a common term that is used daily in the food industry and by consumers. It is usually expressed on a printed date label (Kilcast & Subramaniam 2000). The shelf life shall be stated as minimum durability or "used by" and followed by a date presented in the order of day, month, and year. Highly perishable foods that after a short period can cause harm or illness should be labeled with "used by". The law does not require an indication of shelf life on all kinds of perishable food. Exceptions are made for products such as fresh fruit, beverages containing 10% or more alcohol by volume, and pastries, which are normally consumed within 24 hours of being manufactured (EC 2011).

The assessment and affirmation of shelf life is performed by food producers. The assessment usually consists of microbiological stability measurements, physical measurements, chemical measurements, and organoleptic tests performed by a sensory panel or instruments such as electronic noses. Microbiological stability tests include measurements of the total microbial load, indicating time to spoilage, and the growth of specific microbial pathogens, indicating time to harm. The stability tests are performed at the stated storage temperature (printed on the food package) and measured at staged intervals. The stability tests also include "challenge tests" where specific pathogens are inoculated into the food to simulate contamination. The challenge test can include temperature variations to simulate temperature abuse (Kilcast & Subramaniam 2000). The threshold limit value for the period of shelf life is called the "microbiological criterion" and is determined and legislated in Europe by the European Council (EC 2005b). The microbiological criterion defines the acceptability of the product, based on the absence, presence or number of microorganisms, pathogens and/or toxins. The criterion is defined for food groups and different types of processing techniques, such as minced meat. The criterion is furthermore divided into two parts: 1) process hygiene criterion, indicating the acceptable functioning of the production process, and 2) food safety criterion, defining the acceptability of the food placed on the market (EC 2005b). Some fluctuations in microbial load are normal between batches of a food product. The majority of the food producers leave a safety margin between the microbial count and the microbiological criterion to ensure the food quality all the way to the point of sale, in spite of microbiological fluctuation, contamination and temperature abuse. By doing so, the printed shelf-life date on food products is often reduced to 70% of the time to spoilage (Kilcast & Subramaniam 2000). The stated storage temperature shall not be exceeded throughout the SC. However, temperature fluctuations that result in decreased shelf lives and food waste have been reported (i.e., Jedermann et al. 2014, Kuo & Chen 2010, Olsson 2004). Temperature abuse resulting in food waste and foodborne illness has also been reported in the literature (Cartwright et al. 2013, Iwamoto et al. 2010, Adams & Moss 2008, Prescott et al. 2005). Nevertheless, most food products are distributed in intact cold chains. The regularity of intact cold chains has increased and temperature abuse has been less reported over the years (in Sweden). In Sweden, distributed chilled fresh food is frequently kept at lower temperatures than stated on the packages. The intact and decreased temperatures in the cold chains contribute to increased food quality and shelf life. The temperature levels and variations in the supply chains, both high and low, call for increased temperature control in FSCs and new innovative solutions to determine or change shelf life according to storage conditions.

2.2. Food packaging and logistics

It is important to note that food quality is not only defined and dependent on food and environmental characteristics and microbiological growth, but also on the features of the packaging system, the service and the usability of the food product. As in most supply chains, products are placed in packages to facilitate protection, convenience, handleability and communication from the point of origin to consumption. For most food products, the packaging is an essential element for all FSC actors as well as consumers.

2.2.1. The food packaging system

The choice of packaging material and design is essential for maintaining the quality of chilled food products. Different types of protection can be achieved by different levels of packaging (Kilcast & Subramaniam 2000, Robertson 2013). Food packaging, or a food packaging system, consists of three levels of packaging (see ***Figure 3***): (1) the primary package contains and preserves the product (all food items from raw material to processed products) and is also called consumer package or sales package; (2) the secondary package contains several primary packages to simplify stacking and handling. Secondary packaging is also called retail package or grouped package; and (3) the tertiary package that contains several secondary packages that ease the supply chain handling, transport and distribution, and reduce physical damage to the rest of the packaging system. The tertiary package is also called transport package or pallet (EC 1994, Jönson 2000, Hellström & Saghir

2007). The three packaging levels create an integrated and interdependent packaging system (Olsson & Larsson 2009).

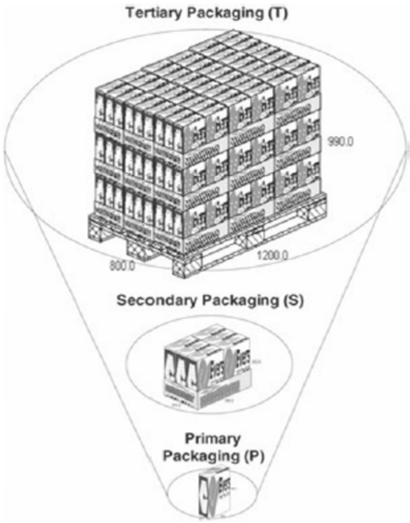

Figure 3.
Levels of packaging in a packaging system. (1) Primary package, (2) Secondary package and, (3) Tertiary package (Hellström & Saghir 2007).

The packaging system adds value and service to the products customers and consumers purchase. The packaging system should thereby be designed in parallel, or integrated, with the food product design and development in order to optimize service and usability. The functionalities and features of a food package are multiple and can be seen as a product-packaging service system (PPSS) (Olsson & Larsson, 2009). The packaging contains, preserves, and protects the product from contamination, spoilage and mechanical damage. Hence, a misalignment in the product-packaging design development can cause over packaging or food quality loss and food waste due to poor packaging or choice of packaging material (Twede 1992). The package also works as an information carrier that communicates and promotes the product, and informs the consumer and customer (EC 2018, FAO/WHO 2018). The primary package is required by law to carry information to the consumer that includes: product name; list of ingredients and quantity of ingredients/category of ingredients; net quantity; minimum durability/best before date or use by date; storage conditions; conditions of use; name and address of produces, business, packager or seller; place of origin; instructions for usage; and alcohol content (only on products containing more than 1.2%) (EC 2011). The package, in addition to being an information carrier, is designed to make the product as convenient, attractive and usable as possible (Kilcast & Subramaniam 2000, Robertson 2013). The PPSS shall be easy to handle for the supply chain actors and consumers. It shall also be easy to carry, open and close, and easy to dispose, recycle or reuse. The usability of the PPSS shall be designed to fit the food products' consumer group and specific activities at the time of usage. The PPSS design shall consider the package print to attract the right type of consumer group (Olsson & Larsson 2009).

Packaging, especially food packaging, is often considered an environmental burden that fills landfills and begrimes societies (Grönman et al. 2013, Lindh et al. 2015). Food packaging has mostly been discussed in terms of reduction of material usage, type of material and recycling (Williams & Wickström 2011). However, the environmental impact of the packaging system is small compared to the environmental impact of cultivating/growing and processing the food the package contains (FAO 2011, Grönman et al. 2013). Although material use and recycling are important issues, it is of greater importance, both from an environmental and an economical perspective, that the packing system fully protects the product inside. A reduction of packaging material can result in an increase of both food and packaging waste. The packaging system should thus be designed to optimize, not minimize, material usage. An optimized packaging system design does not only fulfill all product requirements, but also operations, logistics, service and management requirements (Grönman et al. 2013, Olsson & Larsson 2009, Hellström & Saghir 2007). Molina-Besch (2016) provides prioritization guidelines for green food packaging development that can help practitioners improve their food packaging system and develop packaging solutions that contributes to minimizing environmental impact along the FSC.

2.2.2. Packaging logistics in food supply chains

Optimizing the design of an entire supply chain or its components requires packaging logistical thinking (Twede 1992, Saghir 2002) (in this context, similar to life cycle and system thinking). Saghir (2002, p.11) defines packaging logistics as, "*The process of planning, implementing and controlling the coordinated packaging system of preparing goods for safe, secure, efficient and effective handling, transport, distribution, storage, retailing, consumption and recovery, reuse or disposal and related information combined with maximizing consumer value, sales and hence profit*". Hence, the assessment of supply chain design needs to consider the requirements of both packaging and logistics, and their interactions with each other and the surrounding environment. Full supply chain assessments are also required to optimize supply chain components, the packaging system, internal logistics and external logistics. Hellström and Saghir (2007) state that understanding the packaging system's environment is a prerequisite for making any packaging decisions, especially from a SC perspective. Hellström and Saghir (2007) used mapping to elucidate the interactions between the packaging system and logistics. Mapping can give detailed insights into the requirements placed on each level of the packaging system and on the logistics. ***Table 2*** provides an overview of the interactions between the packaging system and the physical logistics in a typical chilled FSC. The interactions highlight the SC actors and logistical activities that are most important in the optimization process of a packaging level, or vice versa.

Table 2.
Interactions between the packaging system (primary packaging, secondary packaging and tertiary packaging) and logistical operations in a typical chilled FSC. Inspired by Hellström and Saghir 2007.

Food supply chain actor	Logistical activities	Packaging level		
		Primary	Secondary	Tertiary
Producer	Filling process	X		
	Palletizing and wrapping	X	X	X
	Cold storage			X
LSP	Receiving			X
	Transport			X
	Delivery			X
Wholesaler	Receiving		X	X
	Cold storage		X	X
	Picking and assembling		X	X
LSP	Receiving			X
	Distribution			X
	Delivery			X
Retailer	Receiving		X	X
	Cold storage			X
	Replenishment	X	X	X
	Re-use, recycle and waste		X	X
Consumer	Picking	X	X	
	Transport	X		
	Cold storage, usage	X	X	
	Recycle, waste	X		

The mapping of packaging, logistical and supply chain interactions does not only help managers optimize their entire supply chain or parts thereof; mapping also assists managers in finding dysfunctionalities and critical operational control points that can be monitored or improved to reduce risks of contamination or other operational failures (Olsson & Skjöldebrand 2008). Examples of packaging logistical improvements are the optimization of packaging material in the packaging system and the optimization of filling rates (volume and weight) on pallets and transportation containers (Olsson & Larsson 2009). Other examples of optimization is handleability improvements of the packaging system that, with or without the help of technology, can reduce the operational workload for supply chain personnel (Regattieri & Santarelli 2013). However, requirements from different logistical operations and supply chain actors many times do not correspond with each other. Considerations and trade-offs between requirements have to be made keeping in mind the total supply chains financial, environmental and social impacts.

The functionality of packaging logistics does not only depend on the physical operations. The exchange of information (internally and externally) between supply chain actors has an equally large impact on the physical product flow (***Figure 1***) and supply chain attainment. The flow of information travels both backward and forward in the supply chain. Information needs to be shared before, during and after the sale of products in order to deliver them at the right time, place and price to satisfy suppliers, customers and end consumers (Singh 1996). Supply chain information sharing is essential for coordinating, monitoring and planning processes and activities within the supply chain (Lambert et al. 1998; Mentzer et al. 2001). Moreover, shared information captures data that can provide companies with insights that can increase the efficiency and effectiveness of their logistical operation (Singh 1996). Thus, information sharing facilitates the matching of supply and demand and with that, the possibility to reduce variability and inventories (Bourland et al. 1996). What is specific to FSCs, especially those that are chilled, is that a mismanaged information flow can have drastic consequences resulting in harmful food or food waste, financial loss and reduced consumer trust. Thus, it is the coordinated combination of product and information flow that can enable a well-functioning, integrated and successful supply chain (Singh 1996). The search for efficiency and effectiveness through integrated design, coordinated operations and standardization in handling is the heart of packaging logistics (Gustafsson et al. 2006).

As already mentioned, food products are time and temperature sensitive. For this reason, food logistics is often mentioned separately, or with a specific notion from other logistical operations. This has become particularly evident in the area of chilled fresh food, with its emphasis on freshness, quality and timeliness at a low cost (Gustafsson et al. 2006). Fredriksson and Liljestrand (2014, p.13) define food logistics: "*Food logistics analyses logistics activities within a food supply chain context by problematizing food product characteristics and by examining the constellation of food supply chain actors*". Food logistics is facing critical changes in response to consumer needs, with a larger diversity of food and on-the-go products and high quality and safety demands. Furthermore, the food industry tends to have a very long supply chain, with many actors and sub-contractors included (Ruiz-Garcia et al. 2009). Food logistics may thereby be even more reliant on a well-coordinated information flow. Hence, new opportunities for cooperation arise.

There are many information and communication technologies (ICT) that helps managers distribute, monitor, collect and categorize supply chain data. Wireless sensor networks, such as Bluetooth, and RFID, are technologies that allow the communication of information from the item to which the tag is attached to a gateway unit and further on to supply chain actors and networks. RFID was mainly developed as an identification system but has over the years been incorporated into various wireless sensor systems (Guillory & Strandhardt 2012, Ruiz-Garcia et al. 2009, Pålsson 2007). Some types of RFID tags have an integrated temperature sensor and may thus be used for cold chain monitoring. Using RFID temperature tags corresponds to conventional methods in terms of accuracy, but is superior in performance in terms of fast instrumentation as well as accessibility of sensor data without line of sight, amongst others things (Amador et al. 2009). However, the relatively high water content of food causes signal attenuation and problems in wireless communication. Wireless communication in combination with metals usually involves penetration problems (Jedermann et al. 2011; Ruiz-Garcia & Lunadei 2011). Still, wireless sensor networks and RFID have tremendous possibilities in the field of food logistics, such as for monitoring environmental loads, livestock and traceability, as well as humidity, vibration and cold chain control (Ruiz-Garcia et al. 2009). Baars et al. (2009) state that a large body of research exists on RFID benefits; however, they found an absence of research with a comprehensive approach. Both industry and academia are unanimous that food logistics is in need of increased efficiency and the atomization of all the monitoring processes that occur in a supply chain (Ruiz-Garcia et al. 2009, Pålsson 2007, Gustafsson et al. 2006).

2.3. Food SCM and innovation

With the demand for increased integration in the FSC, packaging logistical processes can no longer be viewed as separate operations (Gustafsson et al. 2006). Supply chain integration is possible by establishing SC alignments including a collective management strategy (Mentzer et al. 2001, Miemczyk & Howard 2008) where the financial model emphasis is moved from “price per unit” to “job to be done”. Hence, the SC strategy shifts to a supply chain perspective that focuses on fulfillment of needs instead of the amount of sold products (Boons & Lüdeke-Freund 2013). Lambert & Cooper (2000) argue that risk and gain sharing are critical in order to establish SC focused strategies. Another important factor for SC integration is to establish strong and trustful collaborations between the SC actors (Liebl et al. 2016, Gustafsson et al. 2006). Transparent SCs focused on knowledge diffusion and quality information sharing are also a key factor for increased supply chain integration (Prajogo et al. 2014).

The implementation of innovations and new technology in a supply chain require a high level of supply chain integration in order to be fully functional and successful. It is also of great importance for the success of the implementation to find the right incentives for both the total supply chain and the actors involved in it (Liebl et al. 2016). However, high implementation costs are one of the most commonly reported barriers for implementation failure (Liebl et al. 2016, Jedermann et al. 2009, Jones et al. 2005). Other common implementation barriers are taxes and regulations (Liebl et al. 2016). Hellström et al. (2011) focused on three business layers to identify opportunities and challenges within an inter-organizational implementation: the strategic layer, the business model layer, and the process layer. These managerial opportunities and challenges can be matched with the mapping scheme of packaging and logistics interaction in order to evaluate the innovation and technology opportunities. The evaluation can provide collective business and process-layer based incentives for technology implementation in the supply chain as well as specified incentives for each actor involved in the supply chain.

De Marchi and Grandinetti (2013) report the importance of a large knowledge value network, external of the supply chain partners, during the development and implementation of supply chain innovations. An external value network (e.g., universities, research institutes and external R&D divisions) is made up of objective partners who focus solely on the innovations and the total supply chain outcomes. The external partners compel the supply chain actors to consider innovation characteristics, complexity and trade-off effects beyond their own company walls. Preferably, these considerations include environmental, economic (i.e., eco-innovations) and social dimensions (i.e., SSCIs). Eco-innovation is defined as, "*new products and processes which provide customer and business value but significantly decrease environmental impacts*" (James 1997, p.53). The concept of eco-innovations derives from green innovation and environmental innovation. However, even though research on eco-innovation is focused on product and process development, there is an increasing trend of taking eco-innovation research to a more complex level, including all dimensions of the triple bottom line, that is, environmental, economic, and social dimensions (De Carvalho & Barbieri 2012). This research is mainly referred to as sustainable supply chain innovation (SSCI). SSCI is a novel research area and was only recently defined in the literature by Gao et al. (2017, p. 1530) from a supply chain innovation perspective, "*If the supply chain innovation results in balanced performance of economic, social and environmental dimensions, in other words, all three dimensions have positive innovation performance. It is called a sustainable supply chain innovation (SSCI)*".

2.4. Dynamically predicted shelf-life service

The DPSL service concept (see ***Figure 1*** *in* ***section 1.3***) entails a service system including sensors that are attached to a food product (primary or secondary packaging) and provides data (position, time, identity, temperature, mechanical impact, etc.) to a cloud-based information system. The data is processed with, for example, prediction models for dynamic shelf-life (DPSL) and other information that can be gained from the data. The data can be communicated to the FSC actors involved in the product flow as well as customers and end-consumers through different digital interfaces (web pages, mobile apps, enterprise resource planning [ERP, business systems]). The concept of the DPSL service was developed and tested in real Swedish FSCs in the frame of the Dynahmat innovation project. The aim of the Dynahmat project was to reduce food waste and increase the level of innovation, traceability, and transparency in the Swedish food industry. The goal of the project was to develop intelligent packaging and logistics solutions that increase food quality control and the FSC information flow. Dynahmat, which mainly was focused on innovation creation, provided significant results, insights and outcomes to the knowledge frame of this dissertation.

2.4.1. Dynahmat – significant results, insights and outcomes

Dynahmat developed a cloud solution with web-based user interfaces and open application programming interfaces (APIs) for sensor input, prediction models, and data output. A temperature sensor solution based on wireless communication and a cellphone application for usage in the supply chain were also developed in the project. A parameterized solution for prediction models was integrated with the cloud system enabling continuous feedback on food quality, that is, DPSL.

The Dynahmat concept is based on an open system solution that enables the integration of different technologies and thereby reduces the risk for locked-in solutions. The Dynahmat concept empowers a new industrywide paradigm built on digitalization and the inclusion of accurate and accessible data shared among FSC actors. The concept focuses on sustainable development by increasing resource utilization, the quality of food, and the FSC operation.

The Dynahmat constellation presented a unique opportunity for open discussions to learn from each other, think in new ways and take advantage of the solutions and ideas that arose during the project. Another great advantage was its close connection to practice. The field test provided us with the ability to test the prototypes in everyday operations in real FSCs, instead of only performing simulations or laboratory tests where the external impacts affecting the system and overall complexity are lost.

Another project conclusion was that all actors have a strategic intention to both improve efficiency and quality as well as lower product waste in the food supply chains. The findings show that there are many opportunities connected to the concept of dynamic shelf life, such as better guarantees for products delivered, tracking and traceability of the goods, more visibility, collaboration, and information sharing in the supply chain. Furthermore, Dynahmat enhances the ability to measure key performance indicators for FSCs and their individual FSC actors. One of the most prominent financial incentive for the FSC actor was the communal, automatic and continuous temperature determination that enables the measurement of temperature with the same equipment and in the same way throughout the FSC. This decreases the discussions and legal fees and time spent on product returns or disposals if temperatures that are too high are registered. At the same time, a number of strategic concerns about the realization of the Dynahmat concept were found, especially issues related to the constellation of business models. The whole food industry has generally a retroactive approach, especially to more extensive changes and innovations, causing the industry to wait for someone else to take the first step. Uncertainties about risks, true value, investments and costs for each actor in the FSC are of great concern. An implementation would require high initial investments for most of the actors in the supply chain, such as new software, integration into existing ERP systems, scanning/monitoring systems, hardware in terms of readers and sensors, and staff training. Those activities are all costly and require numerous resources. In addition, the increased visibility in the FSCs will leave the actors' operational performance more exposed to scrutiny and increase accountability. Hence, a realization of the Dynahmat concept places extended requirements on coordination and communication within FSCs.

3. Research methodology

The main topic of my research education is food packaging logistics. Packaging logistics research falls within the interlinked areas of packaging, logistics and sustainable development. It integrates these areas into product, process and service innovations in an applied and multidisciplinary environment (PLOG 2019). In its focus on applied research, this dissertation takes a pragmatic approach that integrates different perspectives and knowledge areas to interpret empirical data (Saunders et al. 2009). My research combines my core competence areas of food microbiology and packaging logistics along with SCM, sustainable innovation and IoT. Because of this, the multidisciplinary stance and purpose of my research necessitates a mixed method design (Saunders et al. 2009).

The overall research design and approach is based on abductive reasoning. Abductive reasoning is useful if the objective is to discover new things, generate new concepts and develop or refine theoretical models (Dubois & Gadde 2002). Abductive reasoning is explained by Kovács and Spens (2005, p.136) as *"a systematized creativity or intuition in research to develop 'new' knowledge"*, which often results from incomplete or unexpected observations from experience and reality that call for an explanation of an anomaly that cannot be explained by only using established theories (Kovács & Spens 2005, Mitchell 2018). "Systematic combining", which is grounded in abductive reasoning, was used to pragmatically approach the widespread food waste challenge by introducing intelligence into the food packaging system. Systematic combining is a process where the theoretical framework and empirical fieldwork evolve simultaneously. In this research, the process of matching theory to reality affects and is affected by what is going on in reality, by the available theories, by the innovation project (Dynahmat) that gradually evolves, and by the analytical framework (Dubois & Gadde 2002).

This research endeavor began with the aim of learning how packaging and logistical solutions can decrease food waste in FSCs. One challenge found in the empirical reality showed a mismatch between the printed shelf life on packaging and the actual quality of the food inside, thus resulting in an unnecessarily large amount of food waste. However, there was a lack of explicit theories and frameworks to guide and explain the phenomenon. Hence, an iterative process was performed that combined empirical observations, theory and findings from field tests and research studies to create new understanding and knowledge in the field. The explicit and narrow research topic – sustainable food supply chain innovation (SFSCI) – is a somewhat unmapped research area. Both SFSCI and the main problem area – food waste – are multi-perspective in nature, and face challenges that are primarily found in the empirical reality. Hence, a study with an explorative approach was initially chosen to learn about and understand the field of research (Study A). This was followed by an evaluative study (Study B) to further assess questions left unanswered when matching the theoretical and empirical realm in the explorative study. The third and final study (Study C) again uses an explorative approach, placing the concept of the DPSL service in the more comprehensive context of SSCIs, to investigate the critical factors for realizing these types of innovations. Due to this abductive process, the road to achieving my research aim was not established from the start. The research design had an intentional direction and goal that emerged as the research results in the three studies came in, and as project applications where developed and funded. The scope of the research, including the FSC system (see ***section 3.2***) and the analytical framework (see ***section 3.4***) gave firm guidance and a sense of direction during my studies and research process.

3.1. Research design

The research design consists of three studies (A, B, C) guided by the three RQs that frame the search for knowledge (***section 1.4***). The research design is illustrated in ***Figure 4*** and shows the three studies that resulted in five academic papers. The research design includes insights from the parallel innovation project, Dynahmat, that also contributed to answering the three RQs. Study A takes an explorative approach and uses mixed research methods in order to understand the opportunities and challenges for a DPSL service in future FSCs. Study A resulted in two per-reviewed conference papers: Papers I and II. Study B takes an evaluative approach, addressing the emergent and central questions and problem formulations derived from Study A and Dynahmat. Study B included field tests and experimental research to assess the limitations and operational requirements for realizing the DPSL service in an FSC. Study B resulted in two peer-reviewed journal papers published in *Food Control*: Papers III and IV. Study C placed the concept of the DPSL service in the larger context of supply chain innovations, eco-innovations and SSCI in order to gain inspiration, find common critical factors and general frameworks and models for SSCI realization. Study C was a literature review study in which a narrative approach was initially applied to explore and map the research area and learn its concepts and constructs. The narrative study was followed by two literature studies using a systematic approach. The literature studies explored knowledge in the fields of eco-innovations and SSCI. The first resulted in a conference paper (Göransson & Nilsson 2015) on enablers and hinders for eco-innovations in supply chains, which is not included in the dissertation. The second resulted in Paper V on the critical factors for SSCI realization.

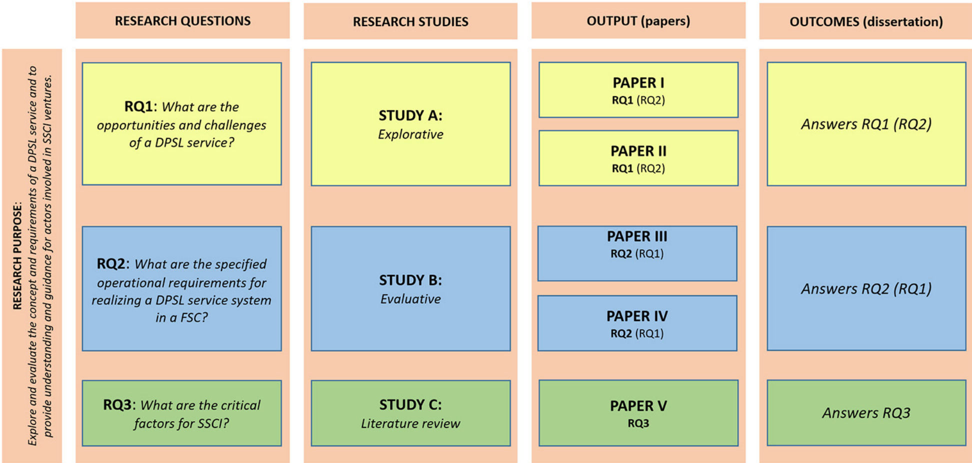

Figure 4.
The research design. This dissertation consists of three research studies A, B and C, guided by the three RQs. Study A resulted in Papers I and II and primarily answers RQ1. Study B resulted in Papers III and IV and primarily answers RQ2. Study C resulted in Paper V and answers RQ3.

In Study A, the foundation of a DPSL system was explored and framed with various smaller studies using mixed research methods (Eisenhardt 1989). Study A's exploration of the role of DPSL in future FSCs generated many question to be further investigated. Some of the most prominent were based on the unknown operational requirements of the DSPL service. These requirements were investigated and evaluated in-depth in Study B. The evaluative approach was motivated by the importance of these requirements for the foundation, setup and design of the entire system. The outcomes of such operational requirements also affect the business models and strategic discussions within the FSCs. In Study C, DPSL was placed in a larger context focusing on sustainable ventures in supply chain contexts. Study C was designed as a literature review in order to broaden the field of research and explore the concepts of eco-innovation and SSCI, evaluate the critical factors of realizing ventures in existing literature, and generate suggestions for a process model used to realize SSCI. The motivation behind Study C came foremost from the innovation project, Dynahmat. Before and during the project, the Dynahmat group tried to find frameworks and models that could guide us in the innovation process. While we found a number of insights and frameworks from a company perspective on innovation and sustainable innovation, we were not able to find anything significant on SSCI. Hence, a literature review exploring critical factors in the realization process of SSCIs was called for to be able to propose new process models for the realization of SSCIs (Study C).

3.2. Research scope and unit of analysis

The main research focus in this dissertation is on the interconnection between food microbiology and packaging logistics. Using a system perspective, components of the FSC system and the interactions that take place between them were studied to fully obtain a comprehensive picture of the system. In this dissertation, the overall unit of analysis is the FSC system, which is divided into three system levels (see ***Figure 5***): food product level, packaging level, and supply chain level. This is based on the three main theoretical knowledge areas: food quality and shelf life, SCM, packaging logistics (***Figure 2***). The research conducted on the food product level focuses on microbiological growth, food quality and food shelf life. The food product level is never investigated separately, though, because food quality and shelf life are highly dependent on the package in which the product is packed. The packaging level focuses on the different packaging system levels (primary, secondary and tertiary packaging) and the interactions between them, the product and the users (supply chain actors and consumers). Preservation of the food product and communication of product information are the packaging functions central in this research. The supply chain actors consist of food producers, logistics service providers (LSP, transporter and distributors), wholesalers, and retailers and to some extent, consumers. The DPSL service system also includes packaging suppliers, sensor suppliers, technology suppliers, and information providers. These actors did provide some empirical content but are outside of the main scope (see ***Figure 1*** and ***Figure 5***). The FSC actors are studied in terms of their interaction with the product/packaging system on an operational level, and how they utilize and communicate product information. On the supply chain level, the whole FSC system is taken into account by examining the aspects of interaction, collaboration and information flow between the FSC actors. The opportunities, challenges and critical factors of the DPSL service are investigated in relation to the different components of the system.

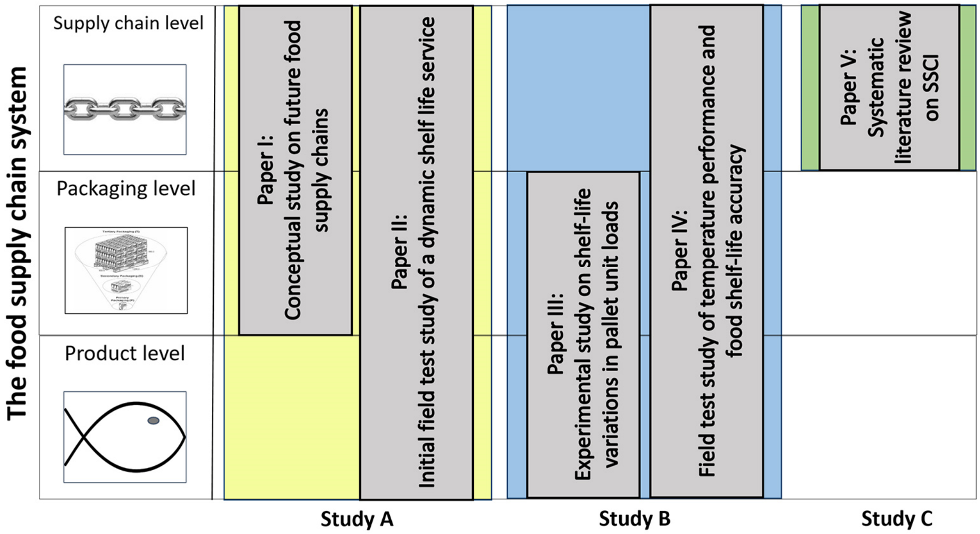

Figure 5.
The research scope and unit of analysis. The FSC system is the overall unit of analysis of this dissertation. The FSC system is divided into three system levels: product, packaging, and supply chain level based on the three theoretical knowledge areas. This figure illustrates the unit of analysis of the three research studies A (yellow), B (blue) and C (green) and the five appended papers.

Study A's unit of analysis is the entire FSC system. The study explores the operational, business model, and strategical opportunities and challenges of the DPSL service concept. Paper I examines these opportunities and challenges on the packaging and supply chain levels. Paper II considers them on all three levels when exploring the initial field test of the DPSL service.

Study B's unit of analysis is also the entire FSC system. The study evaluates the operational requirements necessary for realizing a DPSL service. Paper III's unit of analysis includes the product and packaging levels. The possible shelf-life variations in pallet unit loads are evaluated. This paper also evaluates where in the packaging system (primary, secondary or tertiary level) the sensors can be most adequately and conveniently placed. Paper IV's unit of analysis is the whole FSC system. Data from field tests, including temperature performance and food shelf-life accuracy, are evaluated.

In Study C and Paper V, the unit of analysis is the supply chain level. Critical factors for realizing SSCIs are explored and a process model is proposed to provide understanding and guidance for SSCI ventures.

3.3. Research process and methods

My education and research were initially in food microbiology and engineering. After taking an interest in food packaging and logistics, my vision became one of contributing to sustainable development and reducing food waste by introducing more intelligence into the food packaging system. The research for my Master's thesis, "Food Packaging Innovation" was carried out at Packaging Logistics and Applied Microbiology. It was about using conductive biosensors to determine and communicate food quality. The thesis was presented as a two-part study that 1) explored the effects of implementing biosensors in the FSC, and 2) experimentally developed a method for the non-invasive determination of food quality and shelf life of minced meat using conductive sensors (Göransson 2011). The experimental study included laboratory experiments where the microbiological growth in minced meat, at different temperatures, was matched with the change in conductivity over time. Correlations were found between the bacterial growth and change in conductivity that enabled non-invasive food quality and shelf-life determination techniques.

The promising results from the Master's thesis research resulted in a continuation of the exploration of the research area of food packaging logistics and the development of food quality and shelf-life indicators, such as biosensors and continuous food quality control. A research group was formed, consisting of many who had been involved in my studies during my Master's thesis research. Together we designed the concept of Dynahmat and applied for research grants. During the initial discussions about Dynahmat, I further formulated my research topic and received guidance in continuing on my research path towards a Ph.D.

Figure 6 illustrates the process of my Ph.D. research studies in which a systematic combining approach was applied. Food waste challenges in the empirical realm were matched with the theoretical realm and new concepts were explored in Study A. In Study B, the challenges of availability and accuracy of food quality data were defined, matched with theory, and evaluated in relation to the concept of the DPSL service. In Study C, we found that there was a lack of frameworks and models to guide the process of realizing SSCIs. Critical factors for doing so were explored and a process model for the realization of SSCIs was proposed. The results and findings from the three research studies were analyzed and are presented in the appended papers. The results and findings from the three research studies were also analyzed to provide overall key findings in the dissertation and answer the three RQs. In the coming sections, the research process and methods used in the three research studies (including parallel innovation projects and sub-studies) are explained in detail.

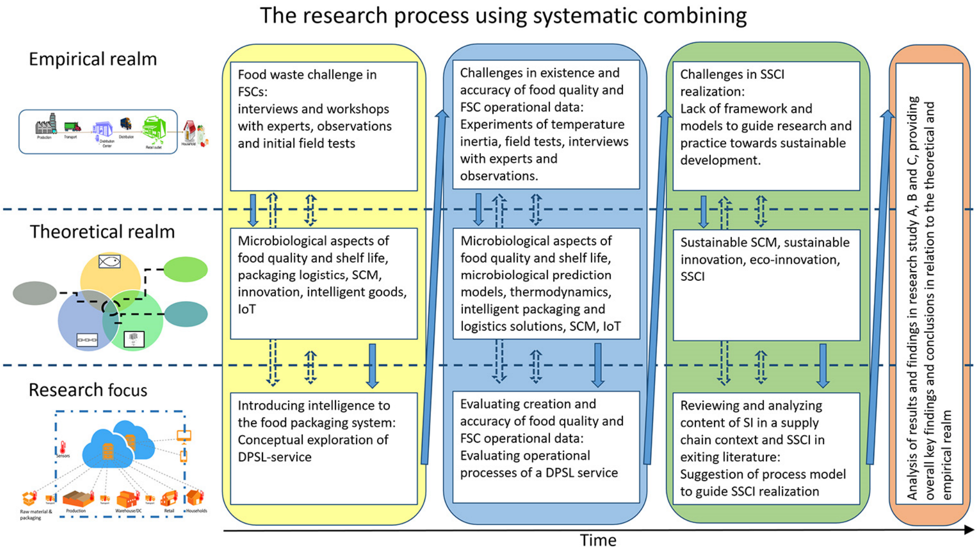

Figure 6.
Illustrates the dissertation research process of using systematic combining. Food waste challenges found in the empirical realm were matched with the theoretical realm and new concepts were explored in the research of Study A. In Study B, challenges of the availability and accuracy of food quality data were found, matched with theory and evaluated in relation to the concept of the DPSL service. Study C found that frameworks and models to guide the realization process of SSCIs were lacking. Critical factors for realizing SSCIs were explored and a process model for realizing SSCIs was proposed. The results and findings from the three research studies and their respective appended papers were analyzed to present the key findings of this dissertation and to answer the three RQs (SI stands for sustainable innovation).

3.3.1. Study A – exploring the research area of SFSCI and the concept of a DPSL service

Study A was designed to explore the concept of a DPSL service using several different approaches, stances and methods. Hence, this explorative study included project results and sub-studies that together contributed to the understanding of different approaches, technologies and concepts and to establishing an empirical arena for subsequent studies. The two projects that were run in parallel were mainly based on innovation creation, and only parts of the projects' findings could be used in Study A. On the other hand, the innovative project environment provided a platform to explore and find evidence to support the research in practice. The project environment enabled me to expand my knowledge in areas outside of the research scope of the dissertation. I was also able to reflect upon my research in a broader context, which both directly and indirectly affected the evolution of the research. Some of these reflections are not further developed in this dissertation but are listed as future research. One example is the development of a business model for supply chains, especially SSCIs.

Study A was initiated before I started my Ph.D. studies and included: 1) a microbiological experimental study; 2) two innovation projects: Fresh Pac and Dynahmat (read more in ***section 2.4*** and ***3.1.1***) the main explorative study consisting of a narrative literature review, interviews, workshops and an initial field test. Even though Study A was of an explorative nature, the sub-studies have different research approaches and methods.

Experimental study - microbiology

The experimental study on microbiology included in my Master's thesis was presented as a paper at the MATBIM Conference in 2012 where I also received more guidance from academic colleagues for my upcoming Ph.D. studies. As a result, we continued the explorative and experimental study on conductive biosensors in the form of another Master's thesis project carried out by two electrical engineering research students. The thesis was entitled, "Biosensor for Quality Control" (Brosjö & Norrgren 2012) and was a collaboration between Packaging Logistics, Applied Microbiology and Biomedical Engineering. The two students designed small sensors that were tested in the experimental setup that I had designed and presented in my thesis. The results of the experiment were inconclusive for the most part, with the exception of when the food package (and sensor) was excluded from any mechanical movement, which is not realistic outside of the laboratory. However, the conclusion was that it might be possible to non-invasively detect microbiological growth in food if a more robust sensor or a different determination technique was used.

Fresh Pac

In parallel with the "Biosensor for Quality Control" Master's thesis project, the findings and ideas from my Master's thesis resulted in a collaboration with LUIS (Lund University Innovation System) and the Sten K. Johnson Center for Entrepreneurship. The innovation project, Fresh Pac, was launched with two Master level students in entrepreneurship (funded by LUIS). Fresh Pac was a fictional startup company that provided biosensors that detected the actual quality of the food in the food supply chain. The Fresh Pac idea was entered into the innovation competition, Venture Cup Syd, where it placed second. During this time, I took an entrepreneurship course for Ph.D. students in which I created a business model based on Fresh Pac as the examination assignment. The course introduced new approaches and methods to use in research that promoted innovation and entrepreneurship. The business model was initially included in my research studies as an attempt to be more creative and innovative in my educational program. However, as business model research is slightly outside of my research scope, the study was not included in the dissertation, but did give valuable insights into Study A.

Dynahmat

The initial findings of the innovation Dynahmat project provided Study A with valuable insights as the project ran in parallel with Study A. The five-year (2012-2017) project was funded by VINNOVA (Sweden's Innovation Agency), Formas (Swedish Research Council), Svensk Dagligvaruhandel (Swedish Grocers' Branch Organization), Livsmedelsföretagen (Swedish Food Federation), and Stiftelsen Lantbruksforskning (Swedish Farmers' Foundation for Agricultural Research), under the umbrella program "TVÄRLIVS - A Sustainable Innovative Food Supply Chain that Meets Future Needs". Dynahmat involved 20 actors covering the FSCs of three food products (fresh cod, sliced smoked ham, and cottage cheese) from packaging and production, via transportation, wholesale, distribution, retail outlets, information technology providers, to the end customer. The project also involved five research groups (the steering committee): three from Lund University (Applied Microbiology, Biomedical Measurements, and Packaging Logistics), Computer Science from Malmö University, and RISE. Dynahmat was organized into six work packages (WP) to explore and evaluate different aspects of the innovation.

WP1 Exploration-driven Logistics and Packaging Innovation constitutes the core of the project. Here, the practical innovation process of field testing and verification of the designed and developed solutions and systems was carried out. In total, eight field studies (including several field tests) were carried out to learn about, gain insights, and develop the concept based on real-life experiences from testing the different aspects of Dynahmat in practice.

WP2 Evaluation of Sensor Technology concentrated on the development and evaluation of sensor tags for the wireless communication of food package temperature and food quality parameters. Calibration of the sensor tags was performed in a climate chamber before the sensors were used in WP1.

WP3 Modeling and Prediction of Shelf Life investigated the relationship between food quality and sensor response. The microbiological quality of smoked ham packed in a modified atmosphere, fresh cod fillets packed in a modified atmosphere, and cottage cheese were matched with existing prediction models (from scientific publications) for use in the prediction of dynamic shelf life (DPSL).

WP4 Evaluation of System Solutions from an ICT Perspective concentrated on developing a cloud solution for receiving sensor data and calculating DPSL. The cloud solution, "the Dynahmat system", consists of a web server with PHP support and a relational database. The three prediction models (smoked ham, fresh cod, and cottage cheese) from WP3 were parameterized to enable easy usage, without prior knowledge of the algorithm setup or prediction models. WP4 also developed a prototype for a consumer app, "Smart Food", which displays DPSL information to consumers. The app was developed as an isolated application for mobile devices with a local, internal database containing mock-up data.

WP5 Implementation Challenges in the Food Supply Chain concentrated on developing business models and evaluating opportunities and challenges associated with the realization of the Dynahmat concept. This was mainly executed through workshops and case studies.

WP6 Consumer Confidence, Honesty, and Legislation concentrated on the legislation and public view of food waste and shelf-life labeling. Surveys were performed with the Consumers Association of Stockholm and Bioscience to investigate the attitude of Swedes to food waste and printed labeling systems.

Explorative study

This study explored the role and use of food quality sensors in FSCs. It started as the initial findings from the two innovation projects and the experimental study on microbiology were coming in. Because the results of the experimental study on conductive biosensors were inconclusive, a search for other types of direct and indirect determination techniques for measuring food quality and shelf life was initiated. The two innovation projects stressed the importance of incentive alignment among FSC actors and raised questions about the concept and functionality of the DPSL service in practice. Hence, we held interviews and workshops with project partners (FSC actors) and performed field tests to explore the concept and functionalities of a DPSL service, and to find incentives for innovation implementation among the FSC actors and the challenges involved.

An important task of the research process was to review the existing literature in the field of study. A literature review allows researchers to critically assess the literature and justify their research because the review provides the existing fundamental knowledge in the field (Bryman & Bell 2011). *A narrative literature review* was carried out to generate an overall understanding of intelligent food packaging solutions, food waste challenges, and the challenges perishables place on their supply chains. The scope and keywords were initially wide and unstructured, which is useful in a qualitative and comprehensive study (Bryman & Bell 2011).

The narrative literature review was followed by interviews with experts from each discipline of the FSC (see Papers I and II) in the Dynahmat project (DYNAHMAT 2017). The interviews were unstructured and focused on food waste challenges in FSC, printed date label system challenges, and challenges and possibilities for the implementation of intelligent food packaging systems in FSCs. Complementary semi-structured interviews were conducted later on with refined follow-up questions from the previous unstructured interviews; one or several employees were interviewed at 11 companies in the Dynahmat project. These interview target groups were selected to cover viewpoints from the entire SC including different company positions, such as management, production, logistics, sales and R&D. The interviews aimed to determine their willingness for innovation, and to investigate their incentives and views on the possibilities, risks and requirements of a DSLP system.

In addition to the interviews, three one-day workshops were carried out with representatives from all 20 companies in Dynahmat. The workshops were designed as focus group interviews, seminars, and concluding discussion sessions to gain insights and knowledge about the barriers and challenges actors face with the current date labeling system, and to find new opportunities to change the current situation. The goal of the workshops was to get the members to collaborate as a FSC unit and not as separate actors. This was done in order to gain a holistic view of the overall challenges and to create a shared perspective of the DPSL service concept. The findings were divided into three themes: strategic, business model, and process. These identified the most important opportunities and challenges for the implementation of sensors and biosensors in food supply chains.

Initial field test

The first field test was carried out in parallel with the semi-structured interviews. A primary prototype of the DPSL service system, including time and temperature sensors and an information system platform, was tested in one of the FSC (fresh cod) included in Dynahmat. The pilot field test was performed to explore and test the experimental setup and method, and to analyze the initial data in reference to the upcoming field tests included in Dynahmat. The initial field test was performed by two researchers and included observations of daily routines; interviews with the personnel handling the food and the setup's packaging system; placing, starting and returning sensors; and collecting and categorizing data. The field test was performed to obtain the temperatures, with corresponding time stamps (location was also noted manually), of food products traveling along the cold chain from production to consumption. The cold chain monitored included three actors: a producer, a transporter, and a retailer. One end consumer was also involved. The initial field test was performed in a shorter FSC so that the researchers could easily follow the food products. Temperature sensor tags were placed close to packed food products for consumers in order to obtain measured data as close to the actual product temperature as possible. The sensor tags logged time and temperature from the time of packaging at the production site, to the time of consumption in the household. Handling activities and other environmental conditions were observed by two researchers throughout the entire cold chain. These observations enabled us to map the activities to different temperature changes.

The empirical data collected in Study A resulted in the explorative conference Papers I and II and gave valuable input to Dynahmat and the development of the DPSL service. Study A also gave the main input to RQ1 and RQ2 to some extent.

3.3.2. Study B – Evaluating critical aspects of the DPSL service

The explorative study was followed by an evaluative phase (Study B), addressing emergent and central questions and problem formulations derived from Study A and developments in Dynahmat. Study B included extended field tests and experimental research to assess central limitations and operational requirements for realizing the DPSL service in FSCs.

Field tests – round one

The continuation of the development of the DPSL technology initiated new field tests to test and evaluate the technological capabilities. These field tests were performed in FSCs including mainly fresh cod and sliced smoked ham, but also cottage cheese. The field test was extended to include distribution in southern Sweden and included food producers, transporter, wholesaler, distributors and retailers (including retail displays). In the initial field test (included in Study A), the time and temperature from sensors (RFID and Bluetooth) were downloaded manually after the field test. In these extended field tests, the sensors communicated time, temperature and location data to the cloud continuously during the field test (close to real time). In the cloud, microbiological growth prediction algorithms specific for each food product were generated and continuously updated the DPSL based on the time and temperature data received.

Experimental study – thermal inertia

The field test data showed that the temperatures were mostly below the maximum recommended temperature for the food product examined, but broken chill chains with temperatures well above the maximum recommended temperature limit were also registered. This raised the question of how much the temperature in relation to time affects the quality of the food and hence its shelf life. Moreover, questions concerning the accuracy of the sensor measurements and the distance between the food product and the sensor were raised among Dynahmat's FSC actors. Consequently within Dynahmat, problem formulations of potential temperature variations within a pallet (tertiary package), and the effect the variations had on the pallet's food packages were also discussed. These questions initiated the experimental research study, which examined the magnitude of any variations that might exist between different products on a pallet in terms of the remaining shelf life, and how close temperature sensors must be placed to the products to get reliable shelf-life calculations. The experimental study collected temperature data, and identified the corresponding thermal time constants, from 83 different sensor locations in a pallet fully loaded with primary packages of sliced smoked ham. The thermal time constants were then used in microbiological prediction models to investigate possible food quality variations within a pallet unit load. The findings of this experimental study are presented in Paper III.

Field tests – round two

The field tests were continuously performed and refined as findings from the experimental study were established. The data from all field tests were collected to evaluate temperature performance of cold FSCs in relation to the product shelf life of perishable products. Product shelf life was divided into two categories for further performance evaluation: printed shelf life and dynamically predicted shelf life (DPSL). Different scenarios were created based on this in-depth study of the actual temperature data of food products. The scenarios represent the most and least efficient complete FSCs and illustrate food quality and shelf life differences within the same food segment. The findings from the extended field test study is presented in the conference paper, "Food Supply Chain Improvement – Evaluation of Shelf-life Accuracy" (Göransson et al. 2017) and revised and developed into Paper IV.

Study B mainly provided input to RQ2, and RQ1 to some extent, along with valuable guidance to Dynahmat and its FSC actors.

3.3.3. Study C – Exploring the critical factors in the realization process of SSCIs

In Study C, the concept of the DPSL service, that was explored and evaluated in Studies A and B, was explored this time in the larger context of supply chain innovations, namely: eco-innovations and SSCIs.

Literature review – eco-innovations

The implementation of DPSL is complex and challenging in practice and there is a lack of scientific literature on the implementation process of innovations in FSCs. Hence, I needed to find new inspiration. A second narrative literature review was performed to map the research area, gain inspiration and find common critical factors among other supply chain innovation processes described in the academic literature. The narrative literature review focused on eco-innovations (green, environmental, sustainable and ecological innovations). At this point (2015), there was a modest amount of literature on the subject but I anticipated this to be an upcoming area in supply chain and innovation literature. The narrative literature review was followed by a smaller systematic literature review on enablers and hinders in the creation of eco-innovations, not only in SCs, but also at any of the three levels in the FSC system (product, packaging, SC). A systematic literature review is a replicable, scientific and transparent process (Bryman and Bell 2011). Bias in such a study can be minimized and the study easily reproduced by performing an exhaustive review that follows a manual, and in which each step of the process is recorded. The enablers and hinders for implementation of eco-innovation were collected and analyzed, and later placed in a supply chain context. This systematic literature review was presented as a conference paper, "Enablers and Hinders for Eco-innovations in Supply Chains – Evidence from Literature" (Göransson & Nilsson 2015).

Literature review – SSCIs

Before and during the development of Study A and Dynahmat, we searched for frameworks and models that could guide us and provide the most critical factors for creating innovations in the supply chain context, with specific emphasis on the three pillars of sustainable development. While we found several insights and frameworks from a company perspective on innovation and sustainable innovation, we were unable to find anything significant on SSCIs. However, as I anticipated, innovation in the supply chain context became a fast-growing field in the years following 2015. An additional and more extensive systematic literature review was performed, including 160 papers and a wider scope that covered sustainable innovations in the SC context and SSCI. This literature review explored how to make real and significant changes in a supply chain context and the critical factors that are central and important for the creation of SSCIs. The study provides key insights on how sustainable innovations involving parts or whole supply chains can be realized effectively. A transformation model for effective SSCI realization is proposed to guide researchers and practitioners in increasing the transitions needed for sustainable development. Paper V presents the systematic literature review on critical factors for the realization of SSCIs.

Study C provides input to RQ3 and valuable guidance for innovation creation projects such as Dynahmat, and for researchers and practitioners in the field.

3.4 Analytical framework

The analyses of the results and findings in the appended papers and research studies were performed within the analytical frame of the dissertation (see ***Figure*** *7*), which is found in the overlap of the main knowledge areas (***Figure 2***). The analytical frame consists of: intelligent packaging and logistics solutions, and IoT; food supply chain and packaging logistics; and sustainable food supply chains and innovation. The results from the appended papers and research studies were analyzed by using a systematic combining approach to match the theoretical and the empirical realms. This was achieved with help from the analytical framework. The results from each research study were analyzed and evaluated to answer the RQs, find theoretical and practical implications, find questions that were still unanswered in the theoretical realm, find challenges in the empirical realm to explore or evaluate, and find new research opportunities (e.g., the continuation of the ongoing research studies and suggestions for further research). At the end of the research process, the results and findings from the three research studies and appended papers were analyzed to determine the key findings (presented in ***section 4.6***) and to answer the three RQs (presented in the concluding ***chapter 6***).

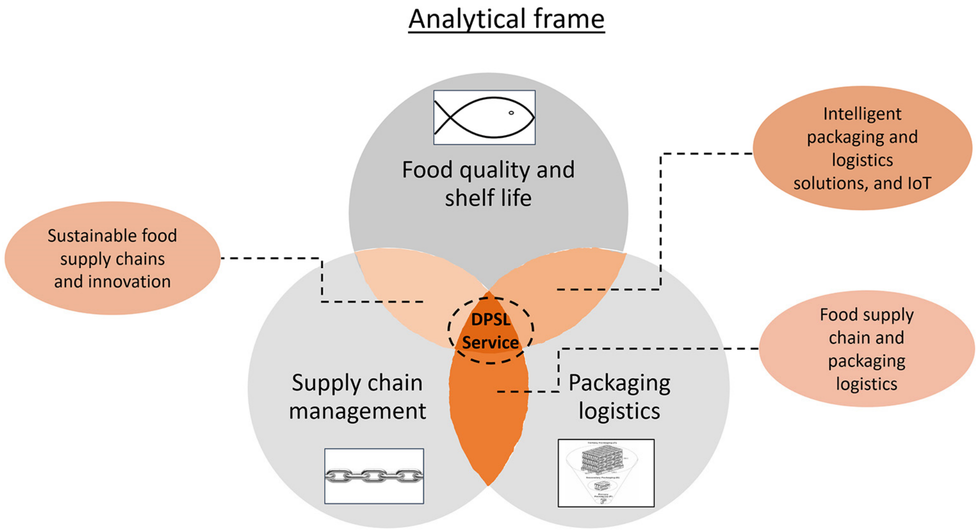

Figure 7.
The analytical framework of this dissertation is found in the overlap of the main knowledge areas. It consists of intelligent packaging and logistics solutions, and IoT; food supply chain and packaging logistics; and sustainable food supply chains and innovation.

3.5. Research quality

An important part of the Ph.D. education is to continuously reflect on the methodological choices made and to understand how these choices affect the research process and outcome. There are several models available to guide researchers in their reflections on the quality of their research. These models usually focus on quality assessment of the natural science or social science paradigm, or assessment of qualitative or quantitative research. The interdisciplinary nature of this research covers both the natural and social science paradigms. For example, the studies have included microbiological growth, thermal inertia and temperature variations (i.e., studies that are based on clear definitions of terminology, quantifiability, highly controlled conditions, reproducibility, predictability and testability) (Mårtensson et al. 2016). At the same time, the controlled environments of natural science are placed in the complex and empirical context of FSCs (with a worldview regarded as being socially constructed) where quality parameters of usefulness, relevance and meaning are central (Nilsson & Gammelgaard 2012). Hence, the parameters of the two different paradigms place different requirements on the researcher. In conducting this research, I had an overall systems perspective of the FSC while targeting specific aspects of the system on a more detailed level (e.g., research quality addressed in the different papers). Consequently, when assessing the overall quality of my research, I chose to use Lincoln and Guba's (1985) model, focusing on trustworthiness. Trustworthiness is evaluated through credibility, transferability, dependability and confirmability.

Credibility refers to credible and truthful findings and interpretations (Lincoln & Guba 1985). When studying the phenomenon of food waste, which everyone recognizes and can relate to, it is difficult to exclude personal preconceptions. I have used and triangulated multiple methods and sources of evidence to diminish personal bias. The Dynahmat project made it possible to discuss and collaborate with fellow researchers from other disciplines, and different FSC actors and stakeholders. In this way, I could see the different perspectives when discussing a problem, phenomenon, result or finding. Different data collection methods, such as interviews, workshops, observations and measurements in the field, were used to enable triangulation of results to corroborate the findings. Time and temperature measurements in the field were conducted over several years and during different seasons to provide reliable and trustworthy data. The results and findings were discussed with co-authors and supervisors to further confirm my interpretations and credibility and to provide structured and intelligible key findings.

Transferability refers to the generalizability of the findings to other contexts (Lincoln & Guba 1985). The field tests were performed in FSCs of three different food products (only two are discussed in this dissertation, namely sliced smoked ham and fresh cod, while field tests of cottage cheese were excluded due to insufficient data). Hence, the functionalities of the DPSL service setup were designed to easily replace the product specific microbiological prediction model (including parameters specific to both the product and the primary packaging). The DPSL service can therefore be applied to other chilled, packed food products to provide product specific shelf-life and temperature data. The service can also be applied to other temperature sensitive products, such as frozen food, horticultural products and pharmaceuticals. The overall key findings do not have to be limited to chilled foods, but are limited to packed products, preferably (but not necessarily) within a system using returnable packaging.

Dependability refers to the reliability and stability of data and the reproducibility of findings (Lincoln & Guba 1985). In the natural science paradigm and qualitative research, dependability is a key requirement; but, in qualitative research, dependability has to be established by the researcher. In my research, this mostly refers to interviews, workshops and observations where protocols were established and tested in advance. In my overall analysis, I coded the results and findings from the papers and studies in relation to the four areas of my analytical framework, providing a clear structure and stability.

Confirmability relates to objectivity and the ability to confirm data of informants who were in one way or another involved in the study (Lincoln & Guba 1985). In the social paradigm, reflexivity is essential to expressing my interpretation of the research results. I have tried to elucidate my interpretation by clarifying my beliefs and approach to research (pragmatism), my affinities to research communities and the discourse in the food microbiology and packaging logistics community, and by reflecting on demarcations and biases (Alvesson & Sköldberg 2009). My interpretations of the data from interviews, workshops and observations were discussed and affirmed by the managers and personnel of the FSC actors involved. We also discussed them in the interdisciplinary research group of Dynahmat, the members of which could challenge my interpretations from several perspectives and from their background knowledge and expertise. The research group included co-authors and supervisors who were part of an ongoing dialogue on data interpretation and reflections on results and findings. This occurred more often at the end of the research process when I was to describe the main theme and line of reasoning and analyze the overall findings.

4. Results

This chapter summarizes the results and findings of the five appended papers and presents the key findings of the dissertation. It also describe how the appended papers are interlinked, built on one another and how they together with the three studies (A, B and C) establish the foundational knowledge of the research. The chapter ends with an analysis and overview of the key findings of the dissertation.

4.1. The Role of Biosensors in Future Food Supply Chains – Summary of Paper I

Food waste is a complex problem and occurs in all parts of the food supply chain, from primary production to households. There are many reasons why food waste has become such a prevalent phenomenon and a part of everyday life. The following factors all lead to the loss of perfectly edible food: demanding business agreements, retail sales campaigns, product returns and rejections, broken chill chains, lack of information flow and transparency in the supply chain, and lack of food handling knowledge among consumers.

By introducing extrinsic sensors or biosensors into the food packaging system, the quality of food products can be determined in a real-time feed along the FSC. These sensors function as an adaptive shelf-life indicator that considers temperature change, microbiological growth, raw material quality, humidity, product information, and the quality of the food handling depending on the level of intelligence of the sensors. Adaptive shelf-life systems also include communication technologies and generic, interactive information platforms that provide FSC actors with the desired information. It is important to come up with strategic and business incentives for all the actors involved in order to successfully implement adaptive shelf-life systems in FSCs.

In Paper I, we explore the role of biosensors and adaptive shelf-life systems in future FSCs to reduce food waste. Opportunities and barriers for introducing an adaptive shelf-life system are conceptually evaluated on three levels: the strategic level, business model level, and process (operations) level. The findings are based on an investigation into earlier implementation ventures of sensors in FSC, literature studies of biosensors, consumer behavior and food handling in FSC, and an empirical study including interviews and workshops conducted in the Dynahmat project. The workshops were designed to gain shared perspectives and a holistic view of the concept of an adaptive shelf-life system. The workshops were followed by unstructured interviews with actors from each supply chain segment. The aim was to investigate the FSC actors' food waste challenges and possible incentives, such as biosensors, increased product quality control and information flow, to reinforce technology implementation.

The results indicate that an implementation of biosensors in food supply chains increases quality control of both the food products and operational procedures by monitoring microbial and extrinsic changes, such as temperature. Automatic documentation and warning systems increase the FSC actors' self-monitoring and enable an increased information exchange in the FSC. The participants of the study emphasized that specified and updated food quality information to consumers increases trust in shelf-life labeling systems, which can result in decreased food waste. The Swedish FSC actors demonstrated a willingness and strategic intention to invest in innovations that can lower the environmental and economic impacts of food waste and increase consumer trust. The main challenges of these types of innovation ventures are on the business model level, that is, on how to set up business agreements, develop incentive plans for different actors, and share the risks associated with new technology implementations. Consequently, for the implementation of new technology – in this case biosensors – the most prominent challenge is to develop appropriate business models that consider both the individual actor's needs and those of the food supply chain, society, and the environment. ***Table 3*** describes the most important opportunities and barriers when implementing an adaptive shelf-life solution in FSCs.

Table 3.
Identified opportunities and barriers in implementing biosensors in future FSCs based on the supply chain investigated in the Paper I study (Paper I, p.12.)

Business layers	Identified supply chain opportunities	Identified supply chain barriers
Strategic	Increase customer/consumer trust, lower product waste, increase brand value.	Investments and cost sharing, models for handling differentiations in food quality, returns and discards, information sharing and generic technology platforms.
Business model	Quality based food prices, "who to blame" traceability, less legal assistance and third party involvement, increased transparency.	Revenue sharing, implementation costs, cost per sensor, intellectual property rights, sharing of information regarded as company secrets, mostly revenue in soft values – difficulties to put prices on soft values.
Process	Product and process quality assurance, traceability, decreased workload.	More food waste initially, changed internal/external handling routines.

4.2. A Field Test Study on a Dynamic Shelf Life Service for Perishables – Summary of Paper II

The quality of perishable food products, such as fresh meat and fish, is highly time and temperature dependent. This places high demands on a well-functioning FSC. Insufficient supply chains can lead to food quality loss, product returns and food waste. Well-functioning supply chains (maintaining storage temperatures below the maximum recommended storage temperature) contribute to preserving food quality and increasing food shelf life. This, however, may also result in the waste of perfectly good food due to misalignments between the actual food shelf life and the printed shelf life. This calls for a service that states the actual food quality and shelf life (in real time) to reduce food waste.

Paper II continues exploring the concept of an adaptive shelf-life system described in Paper I. The focus moved from biosensors to extrinsic temperature sensors. The temperature sensors can provide real-time temperature data of the packed food products distributed in FSC. The temperature data is used in product-specific microbiological prediction models to dynamically predict the food shelf life.

Paper II provides insights and results from initial field tests of what is called a *dynamic shelf-life prediction* (DSLP) service in this paper (an early version of the DPSL service described in the dissertation). Semi-structured interviews were carried out with food supply chain actors to identify possibilities, risks and requirements of a DSLP service.

The fundamentals of a DSLP service includes the collection of accurate data and information sharing among the FSC actors. The field test and DSLP revealed that the shelf life of perishables, in this case fresh cod, are sensitive to small temperature differences along the cold chain. A constant difference of only 0.5°C decreases shelf life by a whole day. The field tests showed that temperature variations, significant enough to affect the shelf life, take place even within small areas, such as a pallet or retail package. The main practical requirements of a DSLP service are that the sensors should obtain precise and tamper-safe temperature data and be placed close to the food products. Results from the interviews confirm the importance of accuracy. The interview findings stressed the importance of increasing the quantity and quality of the information flow between FSC actors, especially product temperature data. The quality level of the information shared is highly dependent on integration and collaboration in the FSC. The FSC actors were positive to sharing continuous temperature data with each other but did not want the information to reach competitors. The DSLP service has the potential to provide specifically designed information combinations for each FSC manager, especially if the DSLP system is integrated into the actors' enterprise resource planning systems. An implementation of a DSLP service enables pro-activeness and new business opportunities and increased transparency within the FSC. The interviewees emphasized the importance of sharing revenue and costs among the actors for a successful implementation.

4.3. Shelf-life Variations in Pallet Unit Loads During Perishable Food Supply Chain Distribution – Summary of Paper III

In Paper II, we identified that the accuracy of both the data and technology are crucial factors for delivering reliable temperature and DPSL data. The study also identified significant variation of the temperature data within small areas, such as in a secondary package. Hence, the placement of a food product in a packaging system can affect the food quality and shelf life.

Paper III addresses the magnitude of the variations that may occur between different products on a pallet in relation to the remaining shelf life. Paper III also addresses how close to the products the temperature sensors must be placed in order to get reliable shelf-life calculations.

Hence, the questions posed in Paper III are:

How do different product locations on a pallet affect the corresponding product shelf lives?

How close to the products must the temperature be measured in order to get reliable shelf-life calculations?

Paper III presents an experimental study that collected temperature data, and identified the corresponding thermal time constants from 83 different sensor locations in a pallet fully loaded with primary packages of sliced smoked ham. Thermal time constants were identified by studying the temperature changes when the pallet was exposed to instant temperature drops (16°C-2°C) and temperature elevations (2°C-16°C). The thermal time constants were then entered into microbiological prediction models to determine possible food quality variations within a pallet unit load. To calculate the maximum difference in shelf life between the packages in a pallet unit load, two spots with the most extreme thermal time constants in the pallet unit load where compared when the temperature was elevated from 4°C to a higher temperature (ranging from 4.5°C to 12°C), during different time periods (ranging from 0.5 h to 200 h).The packaging system included primary packages placed in returnable crates, which in turn were loaded onto a returnable pallet (see ***Figure 8***).

In order to generate an accurate temperature value for each sensor location, the influence of the sensor tag dynamics was investigated and taken into account.

Primary packaging dynamics were also investigated and taken into account when performing product shelf-life predictions. The analyses included effects in both real/measured temperature scenarios and simulated temperature scenarios. For the former, we applied the thermal time constants to data obtained from a sensor that measured the surrounding temperature in a real cold food supply chain, and computed the maximum differences in product shelf life. For the simulated temperature scenarios, we used the GNU Octave software to compute the maximum differences in product shelf life when the surrounding temperature elevated and dropped during different time intervals.

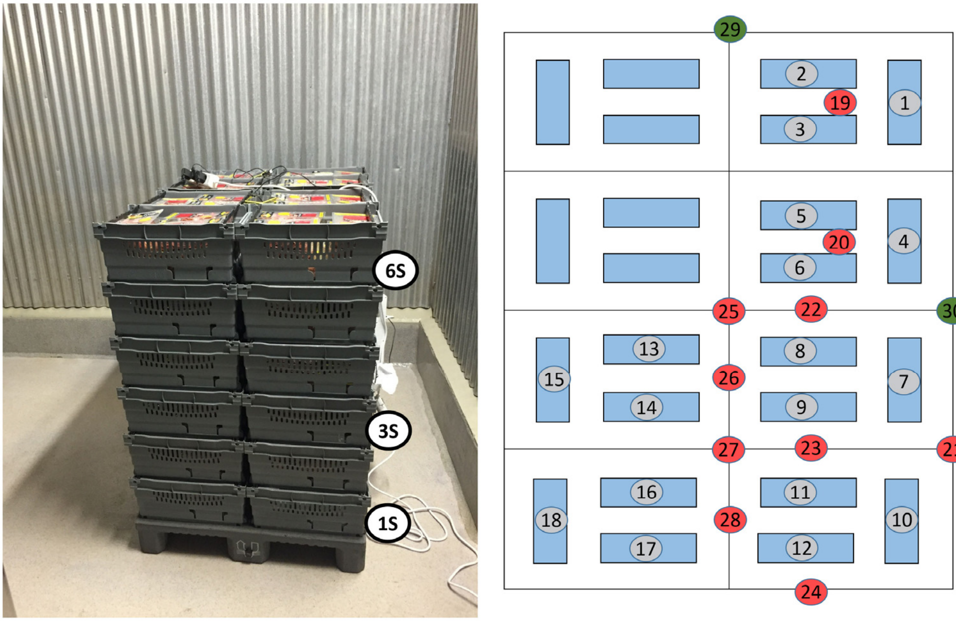

Figure 8.
The left-hand side shows the pallet unit load used in the Paper III experiment. It also show the Secondary (S) packaging layer that sensors are located on (1S, 3S, 6S). The right-hand side shows the locations of the sensors on the first, third and sixth crate layers. Sensors placed on primary package (gray), denoted P, on crate (red) and on pallet (green).

The results show that the thermal time constants are higher in temperature elevation situations than in temperature drop situations. This can be explained by the presence of a refrigeration fan when temperature drops, which causes the products to cool down faster than they warm up in ambient temperature. The sensors that registered the highest and lowest thermal time constants where 24S6 and 3P1S1, respectively. These sensors were placed on the outside of a returnable crate placed on the top layer of the pallet and between primary packages on the lowest layer of returnable crates (see ***Figure 8***) (explained in detail in appended Paper III).

The results from studying the consequences of the difference in thermal time constants (of sensors 24S6 and 3P1S1) in the simulated temperature scenarios are shown in ***Figure 9***. The scenarios show that when the temperature elevation is low, the difference in shelf life between the two sensor locations is low. Similarly, when the time period for temperature elevation is low, the difference is shelf life is also low. However, when the time period increases, the difference in shelf life quickly increases as well (especially with higher temperature elevations). When the temperature elevation lasts for slightly more than 50 h, the difference in shelf life remains the same. This is because the temperature close to the sensors has had time to reach the same temperature as the surroundings. After that point in time, the bacteria level in each of the products grows at the same rate. The difference in shelf life between the products is therefore the same when the temperature elevation lasts for slightly more than 50 h. However, the absolute values of the shelf life of the two products naturally decrease.

As a result, the maximum difference in shelf life between the two most extreme spots in the pallet is approximately 1.8 days, when the temperature elevates from 4°C to 12°C. This means that a temperature elevation of 8°C (from 4°C to 12°C) for more than 50 consecutive hours, which is rarely seen in today's chilled FSCs, results in a difference in shelf life of 1.8 days between the two most extreme spots in a pallet. In relation to the product shelf life set by the producers, which is 25 days, this worst-case scenario has a relatively small effect on the shelf-life difference.

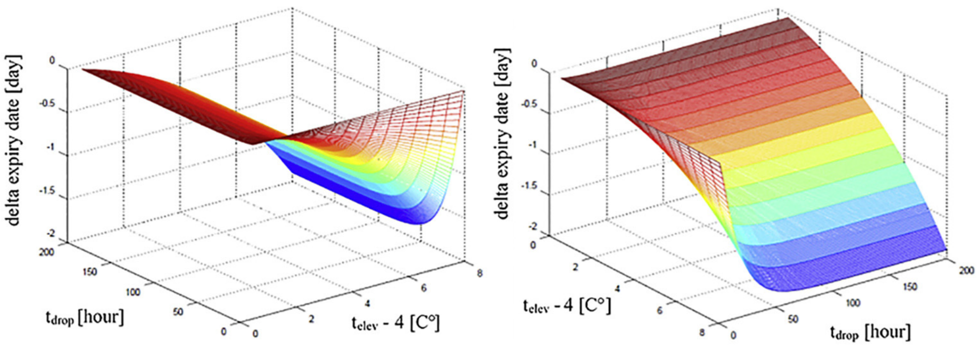

Figure 9.
Differences in shelf-life date between the two sensor locations with the largest difference in thermal time constants when the temperature elevates from 4°C for a limited time period (Fig. form Paper III).

The highest and lowest thermal time constants identified were also used to calculate the maximum difference in shelf life between packages at the two most extreme spots of a pallet unit load in a real chilled food supply chain lasting for about 2.5 days. This resulted in a maximum difference of 0.1 days. The results indicate that the location of a product in a pallet has a relatively low influence on the product shelf life. This means that a temperature sensor used for calculating the predicted shelf life of a product can be placed relatively far from the product itself (e.g., on the secondary package or even on the pallet) without jeopardizing the reliability of the resulting shelf-life prediction. It can also be concluded that the location of a product in a pallet has much less influence on the product shelf life than does a temperature difference of a few degrees during the entire chilled FSC. These findings indicate that continuous time and temperature monitoring on the pallet or crate level may be far more important and descriptive of reality than taking temperature and product samples of single primary packages during perishable food supply chain distribution.

In order to confirm the findings from of the "real/measured temperature scenarios" of this study, the thermal time constants identified need to be applied to several different types of real FSCs to evaluate the importance of continuous temperature monitoring.

4.4. Temperature Performance and Food Shelf-life Accuracy in Cold Food Supply Chains: Insights from Multiple Field Studies – Summary of Paper IV

In Papers I-III, several FSC challenges were identified. Unknown food quality and temperature fluctuations were recognized as two of the main challenges that generate food waste in FSCs and households. In Paper IV, we continued working on the previous research from Papers I-III by evaluating temperature performances in a number of cold FSCs. The FSCs' temperature performance was evaluated in relation to the dynamically predicted shelf life (DPSL) (as it is called in this paper and in the dissertation) and the printed shelf life of perishable food products. Hence, Paper IV investigated the significance of continuous temperature monitoring.

Complete FSC scenarios from food production to retail display storage were created based on an in-depth study of the actual temperature conditions of food products collected from 25 field tests. The Swedish FSCs of two food products were studied: 200 g of sliced smoked ham and 400 g of fresh cod. Both were in modified atmosphere packages. The field tests were divided into two parts of the FSCs: from food production to cold storage in retail (Test 1: Smoked ham, Test 2: Fresh cod), and in retail display storage (Test 3: Smoked ham, Test 4: Fresh cod). In the first part (Tests 1 and 2), time and temperature sensors were placed inside secondary packages (the plastic returnable crates that were used in Paper III) containing the food products. In order to get temperature data as close to the product temperatures as possible, all sensors were placed in direct contact with the primary packages. In the second part (Tests 3 and 4), sensors were placed at the innermost (close to the cooling unit) and outermost positions in retail displays to register possible temperature variations within a display. The temperature data from the field tests were entered into two microbiological prediction models, specific to the food products studied, to predict the actual food quality and shelf life (i.e., DPSL) at any given time in the FSC. The DPSL is presented as loss of shelf life and compared to the lost static shelf life, which is established under the assumption that the food products are constantly stored in their maximum recommended storage: 8°C for sliced smoked ham and 4°C for fresh cod).

The results from the field tests revealed high performance levels for both time and temperature of the FSCs studied from production to retail storage. However, one under-performing FSC from production to retail storage was found. In Test 2 (fresh cod), four sensors partly following the same FSC show temperatures well above the maximum recommended storage temperature (4°C) at the beginning of the supply chain. Notably, the sensors also register temperatures well below zero degrees later on. These temperature fluctuations derived from problems with the cooling unit that emerged during storage and transportation. Because of this incident, the products were placed in a freezer before they reached wholesale in order to reduce food quality loss and to pass temperature-sampling inspections. These food products would not have been accepted if the wholesaler had known their full temperature history throughout the shipment. Due to the short printed shelf life and distribution times, small deviations in time or temperature have substantial impacts on loss of shelf life. Hence, these food products have a slightly shorter DPSL than the static shelf life. In addition, storing perishables in temperatures below zero degrees for a longer period does not affect the shelf life and microbial growth negatively. However, the organoleptic quality of the food may very well be damaged. Data from Test 1 (of smoked sliced ham), showed temperatures mostly well below the maximum recommended storage temperature (8°C). Consequently, all field tests in Test 1 had positive results in the difference between lost DPSL and the static shelf life.

While temperature abuse can occur in the FSC, we have found that the main challenges of cold FSCs are found at the retail outlets when products are placed and stored in retail displays. Temperature fluctuations of several degrees were registered by the same senor but also between different sensors within the same display (3.2-14.2°C for ham and 0.2-7.4°C for cod). Hence, the time a product is located in the retail display and where the product is located in the display have a large impact on the loss of shelf life. Temperature fluctuations at the same sensor location can be explained by cooling unit thermostats turning on and off. Temperature differences between different sensor locations within the same display can be explained by the airflow pattern in the refrigerator and the placement of the sensor in relation to the cooling unit (distance). These results indicate poor design of the retail display studied. Although retail displays with doors were not included, their usage is recommended to decrease temperature fluctuations and temperature differences within a display.

By combining field test data from production to retail storage (Tests 1 and 2) and retail display (Tests 3 and 4), complete FSC scenarios of the most and least efficient FSCs were generated. The FSC scenarios illustrate food quality and shelf-life differences within the same food segment. The FSC scenarios for sliced smoked ham illustrated that that a retail outlet may promote food products with up to a 55% difference in lost shelf life, mainly depending on the retail display time (1-10 days) and retail display design. The fresh cod FSC scenarios illustrate a maximum difference of over 80% in lost shelf life. As for ham, the difference in lost shelf life mainly depends on retail display time (1-5 days) and retail display design. A comparison of two FSC scenarios for fresh cod, both 7.5 days long, shows a difference of 2.5 days between the lost DPSL and static shelf life. This difference is about one third of the entire product shelf life. As a result, the improvement potential in the overall quality of the Swedish FSC for fresh cod and similar highly perishable products needs to be addressed. These results indicate that the least efficient scenario for fresh cod does not measure up to the required FSC operations standard. Consequently, consumers may be exposed to unsafe food products that lead to food waste or foodborne illnesses.

These results emphasize the importance of continuous temperature monitoring to confirm food quality and find temperature abuse that is not visible in today’s praxis. While temperature abuse can occur in the FSC, we found that the main challenges of cold FSCs are in the retail outlets when products are placed and stored in retail displays. It can also be concluded that the retail display part of the cold FSC is missing from most previous FSC studies. In line with previous studies in this dissertation, the results indicate a number of opportunities presented by more accurate and reliable monitoring of temperature in FSCs. A temperature monitoring system can be used to enable dynamic shelf-life prediction, increase FSC transparency, and support food producers to proactively improve printed shelf lives.

4.5. Critical Factors for the Realization of Sustainable Supply Chain Innovations: A Literature Review – Summary of Paper V

Papers I-IV explored and evaluated the possibilities, requirements and challenges of a DPSL service including continuous temperature monitoring. Results indicates that a DPSL service improve the food quality control in FSCs. The concept can also increase FSC collaboration, integration, and transparency, and decrease the food waste in the FSC and by consumers, hence striving for sustainable FSCs. However, involving several stakeholders can be difficult because the establishment of socio-technical systems often implies comprehensive changes within existing supply chains. This is especially true for FSC due to their complex setup, with perishable goods, many partners and long supply chains. In order to realize sustainable development, new systems and business models are called for.

The four research studies presented in Papers I-IV are based on the Dynahmat research and innovation project, which aimed to create sustainable supply chain innovations in the food sector. Before and during the project, we searched for frameworks and models that emphasized the three pillars of sustainable development to guide the development, implementation and realization of sustainable food supply chain innovation (i.e., the DPSL service). While we found a number of insights and frameworks from a company perspective on innovation and sustainable innovation, little research explained how to make real and significant changes in a supply chain context, and the critical factors that are central for the creation of sustainable supply chain innovation (SSCI). This led us to the following research questions:

- What are the critical factors for SSCIs and which of these are essential and critical to the realization of SSCIs?
- How can the critical factors be used to drive SSCIs and contribute to the transitions needed for sustainable development?

The purpose of Paper V was to identify, categorize, and evaluate the importance of critical factors for the realization of SSCI and to contribute a process model for the development of SSCI. Hence, with a specific focus on supply chains, and based on a content analysis of academic literature, the aim was to provide key insights into how sustainable innovation in supply chain settings can be realized effectively. A process model was proposed and developed for SSCIs based on the critical factors identified to guide researchers and practitioners in increasing the transitions needed for sustainable development. The systematic literature review was based on formal and reproducible procedures to search, select, analyze, synthesize, and report the findings, following Denyer and Tranfield's (2009, pp. 671-672) template. Of 217 papers, 160 academic papers qualified for further analysis. All 160 were published after 2000; however, almost 80% of the papers were published 2013 or later, emphasizing the novelty of the research field: Sustainable Innovation (SI) in the Supply Chain (SC) context. A thematic analysis of the papers' organizational and sustainability focus showed that a noteworthy 39 articles discussed innovation on a supply chain level, while taking a comprehensive view of sustainability including environmental, social and economic aspects. These 39 papers on SSCI are the core literature of this study.

An in-depth analysis of the 160 papers resulted in 550 observations of critical factors. In most of the papers, we identified more than one factor that was critical to the realization of SSCI. Based on the coding process, these factors were grouped together in subcategories and then into 14 main categories (see ***Table 4***). When comparing the observations made in the SI/SC (SI in the SC context) and SSCI literature, we found some interesting distinctions (see ***Table 4***). The critical factor category *Collaboration* is highly favored in the SSCI literature. This may not come as a surprise as the SSCI literature involves entire supply chains and networks and hence, necessitates a higher degree of collaboration. This result also elucidates the importance of collaboration in the realization of SSCIs. Moreover, *Political context*, *Governance mechanisms* and *Power balance* also seem to be factors of greater importance in the SSCI literature. It is complex to realize innovations that include several actors, stakeholders, and sometimes entire industries. To realize SSCI requires, to a higher degree, aligned incentives and one champion or whole supply chain or industry to govern the resources, risks and rewards. In some cases, this means that political means are required to enforce sustainability measures on business and industry.

Table 4.
Fourteen main categories of critical factors observed in the reviewed literature and number of observations in the reviewed SI/SC and SSCI literature. Statistical differences between the numbers of observations per main category of a given critical factor in the SI/SC and SSCI literature reviewed are included.

Main categories	Observations in SI/SC (121 papers)	Difference	Observations in SSCI (39 papers)
Collaboration	84	54%	48
Strategic orientation	51	-4%	15
Culture (organizational/supply chain)	41	2%	14
Practices - internal/external	39	6%	15
Political context	29	27%	20
Market influence	32	-14%	5
Governance mechanism	19	15%	12
Technology development/innovation	20	7%	9
Training and education	19	-3%	5
Capabilities	15	3%	6
Power balance	9	16%	9
Cost and revenue sharing	12	0%	4
SC metrics	5	2%	3
Timing	4	4%	3

The need for considerable transitions in both industry and society as a whole is emphasized in most reports related to sustainable development. However, to transform industries to adopt sustainable development, a major motivation would be innovations that can change the setup of supply chains and their ways of sourcing, producing and delivering value to their customers; here lies a foremost potential. The critical SSCI factors reported in Paper V can assist researchers and practitioners in developing and implementing SSCIs. However, treating the critical factors as separate constructs will not sufficiently target the issues of SSCI due to the complexity inherent in sustainable development (Kumar et al. 2016). Instead, comprehensive and integrative models and frameworks (Kumar et al. 2016) that combine the critical factors are needed to guide researchers and practitioners in approaching and developing SSCI.

In Paper V, we presented an SSCI process model that we developed based on our findings from the in-depth analysis of critical factors for the realization of SSCI (see ***Figure 10***). The model is also based on Brown and Katz' (2011) innovation model but contextually changed from a company focus and level to a supply chain level. It is based as well on social, environmental, and economic dimensions in that it functions as a model for SSCI. With the notion that SSCI is a central mediator for sustainability transitions to take place, the model acts in the transformation process from linear, one-way supply chain setups to circular, sustainable supply chain setups. The SSCI model has its foundation in what is considered to be the most critical factor from our research, namely, collaboration. Collaboration is placed in the center for any SSCI to be realized and is included in all three spaces of the design cycle for innovation: inspiration, ideation, and implementation. Collaboration covers intra- and, to a high degree, interorganizational collaboration but also aspects of trust, information, and knowledge sharing.

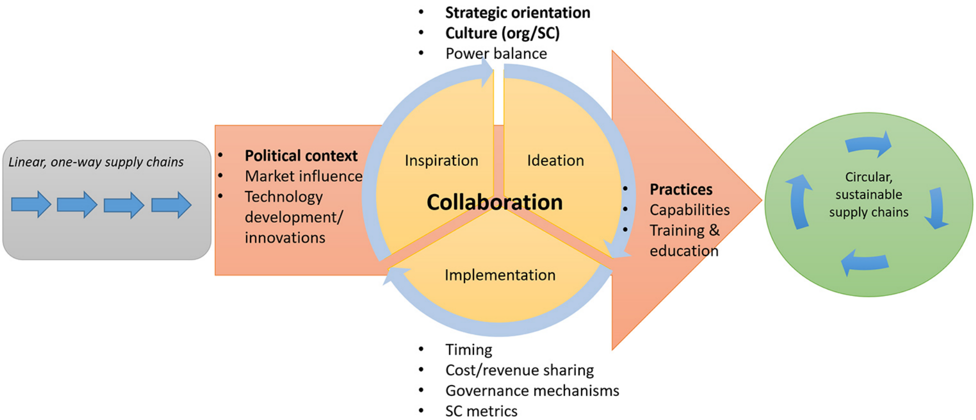

Figure 10.
A process model for sustainable supply chain innovations (SSCIs) in the transformation from linear, one-way supply chains to circular, sustainable supply chains. The process model for SSCI creation is presented in Paper V.

The model offers guidance on how to improve the SSCI process. In practice, the model can provide managers with the most critical factors and advice on how to manage them during an innovation process. In research, such a model can be used to determine if the necessary factors are available and strong enough to make a difference in the development of SSCIs. The model offers guidance on how to improve the SSCI process and facilitates the transformation from linear to circular sustainable supply chains.

4.6. Analysis and overview of key findings

The papers appended to this dissertation explore the concepts of a sustainable food supply chain innovation (SFSCI), namely the DPSL service (including continuous temperature monitoring), and evaluate the concepts' characteristics and functionality. The objectives have been to identify opportunities, challenges and requirements for the DPSL service and similar SSCIs primarily on an operational level, but also on business model and strategic levels.

The results presented in the papers and research studies have been analyzed and evaluated to find answers to the RQs, to find theoretical and practical implications, to find ongoing unanswered questions in the theoretical realm, to find challenges in the empirical realm to explore or evaluate, and to find new research opportunities (the continuation of ongoing research studies and suggestions for others). At the end of the research process, the results and findings from the three research studies and five related papers were analyzed to determine the key findings of the dissertation. The results and findings from the papers, studies and Dynahmat were coded in relation to the four areas of my analytical framework to provide a structured analysis of the findings. The analysis is illustrated in ***Figure 11*** and a descriptive summary of the dissertation's key findings is presented in ***Table 5***. The analysis and key findings are further discussed in ***chapter 5***.

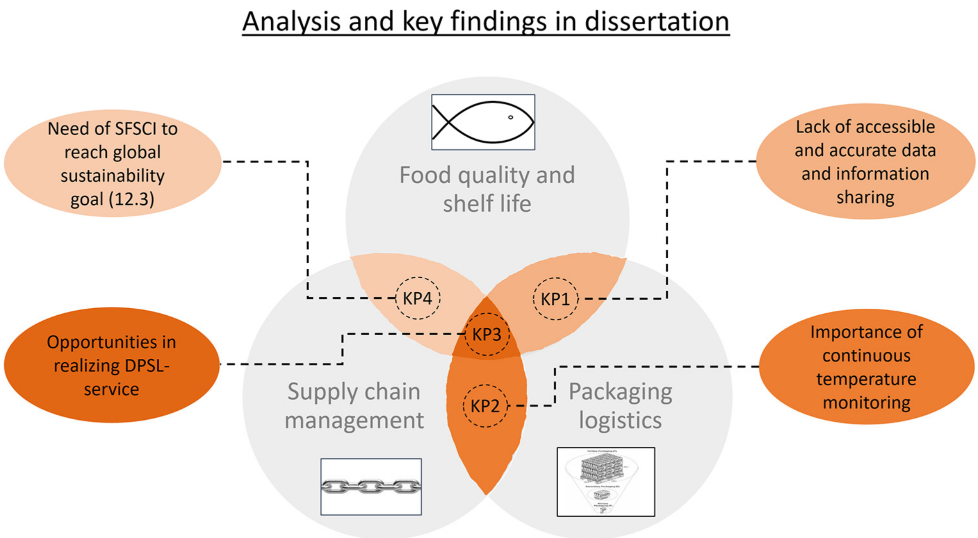

Figure 11.
Illustration of the analysis of findings from the three research studies and five appended papers. The analysis resulted in four key findings, which are related to the main research areas of the dissertation. A descriptive summary of the key findings are presented in Table 5.

Table 5.
A descriptive summary of the dissertation's the key findings.

Key findings (KF)	Discussed in
KF1: Lack of accessible and accurate data and information sharing cause FSC inefficiency and food waste.	
Lack of data and accurate data cause consumer misinterpretation and/or distrust in the printed date labeling system.	Paper I
A large amount of the food waste in FSCs is related to fluctuating and unknown storage temperatures and to the printed shelf-life system.	Paper I, Paper II, Paper III, Paper IV
There is a substantial lack of accurate data that can help inform the FSC actors and consumers about the quality of the distributed food.	Paper I, Paper II, Paper IV
There is a lack of accurate data that informs the FSC actors about the quality of their operational processes.	Paper I, Paper II, Paper III, Paper IV
KF2: Continuous temperature monitoring close to the food products is essential to providing accurate operational and food quality data.	
Substantial temperature differences exists within storage rooms, shipping containers and retail displays, promoting continuous temperature monitoring close to the product.	Paper III
Temperature is preferably continuously monitored on a secondary packaging level (and on returnable crates to decrease electronic waste and enable reusable sensor systems) to provide accurate data that are track, and traceable throughout the FSCs.	Paper III, Paper IV
Reduces risk of missing or covering up a broken chill chain. Results revealed temperature abuse (not visible in current praxis) during transport, but foremost in retail displays.	Paper IV
Enables one communal way to measure temperature with the same technology in the entire FSC.	Dynahmat
Reduce the manual labor of temperature control and documentation. Increase the FSC actors' self-monitoring and provide an automatic warning system. This has the potential to reduce the legal issue of who is to blame when time or temperature restrictions have been violated.	Paper I, Paper II, Paper IV
KF3: Opportunities for realizing a DPSL service	
Provides data on how specific foods are affected by real FSC temperature changes and translate this into an updated shelf life.	Paper II, Paper III, Paper IV
Specified and updated food quality information to consumers to increases their trust in shelf-life labeling systems.	Paper I
Increase operational and food quality assurance.	Paper IV
Increased information sharing of food quality data in the FSC has the potential to increase FSC collaboration, integration and transparency, and proactive self-monitoring.	Paper I, Paper II, Paper IV, Dynahmat
Support for food producers to improve accuracy of printed shelf lives.	Paper IV
KF4: Realization of SFSCIs is needed to reach the global sustainability goal, Target 12.3	
SSCI can be one of the central mediators in facilitating the huge transition needed to reach sustainable development.	Paper V

5. Discussion

Food waste is a comprehensive societal problem that has been given increased attention within academia, media and practice over the last decade. This has improved the overall public awareness but results of actual food waste reduction has not yet been seen. New innovative business solutions that aim to reduce food waste have also emerged. These have mainly been company focused, approaching the food waste problem from one singular perspective that focuses on profit maximization, cost reduction and short-term thinking. In line with Ras and Vermeulen (2009), the research included in this dissertation points out that a predominant company focus can create harmful imbalances throughout the rest of the supply chain, especially from sustainability and long-term perspectives. Although these innovative solutions assist in the challenge to decrease food waste, they generally do not confront and or make attempts to solve the underlying problems that cause food waste. The food waste dilemma is complex and is linked to environmental issues such as resource and energy usage, but also to food quality issues, consumer behaviors, packaging and logistics efficiencies, legislation and policies, business model setups, and the strategic orientations of companies and supply chains (addressed in Papers I-IV). In line with Gao et al. (2017) and Tebaldi et al. (2018), I call for more extensive solutions where companies, authorities, and organizations work together in a supply chain or network context to create SSCIs (addressed in Study C and Paper V). In line with Sanders et al. (2013), I also call for more research on the complexity of the FSC phenomenon with multidisciplinary and interdisciplinary research to create sustainable and circular FSCs in the future.

This chapter highlights the four key findings and other interesting findings from the research studies and appended papers. In light of the related interdisciplinary literature, these findings will be discussed and reflect up on to provide a more cohesive picture of the opportunities and challenges for creating sustainable food supply chain innovations (SFSCIs).

5.1. The food waste challenge

There are numerous underlying reasons why food waste has become a comprehensive societal problem, many of which has been discussed in Papers I-IV. Most of these food waste challenges have developed over time due to the food sector's inability to evolve at the same pace as the rest of society. The level of technology implementation and innovative solutions has lagged behind other industries, leaving the food industry stuck in the 20^{th} century (Bigliardi & Galati, 2013, Beckeman & Skjöldebrand, 2007, World Economic Forum, 2018). Packaging and refrigeration technologies played a big part in industrialization because they enabled the population to move away from agriculture communities and into cities. However, as the interactions between the agricultural community and consumers decreased, food handling knowledge and product quality information was successively lost. In today's society, consumers in general do not have enough knowledge about food and food handling (in line with Frank (2013)). Organoleptic evaluations of food quality are used less often, and many consumers lack confidence in their ability to determine the state of their food products. On the other hand, consumers may not always be able to use established organoleptic recognition techniques because new products and packaging solutions – such as modified atmosphere packaging aimed to prolong shelf life and on-the-go/ready-to-eat meals with mixed food products – have changed the characteristics of foods (Nilsson et al. 2019). Consequently, many consumers look for safety and reliability in the products they purchase that is communicated through the printed date labels and product information transcriptions. According to the EU research project FUSIONS (2016), over 50% of food waste generated in the EU occurs at a consumer level. In Paper I, I argue in line with Møller et al. (2016) that a large part of this waste is due to consumers' misinterpretation or distrust in the printed date labeling system. The uncertainty is somewhat justified as nothing on today's market can ensure the microbiological state of food. I also argue that in order for consumers to make informed decisions about the quality of their food products more, or more accurate, food quality data needs to be passed through the supply chain and reach the end consumer. The inability of FSC actors to share data that is sufficient and accurate has an accumulative effect on food waste throughout the course of the FSC (in line with Aung and Chang (2014a)).

Papers I-IV point out that food is wasted throughout the entire FSC and that a large amount of this waste is related to fluctuating and unknown storage temperatures, and to what is printed on shelf-life labels. Legislation and praxis in the food sector are built on printed shelf-life and temperature restrictions. As described in Papers III and IV, though, these static restrictions do not reflect the actual food quality, which causes unnecessary returns and disposal of food products that are still fit for consumption. The static restrictions of storage temperatures, which normally are sampled manually and based on momentary temperature, do not reveal the full FSC temperature history. According to Paper IV, this has proven to be an insufficient method of assuring food quality (and intact chill chain) since it has been shown that food products unfit for consumption are pushed through the FSC. Hence, one of the key findings of this dissertation research is that there is a substantial lack of accessible and accurate data that can be used to inform FSC actors and consumers about the quality of the distributed food (KF1). Moreover, in line with Barth et al.

(2017) and De Medeiros et al. (2014), the food sector needs more radical innovations that acknowledge transparency and communication within FSCs (including consumers) and push industry developments towards more sustainable and resource efficient production and consumption. To prompt sustainable development in the food sector, empirical studies are needed to explore the paradigm shift from linear FSC to circular sustainable FSC. To do this, methodological development focused on sustainable supply chains as comprehensive entities is also needed (as stated in Paper V).

As the overall aim of the dissertation is to contribute to reducing food waste, I want to verify that I do not prove that the DPSL service system, including continuous temperature monitoring, will reduce food waste in FSCs. Nor do I deliberate on how much food that could be saved by implementing a DPSL service. In order to make such statements, a large-scale pilot project or full-scale implementation of a DPSL service would have to be up and running for a longer period and the food waste would have to be carefully measured before and during the project/implementation. Collecting and analyzing data from a long-term, large-scale pilot in the future would be very worthwhile. Numerous reports and research projects have estimated and measured the current food waste (e.g., FAO 2011, FUSIONS 2016, WRAP 2007, FAO 2011, Ungerth et al. 2008). These reports often concentrate on one part of the FSC or estimate the waste within silos (in accordance with Xue et al. (2017)). These studies also measure waste in different ways and units (kilograms, liters, volume, etc.). One example is that some studies and practices (especially retailers) only register the food waste that is regarded as a financial loss, so that rejects and returns are excluded (in line with Eriksson et al. (2012)). Similar mindsets were revealed in the Dynahmat project as some companies only focused on the food waste within company walls, not acknowledging the increased amount of food waste that was accumulating in other parts of the FSC due to this behavior. Hence, measuring food waste can be a complex task. FUSION (2016) provides a food waste quantification manual to monitor the amounts of food waste and its progression at different stages of the supply chain. A DPSL service can be used as a tool that registers food waste and more importantly, the reason behind it. This would promote more proactive FSC management and would reduce the number of critical points in FSC operations.

5.2. Towards a dynamically predicted shelf-life service

The larger part of this dissertation concentrates on one particular SFSCI, the DPSL service. The service provides continuous temperature monitoring combined with dynamically predicted shelf life to provide FSC actors with updated data related to the quality of the logistical operations and of the food. The results of Papers III and IV state the importance of continuous temperature monitoring to increase the quality control of logistical operations in the FSC, and consequently increase the control of the food quality (KF2). The temperature monitoring in and of itself may give the FSC actors enough data to make informed decision about the operational quality. With the large amount of diverse food products on the market, though, it may be challenging to state the effects different temperature fluctuations have on each specific product in terms of microbial growth and food quality. A DPSL service can provide FSC actors with a tool to make informative and quick decisions about the state of food throughout the FSC. As stated earlier, Paper IV clearly shows how easy it is to miss or cover up a broken chill chain, and how the food quality can be affected by such events in a real FSC. The results from Papers III and IV also show the benefits of a DPSL service by showing how specific foods are affected by temperature changes over time. These two papers also provide evidence that substantial temperature differences exists within storage rooms, shipping containers, retail displays, and to some extent, in pallet unit loads. Hence, in line with Kuo and Chen (2010) and Hafliðason et al. (2012), this research stresses the great importance of continuous time and temperature monitoring on the pallet or crate level. However, it is not necessary to monitor single primary packages during perishable FSC distribution because the accuracy of such data does not increase significantly. Papers III and IV continue by stating that temperature is best monitored on a secondary packaging level, preferably on returnable boxes, to decrease electronic waste, enable reusable sensor systems, and provide traceability and trackability throughout the FSCs (since pallets can be reassembled at distribution centers) (KF3). This makes it possible to have one communal way to measure temperature with the same technology in the FSCs. This particular system characteristic turned out to be one of the major incentives for many of the actors included in Dynahmat. The communal, online, and continuous temperature monitoring has the potential to reduce the manual labor involved in temperature controls. It can also decrease the number of legal issues about who is to blame if time or temperature restrictions have been violated.

5.3. Possibilities and challenges in research and practice that strives for sustainability food supply chain innovation

Ensuring sustainable agriculture, production, supply, and consumption is essential to stop the negative environmental impact and degradation of ecosystems, as the contemporary global food production and consumption places alarming restraints on the earth's natural resources (FAO 2011). There have been vigorous efforts and actions against food loss and waste over the last five years since sustainable production and consumption were declared to be a global sustainability goal in 2015 (UN General Assembly 2015). Global authority programs have since coordinated global and regional initiatives to reduce food waste, such as SAVE FOOD: Global Initiative on Food Loss and Waste Reduction (FAO 2015), and Stop Food Waste (FUSION 2016). The scientific literature and reports published by authorities usually start out by stating the general operational dysfunctions that lead to food waste (many of which were compartmentalized in silos). Over time, the reports and scientific literature have also highlighted the importance of including a holistic FSC systems approach (IPCC 2019, FAO 2019), where FSC collaboration, integration, information sharing, openness and trust are essential to reaching the sustainability goal, Target 12.3 (UN General Assembly 2015). In order to realize sustainable development within FSC systems, a transition is needed from a linear to a circular sustainable FSC (in line with Govindan et al. (2016) and Govindan and Hasanagic (2018)). According to Paper V, this transitional process and paradigm shift require innovations (preferably radical ones) to be developed and adopted into supply chains (KF4). This, in turn, requires supply chain stakeholders, individually and together, to develop and innovate products, processes, services, business models, and organizations that maximize the reuse and recovery of resources while meeting the needs of customers and society. We call these innovations SSCIs in line with Gao et al. (2017) and Tebaldi et al. (2018).

Realizing SSCIs is a comprehensive and complex process because it involves several stakeholders and often demands changes to established sociotechnical systems. In Paper V, we identified, categorized, and evaluated critical factors in the realization process of SSCIs. Fourteen categories of critical factors were considered to be vital to control the realization process: Collaboration, Strategic orientation, Culture organizational/supply chain, Practices both internal/external, Political context, Market influence, Governance mechanism, Technology development/innovation, Training and education, Capabilities, Power balance, Cost and revenue sharing, SC metrics, and Timing). The motivation for initiating this study was to find a framework or model to guide the innovation process of Dynahmat, but also for guidance in research studies. In Paper V, we conclude that no such model has been found and thus, it became imperative to provide both the academic and the practitioner community with such a model. Hence, in Paper V, we suggest a process model for the realization of SSCIs where the identified critical factors are integrated. With the notion that SSCI is a central mediator for sustainability transitions to take place, the model acts in the transformation process from linear, one-way supply chain setups to circular, sustainable supply chain setups. In this model, collaboration is central for any SSCI to be realized, and is included in all three spaces of the design cycle for innovation: inspiration, ideation, and implementation. This is because collaboration covers intra- and, to a high degree, inter-organizational collaboration but also aspects of trust, information sharing, and knowledge sharing. This model can provide managers with the most critical factors for SSCIs, and advice on how to manage these factors in the innovation process. The proposed critical factors and process model can also guide future research by testing the process model as well as the critical factors identified in different supply chain contexts.

Realizing SSCIs in FSCs can add extra layers of complexity because product perishability and a comprehensive FSC setup are included. Hence, today's praxis, regulations and policies may need to be questioned and reevaluated in order to move the focus from cost reduction and profit maximization initially, to a focus on creating sustainable FSC practices. The three research studies (A, B, and C) and the Dynahmat innovation process show that cross-, inter-, and even transdisciplinary research and innovation teams are crucial to the creation of SFSCIs. Transdisciplinary research focuses on the organization of knowledge around a complex domain (Lawrence 2010), such as the food waste challenge or SFSCI realization, rather than specific disciplines. In line with Lawrence, 2010, I promote creating transdisciplinary research teams to approach complex challenges because they enable "*cross-fertilization of knowledge and experiences from diverse groups of people that can promote an enlarged vision of a subject, as well as new explanatory theories. Rather than being an end in itself, this kind of research is a way of achieving innovative goals, enriched understanding, and a synergy of new methods*" (Lawrence 2010, p. 126). Such developments are crucial to reach the global sustainability goals (more specifically Target 12.3 (UN General Assembly 2015)) and enable policies that operate across the food system. According to the International Panel on Climate Change (2019, p. 38), actions need to be soon based on "*existing knowledge, to address desertification, land degradation and food security while supporting longer-term responses that enable adaptation and mitigation to climate change. These include actions to build individual and institutional capacity, accelerate knowledge transfer, enhance technology transfer and deployment, enable financial mechanisms, implement early warning systems, undertake risk management and address gaps in implementation and upscaling*". Many of these actions have been addressed and discussed in this dissertation in relation to the DPSL service and food waste reduction.

After exploring the possibilities of a DPSL service in future FSCs, some challenges and questions remains unanswered. Even though I state the importance of initially focusing on sustainable practices in FSCs, the upfront investments and ongoing costs of realizing a DPSL service cannot be ignored. This research merely states the importance of sharing costs and revenue within the FSC or network. However, I have not further investigated how the setups of such business models are established. Moreover, the dynamically predicted shelf life in this research is based on a static initial bacterial load provided by the food microbiology research team and food producers of Dynahmat. Hence, the initial bacterial load at this point is based on reference samples and is not product (packed product) specific. This means that the DPSL service will not alert if a food product is contaminated before or at the production site. It would be very worthwhile to investigate the possibility of adding the polymerase chain reaction (PCR) technique to quickly detect and identify specific pathogens (Law et al. 2015). The PCR technique, though, cannot separate viable and dead microorganisms, which means that the amount of bacteria cannot be determined. However, PCR samples with increased levels of pathogens can be followed up with extra conventional plating samples. Introducing PCR technology to the packaging line is interesting for future studies, especially in relation to further development of the DPSL service.

6. Conclusions

The research underlying this dissertation set out to explore and evaluate the concept and requirements of a dynamically predicted shelf-life (DPSL) service for lowering food waste, and to provide understanding and guidance for actors involved in sustainable supply chain innovation (SSCI) ventures, especially in the context of FSCs. This concluding chapter provides answers to the three research questions (RQs), states the dissertations' contributions to academia and practice, and offers suggestions for future research.

6.1. Answers to research questions

A substantial underlying reason for food waste is the lack of accurate and accessible data that can confirm the quality of the food and the quality of the operational FSC processes. Fluctuating and unknown storage temperatures cause food waste due to product rejects and returns. The printed shelf-life system also causes large amounts of food waste because it fails to provide enough information and accurate information about the food quality. This leads to consumer misinterpretations of and/or distrust in the printed date labeling system. Hence, the development and implementation of DPSL services is a promising area that can increase quality-related data collection and distribution in FSCs, which in turn can contribute to lowering food waste.

6.1.1. What are the opportunities and challenges of a dynamically predicted shelf-life (DPSL) service? (RQ1)

The integration of a DPSL service in FSCs creates several opportunities for the food industry. This research stresses that continuous time and temperature monitoring is of great importance, as it provides traceability and trackability throughout the FSCs. This enables one communal way to measure temperature with the same technology in FSCs, which was an important incentive for FSC actors to implement the service. Continuous temperature monitoring reduces the manual labor of temperature controls and decreases the number of labor and legal issues that arise when time or temperature restrictions are violated. Sharing temperature data among FSC actors reduces the risk of missing or covering up a broken chill chain since temperature abuse during transport, but foremost in retail displays, was determined in the field tests. This shows the importance of continuous monitoring in detecting temperature abuse that is not visible in today's praxis. Increased information sharing of food quality data in the FSC also can increase FSC collaboration, transparency, and proactive self-monitoring. Continuous monitoring of the temperature close to the food product also enables accurate data determination. This is because substantial temperature differences have been proven to exist within storage rooms, shipping containers and retail displays. The temperature data can be translated into a dynamic shelf life by using product specific microbiological prediction models, and in this way can describe how specific food products are affected by temperature changes in real FSCs.

The integration of a DPSL service in FSCs faces several strategic challenges when striving for realization, challenges that are particularly related to the constellation of business models. Uncertainties about risks, true value, investments and costs for each actor in the FSC is of great concern. An implementation requires high initial investments for most of the actors in the supply chain, such as new software, integration into existing enterprise resource planning systems scanning/monitoring systems, hardware in terms of readers and sensors, and staff training. It is essential to find collaborative ways to address strategically important issues such as cost and revenue sharing, especially in FSCs that include many stakeholders.

6.1.2. What are the specified operational requirements for realizing a dynamically predicted shelf-life (DPSL) service system in a food supply chain (FSC)? (RQ2)

The operational requirements of the DPSL service system were identified by studying the magnitude of any variations that might exist between different products on a pallet in terms of remaining shelf life, and how close to the product's temperature the sensors must be placed in order to determine reliable temperature data and make reliable shelf-life calculations. The concluding remarks from these studies show that the location of a food product in a pallet has much less influence on the product shelf life than does a temperature difference of a few degrees during FSC distribution. This result implies that the continuousness of the time and temperature determination is more significant to the accuracy of the shelf-life predictions than product location in a pallet. Hence, temperature sensors used for calculating the predicted shelf life of a product can be placed relatively far from the product itself, for example, on the secondary package or even on the pallet, without jeopardizing the reliability of the resulting shelf-life prediction. (However, sensors should preferably be placed at a secondary packaging level as pallet unit loads most often are split and reassembled during distribution). In addition, studies were performed to illustrate the differences between printed and dynamic shelf life. The differences between dynamic shelf-life predictions and static printed shelf-life were significant in many field tests. This was mainly due to the FSCs high operational performances (temperature under recommended maximum storage temperature and distribution time deliveries shorter than praxis), except for FSCs, where broken chill chains in retail displays were registered. These studies also illustrate food quality and shelf-life differences within the same food segment, which is information that rarely reaches the FSC managers. Food producers can use such data to evaluate the accuracy of the printed shelf life.

6.1.3. What are the critical factors for sustainable supply chain innovation (SSCI)? (RQ3)

The DPSL service system is still within the SSCI realization process. Many challenges exist, foremost on business model and strategic levels but also on the operational/technology level. Frameworks and models to guide SSCI development and implementation were not found in the academic literature. Hence, it was concluded that the identification of critical factors and the creation of a process model to provide understanding and to guide the realization of SSCIs is imperative for further development of the DPSL service.

We found fourteen categories of critical factors that were crucial to embody and control: Collaboration, Strategic orientation, Culture – organizational/supply chain, Practices – internal/external, Political context, Market influence, Governance mechanism, Technology development/innovation, Training and education, Capabilities, Power balance, Cost and revenue sharing, SC metrics, and Timing. A process model, based on design thinking, in which the fourteen critical factors are integrated, is suggested for the realization of SSCIs. This model provides understanding and guidance of the transformation process from linear supply chains to circular sustainable supply chains.

6.2. Contributions to academia

The research in this dissertation contributes to academia by generating new knowledge in the intersection between the knowledge areas of food quality and shelf life, packaging logistics and SCM. Critical factors and FSC challenges (from production to retail) that result in food waste were identified and analyzed to provide new knowledge on a detailed level, but mostly on an interdisciplinary and comprehensive level in order to give an overall description of food waste challenges in FSCs. Four key findings/challenges facing FSCs and related to the foundation of the academic knowledge were determined. Interdisciplinary and transdisciplinary research are needed to approach these challenges. This research also revealed knowledge gaps, mostly on the comprehensive and systemic levels, where suggestions for further research are provided.

One contribution of this research is the determination and evaluation of central FSC challenges (from production to retail) that aim for sustainable practices and realizations of sustainable food supply chain. The interdisciplinary research that combines food microbiology with food packaging logistics and SCM provides a holistic understanding of the FSC challenges, because the interdependency between the packaging and the product characteristics and requirements are often overlooked in debates about food logistics, security and waste (Fredriksson & Liljestrand 2014, Verghese et al. 2013).

This research adds to the FSC and innovation literature by studying, and to some extent interacting with, an ongoing innovation project for the implementation of a DPSL service in FSCs involving several actors. The research includes all three spaces of the design cycle for innovation: inspiration, ideation, and implementation. The results provide insights and contribute to the literature on the operational, business model and strategic levels.

Thermal time constants (with and without forced airflow) in 83 locations in a pallet unit load were identified to present temperature differences within a pallet unit load (Paper III). The thermal time constants where used in microbiological prediction models to present possible food quality variations within a pallet unit load. This research also presents temperature and shelf-life variation results (between static shelf life and dynamic shelf life) in real Swedish FSCs involving three or more actors (Paper IV). These results stress the need for continuous temperature monitoring to achieve increased operational and food quality control in the FSCs. The research presents possible effects a DPSL service can have on the sustainable development of FSCs. These insights can be used to guide further research, especially in the area of business model development for SSCs and SSCI.

Another contribution is a framework of critical factors for the realization of SSCIs including a process model (Paper V). The factors and model need to be empirically tested and evaluated. They can guide further research to adopt more complex approaches to the development of improved guidance and provide support for the realization of sustainable development. This research stresses the need for interdisciplinary and transdisciplinary research and collaborations to transform from linear supply chains to circular sustainable supply chains.

6.3. Contributions to practice

This research identifies several ways to move FSC practices towards sustainable, cohesive and integrative improvements. This research includes empirical studies of a DPSL service implementation in Swedish FSCs. By studying a service that does not yet exist in an empirical environment, the opportunities and challenges of the service realization were elucidated for the actors in the FSC. Integrating the DPSL service, including continuous temperature monitoring, in FSC practices enables:

- A continuous determination of accurate temperature data and DPSL
- A new tool for food quality and operational FSC processes quality assurance.
    - Increased and proactive self-monitoring and alerts in case of temperature and shelf-life variations.
    - Presentation of how temperature affects the shelf life of specific food products.
- One communal way to measure temperature with the same technology in the FSCs.
- A reduction of manual labor in temperature controls and of the extra work and legal issues that arise when time or temperature restrictions are violated.
- The use of determined data as support for food producers to improve the accuracy of printed shelf life.
- Increased collaboration, knowledge diffusion and information sharing among FSC actors and increased FSC integration and transparency.
- Increased quality and efficiency of FSC practices and the decrease of food waste.
- Interdisciplinary and transdisciplinary collaborations to transform linear supply chains to circular sustainable supply chains.

This research presents a process model to help FSC actors in the realization of an SSCI, such as a DPSL service. The model provides managers with the most critical factors for SSCI, and guides them on how to manage these factors in the innovation process of inspiration, ideation, and implementation. The process model and the critical factors together can work as a mediator when transitioning towards circular sustainable FSC practices.

6.4. Further research

There is still a long way to go before reaching a much needed sustainable development and food waste depletion in the food industry. To prompt sustainable development in the food sector, empirical transdisciplinary research is needed that explores the paradigm shift from linear FSC to circular sustainable FSC. To do this, methodological research and development on sustainable supply chains as comprehensive entities are needed. This research underscores the need for SSCI to mediate the transition from linear FSC to circular sustainable FSC. A process model including critical factors for the realization of SSCI are suggested. However, the model and critical factors need to be tested and evaluated empirically. Further research can investigate if the necessary factors are available and strong enough to make a difference in the development of SSCIs. Such studies could be set up in the context of Dynahmat to evaluate the realization process of the DPSL service. Collecting and analyzing data from the long-term, large-scale Dynahmat project would be a means to investigate the possible effects on actual food waste reduction the DPSL service might have.

The research indicates that wider collaborative efforts with external stakeholders are more emphasized within SSCI than innovation in general. Consequently, while collaboration is by far the most emphasized critical factor for SSCI, more research related to collaboration in the context of sustainable innovations versus economic driven innovations is suggested.

Realizing SSCIs is a comprehensive and complex process because it involves several stakeholders and often demands changes to established sociotechnical systems. To do this, methodological improvement is also needed as more complex phenomena, such as innovation eco-systems and supply chains, need to be studied as comprehensive entities and not, as today, as separate units (single or dyadic perspectives). This is especially interesting in the context of FSCs due to their complex setups, with many partners, long FSCs, and perishable goods. Research that investigates business model development for supply chains is called for, especially for SSCIs that addresses the demand for a more integrative and holistic approach that encompasses several tiers of the FSC.

The purpose of this dissertation was to explore and evaluate the concept and requirements of a DPSL service in the context of FSCs, from food production to retail. From a sustainability perspective, it would be of great interest to include the agricultural industry, end-consumers and waste management actors in future research to reduce food waste within the entire food eco-system.

The dynamically predicted shelf life in this research is based a static initial bacterial load. This means that the initial bacterial load was based on reference samples and thus is not product (packed product) specific. This also means that the DPSL service will not alert if a food product is contaminated before or at the production site. It would be worthwhile to investigate the addition of the polymerase chain reaction (PRC) technique to quickly detect and identify specific pathogens. The PCR technique can, however, not separate viable and dead microorganisms, which means that the amount of bacteria cannot be determined. However, PCR samples with increased levels of pathogens can be followed up by extra conventional plating samples. To introduce PCR technology to the packaging process is worthwhile for future studies, especially to improve the DPSL service.

It would be worthwhile to explore different customer solutions of the DPSL service since the electronic waste of sensors might be too high and too expensive to reach all the way to households. Because the atmosphere of packed products changes when opened, the DPSL service would be limited because the prediction models are based on the packed product atmosphere. Other types of solutions would have to be integrated with the DPSL service to provide end-consumers with accurate information about the quality of their food products.

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Dynamically predicted shelf-life service

Have you ever thrown away food because you thought it had "gone bad" but weren't really sure? Have you ever felt insecure about the actual quality of that package of smoked ham or fresh cod? Do you usually toss it in the garbage if the printed best-before-date has expired? All of us waste food but seldom reflect on the consequences this has on our changing climate, our finances and our social behavior. But we consumers are not the only ones who contribute to food waste. In fact, food waste occurs throughout the entire supply chain, in primary production, at food producers, during distribution and storage, and in retail stores. Some of our central food waste challenges in developed countries are related to the printed shelf life on the package and temperature fluctuations that are strongly linked to consumer behavior, food safety assurance and food quality control from production to consumption. Hence, we need to improve food quality systems so that they convey the actual quality of food products and provide accurate shelf-life information in a clear and credible manner. This doctoral dissertation sets out to explore and evaluate the concept and requirements of a dynamically predicted shelf-life service to increase the accuracy and credibility of shelf-life information and to reduce food waste. The dissertation also provides understanding and guidance for actors involved in sustainable supply chain innovation ventures.

Malin Göransson has a Master of Science Degree in Engineering, Biotechnology from the Faculty of Engineering, Lund University. After completing her Master's thesis at the Division of Packaging Logistics, she was offered the opportunity to continue her research endeavors as a Ph.D. student. Based on the completion of this doctoral dissertation, Malin Göransson has been awarded a Ph.D. in Packaging Logistics.

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