Quality, efficiency, and sustainability in the foodservice supply chain

The case of professionally prepared meals

Wang, Yang; Akkerman, Renzo; Grunow, Martin

Publication date:
2013

Document Version
Publisher's PDF, also known as Version of record

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Yang Wang

Department of Management Engineering
Technical University of Denmark

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The case of professionally prepared meals

PhD thesis
Yang Wang
2013
ISBN: 978-87-92706-86-7

Technical University of Denmark
Department of Management Engineering
Produktionstorvet 424
2800 Kongens Lyngby
Denmark

Tel: +45 4525 4800
E-mail: phd@man.dtu.dk

Printer: Schultz Grafisk A/S

Preface

This dissertation is submitted to the Department of Management Engineering, Technical University of Denmark, in partial fulfillment of the requirements for acquiring the PhD degree. The work has been supervised by Associate Professor Renzo Akkerman and Professor Martin Grunow. The dissertation consists of a recapitulation of the research study and a collection of three research papers prepared during the period from August 2008 to July 2012.

Supervisors:

Associate Professor Renzo Akkerman
Department of Management Engineering
Technical University of Denmark
Kongens Lyngby, Denmark

Professor Martin Grunow
Chair of Production and Supply Chain Management
Technische Universität München
Munich, Germany

Assessment Committee:

Professor Michael Zwicky Hauschild
Department of Management Engineering
Technical University of Denmark
Kongens Lyngby, Denmark

Research Manager Ulf Sonesson
SIK – The Swedish Institute for Food and Biotechnology
Göteborg, Sweden

Associate Professor Dong Li
e-Business, Operations and Supply Chain Management Division
Management School, University of Liverpool
Liverpool, United Kingdom

Acknowledgements

I would like to express my deep thanks to my principle supervisor Associate Professor Renzo Akkerman of the Department of Management Engineering, Technical University of Denmark, whose support has been a mainstay since I started my graduate studies. Without his strong encouragement and valuable suggestions, this dissertation would never have been accomplished. I would also like to express my gratitude to my co-supervisor Martin Grunow for his insightful ideas and discussions.

I would like to thank the Danish Ministry of Food, Agriculture and Fisheries for partial funding of this research project. Also I would like to acknowledge support from the research partners from the National Food Institute and the National Institute of Aquatic Resources, both at the Technical University of Denmark. My special thanks go to Professor Jens Adler-Nissen, Gine Ørnholt Johansson, and Hanne Løje.

The research presented in this thesis was carried out in the Department of Management Engineering, Technical University of Denmark. I want to thank its current and past members for creating a pleasant environment to work in. My special thanks go to Christina Scheel Christiansen for her support, not only with all the administrative processes related to my research, but also her help with my daily life in Denmark.

Finally, I would like to thank my friends for being around during this whole endeavor. Most of all, thanks to my parents, my husband, and my lovely daughter for their unselfish love and support.

Yang Wang, Kgs. Lyngby, Denmark, July 2012

Abstract

Consumers have become more and more demanding with regards to food quality, food safety, sustainability, and associated product attributes. Looking at food supply chains from an integrated point of view has therefore become an industry paradigm. The overall aim of this thesis is to contribute to the literature with regards to the development of efficient, high-quality, and sustainable food supply chains; especially focusing on integrated methodologies. In this thesis, research is presented on the inclusion of the specifics of the food industry, food engineering related knowledge, and sustainability assessment methodology into food supply chain management.

This thesis builds on a case from the foodservice industry, which is used throughout the thesis to illustrate the proposed methodologies. As an important part of the food industry, the foodservice industry connects agricultural producers, food manufacturers, and wholesalers with consumers and provides prepared food and drinks ready for consumption away from home. This industry has grown significantly in the past years.

The thesis starts with a further introduction to the food service industry and a discussion of the research questions dealt with in this thesis, followed by a general discussion on the multidisciplinary research project. The subsequent three chapters focus on research towards quality, efficiency, and sustainability in the foodservice supply chain by implementing the integrated methodologies: integrating quality dynamics of food products into supply chain planning and integrating sustainability assessment methodology with supply chain planning. The last chapter of the thesis summarizes the scientific and managerial conclusions of the research project and outlines the future research directions.

Resumé

Forbrugere er blevet mere og mere krævende med hensyn til fødevarekvalitet, fødevaresikkerhed, bæredygtighed og tilknyttede produktegenskaber. At se på fødevareforsyningskæder fra et integreret synspunkt er derfor blevet et industriparadigme. Det overordnede formål med denne afhandling er at bidrage til litteraturen med hensyn til udvikling af effektive, høj-kvalitets og bæredygtige fødevareforsyningskæder, især med fokus på integrerede metoder. I denne afhandling er forskningen præsenteret med inddragelse af de særlige forhold i fødevareindustrien, fødevareteknologisk relateret viden og vurderingsmetoder inden for bæredygtighed og overført til ledelse af logistikkæder inden for fødevareindustrien.

Denne afhandling bygger på en sag fra foodservicebranchen, der anvendes gennem hele afhandlingen for at illustrere de foreslåede metoder. Som en vigtig del af fødevareindustrien forbinder foodservicebranchen landbrugsproducenter, forarbejdningsvirksomheder og grossister med forbrugerne og tilbyder tilberedte produkter og drikkevarer, der er klar til indtagelse udenfor hjemmet. Denne industri er vokset markant i de seneste år.

Afhandlingen starter med en yderligere introduktion til foodserviceindustrien og en diskussion af de forskningsspørgsmål, der behandles i denne afhandling, efterfulgt af en generel diskussion om det tværfaglige forskningsprojekt. De efterfølgende tre kapitler fokuserer på forskning omkring kvalitet, effektivitet og bæredygtighed i foodserviceforsyningskæden, ved at implementere de integrerede metoder: integration af kvalitetsdynamikker i fødevarer med planlægning af forsyningskæder og integration af bæredygtigheds vurderingsmetoder med forsyningskædeplanlægning. Det sidste kapitel i afhandlingen opsummerer de videnskabelige og ledelsesmæssige konklusioner af forskningsprojektet og skitserer de fremtidige forskningsretninger.

Contents

Chapter 1. Introduction

Consumers have become more and more demanding with regards to food quality, food safety, sustainability, and associated product attributes (Van der Vorst et al. 2009). Looking at food supply chains from an integrated point of view contributes to satisfying customer requirements and has therefore become an industry paradigm. The field of food supply chain management has undergone tremendous changes over the past 35 years. Food supply chain management that was once considered the last frontier of cost reduction in the 20th century has now become the major strategic issue for firms in the new millennium (Bourlakis and Weightman 2004). More and more researchers started doing research in relation to food supply chain management (Grunow and Van der Vorst 2010).

Bourlakis and Weightman (2004) and Jongen and Meulenberg (2005) discussed a list of specific process and product characteristics of food supply chain networks that complicate the supply chain planning process. Largely based on these two resources, we can identify the following:

1. Seasonality in production, requiring global sourcing.
2. Variable process yields in quantity and quality due to biological variations, seasonality, and random factors connected with weather, pests, and other biological hazards.
3. Keeping quality constraints for raw materials, intermediates and finished products, and quality decay while products pass through the supply chain.
4. Requirement for conditioned transportation and storage means (e.g. chilling or freezing).
5. Necessity for lot traceability of work in process due to quality and environmental requirements and product responsibility.
6. The fact that the food industry often combines elements from process industries and discrete industries, complicating planning and control.

As an important part of the food industry, the foodservice industry connects agricultural producers, food manufacturers, and wholesalers with consumers and provides prepared food and drinks ready for consumption away from home. It includes establishments that provide a take-away and/or delivery service where the food and/or drinks are prepared within the establishment but consumed elsewhere (Eastham et al. 2001). It provides consumers with value-added products that save preparation time and are available in a range of formats from fresh to frozen snacks, meal accompaniments or even meal solutions (Darlington and Rahimifard 2006). This industry has grown significantly due to demographic and life-style trends (Buckley et al. 2007). For instance, the UK convenience store sector is growing at a faster pace than the overall market (IGD 2012). The UK convenience market generated total sales of £32.4bn in the 12 months to April 2011, a 4.9% increase on the previous year. The value of the market continued to grow despite a 0.4% fall in store numbers, and now represents 21.4% of the total UK food and grocery market. According to the industry reports from Canadean 2012 on foodservice sector in several countries (Canadean 2012a, b, c, and d), the foodservice sectors were all growing in the past five years which is shown in Table

Table 1.1 Foodservice sector in several countries.

Foodservice sector	2006 (million)	2011 (million)	Increase (%)
Spain	€ 107,900	€ 111,600	7.5
Germany	€ 81,931	€ 83,484	1.9
The Netherlands	€ 18,812	€ 19,275	2.5
USA	US$ 515,425	US$ 547,872	6.3

1.1. Despite the fast growth in foodservice industry, the research in foodservice supply chain field is relatively less. This thesis focuses on a case from foodservice industry.

Efficient planning is a very important part of supply chain management. The goal of planning is to maximize the supply chain surplus that can be generated over the planning horizon respecting the constraints (Chopra and Meindl 2007). Traditionally supply chain planning focuses on the efficiency aspect (minimizing cost or maximizing service level) of supply chains including food supply chains. In addition to that, as mentioned in Akkerman et al. (2010), food quality and sustainability are two main food-industry-specific challenges. To this end, in order to include food quality and sustainability issues into food supply chain management and study the trade-offs between efficiency and the other two aspects, integrated research efforts are required. This is the main subject of this thesis.

1.1 Food quality

Product quality is one of the essential food product characteristics to consider during distribution (Akkerman et al. 2010). In food supply chains, there is a continuous change in the quality from the time the raw material leaves the field (or e.g. the slaughterhouse for meat products) to the time the product reaches the consumer (Dabbene et al. 2008). In order to assess the quality changes of food products along the supply chain, food engineering knowledge is required in food supply chain management. There is increasing literature on food product quality issues along the supply chain. For instance, Brown et al. (2001) defined a limitation of product storage time so as to avoid product spoilage. Lütke Entrup et al. (2005) presented mixed-integer linear programming (MILP) models that integrated shelf-life issues into production planning and scheduling. More advanced, a variety of authors included some kind of linear dependency between quality and time in their modeling approaches (Federgruen et al. 1986; Van der Vorst et al. 2000; Hsu et al. 2007; Osvald and Stirn 2008; Chen et al. 2009; Farahani et al. 2012). Some recent papers also try to model quality degradation more explicitly. In Zhang et al. (2003), Blackburn and Scudder (2009), Van der Vorst et al. (2009) and Rong et al. (2011), product quality is represented as a function of time and temperature, thereby really integrating food engineering aspects in supply chain planning. However, the research on integrating food engineering aspects in supply chain planning is still at its infancy and most of the literature on integrating food engineering knowledge is based on product quality. The methods applied mostly are assuming simple relationship between food quality and storage time and temperature. In reality, food product quality depends on more than just storage time and temperature, there are more complicated thermodynamic aspects happening during production, distribution, and storage. In general, including changes in product quality and also other food product attributes is one of the main challenges related to quantitative modeling approaches for food supply chain management.

1.2 Sustainability assessment

Operations management researchers and practitioners face new challenges in integrating issues of sustainability with their traditional areas of interest. During the past 20 years, there has been growing pressure on business to pay more attention to the environmental and resource consequences of the products and services they offer and the processes they deploy (Kleindorfer et al. 2005). In the new economic context the long term success of any organization is built not only on efficiency and profitability but also on its contribution to the future of people and the future of the planet (Barbosa-Póvoa 2009). Over the last years, sustainability has also become of increasing importance in the food industry (e.g. Berlin 2003; Van der Vorst et al. 2009).

To assess the sustainability of the system, the analysis thus not only focuses on commonly-used efficiency-based performance indicators, but also environmental performance, and additionally, people’s health and safety have to be included (Kleindorfer et al. 2005). For instance, interactions between economic and environmental performance are plentiful. Achieving synergies likely depends on industry-specific characteristics (Karagozoglu and Lindell 2000), and an interdisciplinary approach, combining operations management insights with technological expertise is necessary, which has been discussed in both the managerial literature (e.g. Akkerman and Van Donk 2010; Corbett and Klassen 2006) and the engineering literature (e.g. Azapagic et al. 2006; Edwards 2006).

As is the case with the integration of food quality, integrating sustainability in food supply chain management requires multidisciplinary research efforts – combining management approaches, production and food engineering, and environmental studies. Traditionally, the planning of supply chains is driven by increasing efficiency, minimizing costs, or maximizing some service-related measures. In recent years, researchers have also started to integrate environmental considerations in supply chain planning models, for example by adding environmental constraints to their models (e.g. Rădulescu et al. 2009; Subramanian et al. 2010), by developing multi-objective approaches taking into account both economic and environmental impacts (e.g. Quariguasi Frota Neto et al. 2008; 2009), or by using methods like simulation to evaluate trade-offs between economic and environmental performance in supply chain planning (e.g. Van der Vorst et al. 2009; Akkerman and van Donk 2010). In order to evaluate the sustainability of supply chains, environmental assessment methods and tools have to be included. In multi-objective approaches, some paper started to use methodology similar to life cycle assessment to get the value of sustainability parameters (Mele et al. 2011; Bojarski et al. 2009; Azapagic and Clift 1999). But the level of integration between the different research disciplines is still low.

Combining efficiency, quality, and sustainability in food supply chain management covers both the traditional focus of supply chain planning and the two main food-industry-specific challenges. Integrated methodologies and research are required in this sense.

1.3 Research objective

The overall aim of this thesis is to contribute to the literature for creating an efficient, high-quality and sustainable food supply especially with integrated methodologies. As mentioned before, the integration between food engineering, sustainability assessment methodology and supply chain management are relatively low. In this thesis, attempts are made on the inclusion of the specifics of the food industry, food engineering related knowledge, and sustainability assessment methodology into food supply chain management. It is based on existing theory on general supply chain management to improve the efficiency, quality and sustainability of food supply chains. These lead to the research questions of this thesis.

1.4 Research questions

Traditional supply chain planning mainly focuses on resource availability, capacity constraints and customer requirements. For food products, a good assessment of resource usage and customer requirements requires food engineering knowledge. Integrating food engineering knowledge into supply chain management also provides a way to keep track of the quality dynamic of the food product in temperature-controlled environment. This leads to the first research question.

RQ1: How can the quality dynamics of food products in temperature-controlled environments be integrated into supply chain planning and what are the benefits of this?

Next to quality, sustainability is also a main focus in this research project. Hence, this thesis also investigates the possibility to combine supply chain management methods and sustainability assessment methodology, aiming to evaluate the sustainability performance of the supply chain and support the decision-making process. This results in the following research questions.

RQ2a: How to use supply chain planning methodologies in sustainability assessment to improve the sustainability assessment for a supply chain?

RQ2b: Can we integrate sustainability assessment methodology with supply chain management methodology to provide decision support on possible trade-offs between economic and environmental perspectives?

To answer these questions, quantitative operations management methods (Bertrand and Fransoo 2002) and life cycle assessment methodology are applied, which are followed by an illustrative case study. Both research questions are demonstrated by a research project in which a new production and distribution concept is applied aiming to improve the overall sustainability of the supply chain.

Even if this typical case is used throughout the development of the methodologies presented in this thesis, the case is only used to illustrate the methods and we believe that the methods can be generalized to other foodservice supply chains as well.

1.5 Outline of the thesis

In chapter 2, the supply chain for professionally prepared meals which is used as the case throughout the thesis is introduced. The new concept applied in the supply chain is explained and the important supply chain planning decisions are identified and organized in a decision hierarchy.

In response to RQ1, chapter 3 presents a research paper, in which a decision support model based on mixed-integer linear programming is developed for temperature-controlled supply chain. An integral part of the approach is a model of the thermodynamic behavior of the food products that is used to describe the thawing process.

Chapter 4 is based on a research paper in which an integrated framework integrating supply chain planning and life cycle assessment is developed, illustrating how supply chain planning tools can be applied in the sustainability assessment of production and distribution operations. Addressing RQ2a, it shows that using supply chain planning results in life cycle assessment proves to work well, supplying more realistic parameter settings.

In Chapter 5, the framework integrating supply chain planning and life cycle assessment is further investigated to address RQ2b, which mainly focuses on the feedback loop from life cycle assessment to supply chain planning. A multi-objective integer programming model is developed taking both economical perspective and sustainability perspective into consideration, based on the sustainability parameters obtained from the life cycle assessments results.

Finally, a summary of the results of the previous chapters is presented and the thesis concludes with indicating several potential future research directions.

As chapter 3, 4, and 5 are based on research papers, they can also be read as individual contributions, as they each contain brief introductory material as well. This also means there will be a small amount of overlap due to the same reason.

Chapter 2. Professionally prepared meals

2.1 Concept of professionally prepared meals[1]

In this thesis, the study focuses on foodservice supply chains mainly including meal solutions prepared in satellite kitchens, such as workplace canteens, schools, hospitals, and nursing homes. It adopts a definition of the food service supply chain that consists of the following stages: agricultural industry, a production site, and several professional kitchens (as illustrated in Figure 2.1).

Satellite kitchens are an important part of the food service sector and they typically have limited possibilities for storing and preparing all kinds of raw products. This has in many cases created a demand for new types of convenience products (Mikkelsen et al. 2007). The use of meal elements in food service meal production can help solve this problem (Engelund 2007).

Meal elements are elements of a meal, e.g. pre-fried meat pieces, portions of frozen fish or pre-processed vegetables. They can be prepared industrially or at a central kitchen unit and distributed to satellite kitchens, where the kitchen staff can combine them into complete meals. These meals are what we refer to in this thesis as professionally prepared meals, and have several merits (Jensen et al. 2010):

(1) The use of meal elements makes it easier to handle and facilitates easy portion and nutritional control.
(2) Since meal elements are prepared professionally, it is possible to improve the working environment by removing laborious processes such as browning of meat and pre-processing (e.g. pre-frying) of vegetables in the satellite kitchens.
(3) Food safety is improved by allowing products to be tested for food-borne pathogens before use and by preventing contamination sources such as soil from raw vegetables in the satellite kitchens.

2.2 Super chilled production and distribution

To preserve the quality of meal elements and extend their shelf life, one of two treatments is typically applied. One is freezing, which implies the pre-processed elements of a meal are frozen at around −30°C and stored at around −25°C before distribution. The other one is chilling, using a temperature around +2°C to +5°C to chill the pre-processed elements of a meal, which is increasingly used in todays professionally prepared meal solutions offered both in retail and in foodservice.

[1] For more details of professionally prepared meals, please refer to Adler-Nissen et al. (2012).

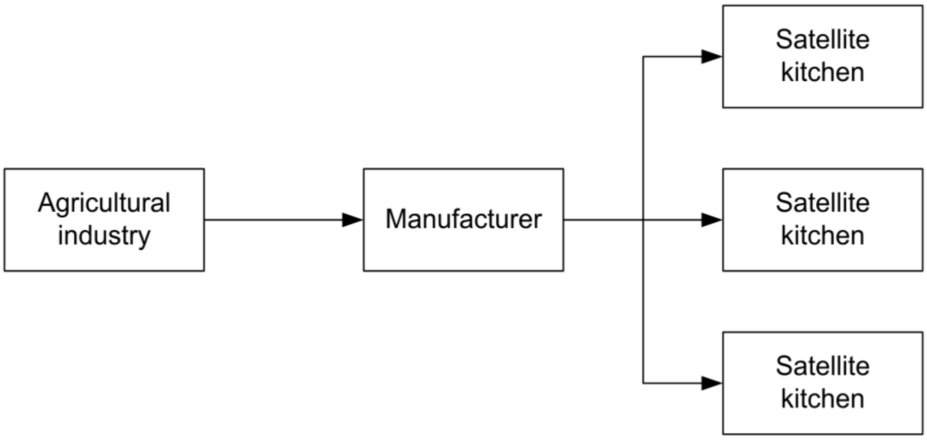

Figure 2.1 Foodservice supply chain studied in the thesis.

In this thesis, a new concept for producing and distributing meal elements is applied. The concept aims to improve the sustainability of the production and distribution system and to prolong the shelf life of the meals by distributing them in the conventional cold chain at +2°C or +5°C after the products have been super chilled. Super chilling is a treatment method between freezing and chilling that chills the product to a temperature slightly below its initial freezing point (Bahuaud et al. 2008), which for instance, for vegetables, is around −1°C. For more information regarding super chilling, please refer to Kaale et al. (2011). Typically products are super chilled first and then distributed at a similar temperature as super chilling (Duy Bao et al. 2007; Dunn and Rustad 2007). However in the new concept developed here, super chilled food products are distributed in a cold chain at +5°C afterwards, making use of fact that by super chilling part of the internal water is frozen and acts as a refrigeration reservoir.

Advantages are here taken of the high thermal buffer capacity of the partially frozen foods as compared with chilled foods, which is due to the dominance of the latent heat term in the energy balance for the thawing process: for example, heating a chilled product with 75 pct water five centigrade consumes about 18kJ/kg, while melting half of the ice content of the same product, even though the temperature of the product stays at around 0°C, consumes 126 kJ/kg. This leads to a significant saving of energy used during distribution compared with typical distribution approach which would significantly increase the sustainability of food distributions systems. Next to the environmental benefits, this also has a positive effect on product quality. Distribution of super-chilled products in the conventional cold chain means that the product temperature will always be lower than the environmental temperature, hence, the product temperature only rises and does not fluctuate, which is often harmful for product quality. Furthermore, the lower temperature (compared to chilled product) also slows down quality degradation. These are further elaborated in Chapter 3.

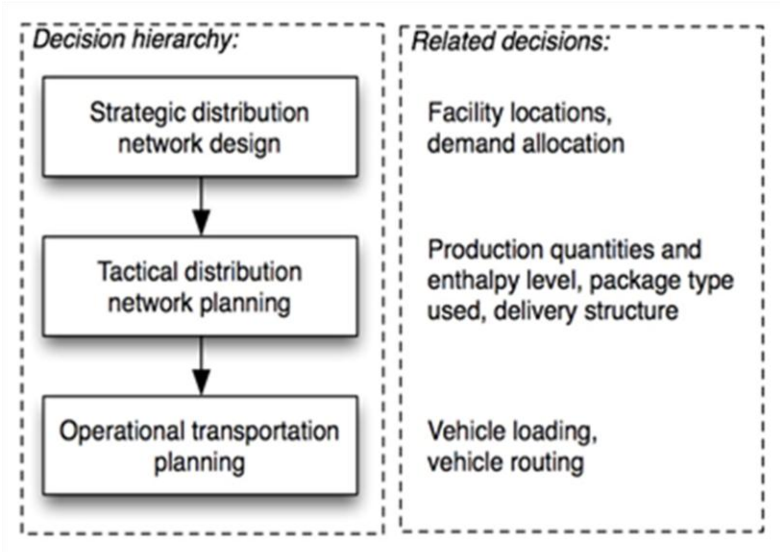

Figure 2.2 Decision hierarchy for distribution planning of professionally prepared meals.

2.3 Planning decisions[2]

There are several trade-offs in production and distribution of super chilled meal elements. One aspect is the choice of packaging materials. This not only affects the amount and type of waste, but also the handling effort of the people involved, and the quality deterioration of the meal elements. Choosing polystyrene boxes, which is a better insulating material, would for instance slow down the thawing process after super chilling, thereby reducing quality degradation. On the other hand, the material is more expensive than regular cardboard. Another aspect is the number of shipments to customers. If we would for instance choose to increase shipment volumes and decrease the number of shipments, we would reduce the environmental impact related to cooling the product during transportation. Also, we would likely increase the efficiency of the transportation network. However, the product quality would be negatively affected by this decision, as part of the shipment would have to be stored to cover future demand, which would lead to quality degradation of the food product, and cause product waste. However, if this new distribution method is able to reduce the product temperature over the initial period of distribution and storage at the kitchens, quality degradation is also reduced, which would create the opportunity to improve economic and environmental performance, without affecting product quality and consumer's taste experiences.

To analyze these trade-offs, we first identify the important decisions and organise these in a decision hierarchy, a well-established method to approach complex decision problems (e.g. Hax and Meal 1975; Meal 1984). The total task of planning the production and distribution system can be decomposed in three hierarchical levels, reflecting strategic, tactical and operational decisions. Figure 2.2 illustrates this decision hierarchy and the decisions involved.

[2] The material in this section has previously been published in Wang et al. (2009).

The strategic decisions mainly deal with the design of the distribution network. The tactical, mid-term planning level mainly deals with decisions on how much to produce in the foreseeable future, and what delivery structure to use in relation to customers. This includes how often we have deliveries to specific customers, affecting to a large extent the total transportation distance covered (relating to cost performance as well as environmental performance). On the tactical level, we also find interesting trade-offs with different packaging options and starting temperature levels, as these factors influence the eventual temperature level at the customer, and hereby determine how much future demand can already be covered by a shipment. Obviously, these decisions are all very much interrelated, and are therefore often combined in one planning model to provide decision support. These decisions then set the targets for the operational, short-term level, in which more detailed decisions on e.g. vehicle routing are made. In response, the short-term planning level gives feedback to the mid-term level.

In the remainder of the thesis, we focus on the tactical network planning problem, as the decisions made on that decision level have a large impact on the eventual performance of the distribution system.

Chapter 3. Temperature-controlled supply chain planning

This chapter is based on the following research paper:
Wang, Y., Akkerman, R., and Grunow, M. (2012) *Temperature-controlled supply chain planning in the foodservice industry*.

Abstract

This paper studies a production and distribution system for perishable food products in the foodservice industry, where the thermodynamics of temperature changes are essential to consider. In this paper we identify the important planning decisions in relation to supply chain planning, and we develop a mixed-integer linear programming to support these planning tasks. An integral part of the approach is a model of the thermodynamic behavior of the food products that is used to describe the temperature changes. An illustrative case study subsequently shows how the resulting model can be used to support supply chain planning for food products that are partially frozen and then subsequently allowed to thaw while being distributed. Compared to the traditional way of using a fixed shelf life based on perishability estimates, the results clearly show that the detailed modeling of product changes allows for a significant decrease in distribution efforts, even with the use of conservative shelf life estimates.

3.1 Introduction

Consumers have become more and more demanding with regards to food quality, food safety, sustainability, and associated product attributes (Van der Vorst et al. 2009). Looking at food supply chains from an integrated point of view has therefore become an industry paradigm, and there is a need for management efficiency and advanced decision support tools (Lowe and Preckel 2004). However, the utilization of operations management techniques is often low, which may be due to the specific product and process characteristics in the food industry (Van Donk et al. 2008), or the fact that the food industry often combines elements from process industries and discrete industries, complicating planning and control. Research in this area is limited, especially with regards to the foodservice industry, where the challenges with regard to food quality and efficient logistics are especially high (Akkerman et al. 2010).

The foodservice industry connects agricultural producers, food manufacturers, and wholesalers with consumers and provides prepared food and drinks ready for consumption away from home. This industry has grown significantly due to demographic and life-style trends (Buckley et al. 2007). It includes establishments that provide a take-away and/or delivery service where the food and/or drinks are prepared within the establishment but consumed elsewhere (Eastham et al. 2001). Satellite kitchens (e.g. in nursing homes or hospitals) are also an inherent part of foodservice supply chains. The facilities in these kitchens are often small and inadequate for storing and preparing all kinds of raw products. Hence, food products are often produced industrially in a central location, after which they are supplied to the satellite kitchens (Engelund et al. 2009).

In this paper, we study the production and distribution planning (with a focus on delivery intervals) for food products meant for the foodservice industry. The main contribution of the paper lies in the integration of a model for the thermodynamic product behavior in the development of a decision support approach for supply chain planning of food products. The modeling also includes a novel and flexible modeling approach for determining the delivery intervals, and it allows us to assess the feasibility and rationality of producing and distributing food products with a certain temperature treatment. We are also able to show that including the product's thermodynamic characteristics in supply chain planning gives significant improvements over the industry status quo of using a shelf life of a certain number of days.

The remainder of this paper is organized as follows. In section 3.2 we discuss how the thermodynamic behavior involved in temperature changes can be included in traditional supply chain planning approaches. Then, in section 3.3 we develop a mathematical model to support decision making on production and distribution planning, followed by numerical analysis of an illustrative case in section 3.4 and 3.5, demonstrating the use of the model and its superiority over traditional supply chain planning methods. Finally, our conclusions and further research plans are presented in section 3.6.

3.2 Temperature-controlled food distribution

To preserve the quality of food products and extend their shelf life, several temperature treatments are typically applied. One is freezing, which implies the pre-processed food products to be frozen at around –30°C and to be stored at around –25°C before they are distributed in the frost chain, where the temperature generally must be kept at –18°C or lower (ASHRAE 2002). Another one is chilling, using a temperature of around +2°C to +5°C (ASHRAE 2002), which is increasingly used in both the retail and the foodservice industry, because it generally leads to a higher food quality. In-between freezing and chilling lies a less common treatment, called super chilling. Here, products are chilled to a temperature slightly below its initial freezing point (Bahuaud et al. 2008), which for instance, for vegetables, is around –1°C. This method combines the shelf-life extension aspects of freezing with the quality-preserving aspects of chilling (e.g. Huss 1995; Fagan et al. 2003; Redmond et al. 2003, 2004; Duun and Rustad 2007), providing an alternative method over conventional chilling (Kaale et al. 2011). Super chilling significantly extends the potential number of environments in which high-quality food can be provided at reasonable costs. Typically, in the provision of food products to the foodservice industry, the products remain in the same temperature category after production, i.e. during distribution and storage. Occasionally, products are distributed at temperatures higher than their initial temperature, such as in freeze-chill distribution (e.g. O'Leary et al. 2000).

Product quality is already one of the essential food product characteristics to consider during distribution (Akkerman et al. 2010). Most of the literature on modeling product quality is considering shelf life and is treating quality degradation as a given. Lütke Entrup et al. (2005), for instance, presented mixed-integer linear programming (MILP) models that integrated shelf-life issues into production planning and scheduling. Brown et al. (2001) defined a limitation of product storage time so as to avoid product spoilage. A variety of authors included some kind of linear dependency between quality and time in their modeling approaches (Federgruen et al. 1986; Van der Vorst et al. 2000; Hsu et al. 2007; Osvald and Stirn 2008; Chen et al. 2009; Farahani et al. 2012). Except Van der Vorst et al. (2000), which used simulation modeling to handle product quality as a performance indicator next to cost aspects, all the other authors mentioned above included the value of food product quality into the objective functions of mathematical programming models, mostly combined with actual production or transportation costs.

Some recent papers also try to model quality degradation more explicitly. In Zhang et al. (2003), Blackburn and Scudder (2009), Van der Vorst et al. (2009) and Rong et al. (2011), product quality is represented as a function of time and temperature, thereby really integrating food engineering aspects in supply chain planning. For instance, Rong et al. (2011) provided a methodology to model quality degradation in such a way that it can be integrated in a mixed-integer linear programming model used for production and distribution planning. The basis of their methodology is that quality degradation of food products in storage (or transport) is dependent on storage time and storage temperature, which are then also considered to be decisions in their modeling approach.

However, the mentioned literature all builds on modeling (constant) environment temperature, whereas the quality degradation of the food products actually depends on the temperature of the product itself, which is not necessarily identical to that of the environment it is in. If the product initially has a temperature different from the environment, product temperature will change until it is in thermal equilibrium with the environment. This process can be quite slow, depending on the thermal buffering capacity of the product and the heat transfer characteristics.

In the remainder of this paper, we focus on a situation in which products are being distributed at a higher temperature than their initial temperature, such as in freeze-chill distribution or in the distribution of super chilled products in the conventional cold chain, as this provides the most challenging environment for temperature-controlled supply chain planning. In these situations, the product temperature will for slowly increase, primarily because of convective heat transfer from the surrounding air. In order to keep track of the temperature and the heat transfer, we use the product’s enthalpy (H in J/kg). This is reflecting the amount of energy bound in the product and thereby the thermal buffering capacity. Most of the energy is in the form of the latent heat of the transformation of water into ice and vice versa. In this paper, we therefore include the enthalpy changes during production and distribution, in such a way that food quality can be guaranteed when the products are used in the satellite kitchens.

Figure 3.1 illustrates the enthalpy increment in a thawing process in a hypothetical example. During the thawing process of the super chilled products in distribution and storage, the enthalpy of a typical product will increase in a manner illustrated in Figure 3.1(b). Figure 3.1(a) presents the corresponding temperature increase with increasing enthalpy of the food product (see e.g. Pham et

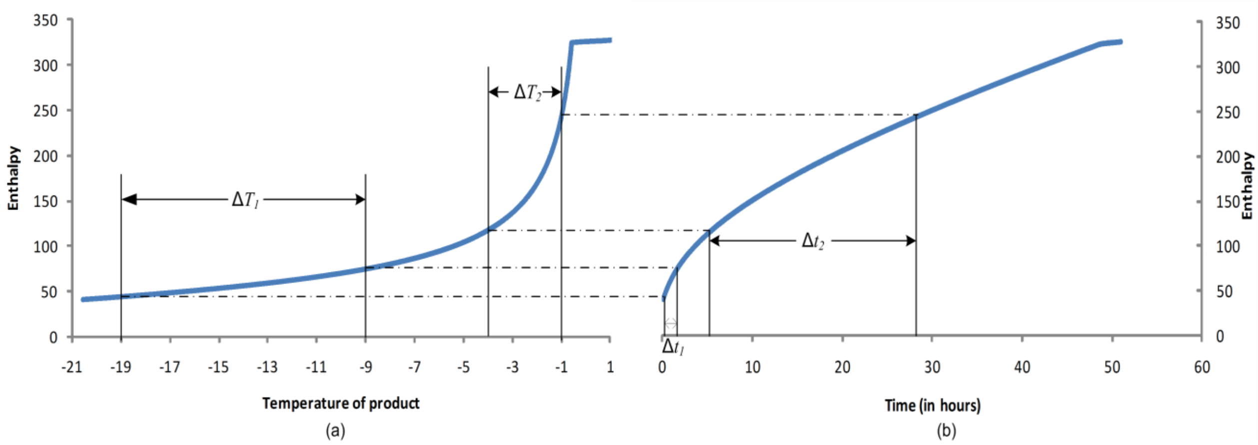

Figure 3.1 Illustration of enthalpy increment in a thawing process.

al. 1994; Singh and Heldman 2009). Most food products have similar enthalpy curves, as these relationships largely depend on the water content of a product, and products suitable for super chilling generally have a high water content (from 60% to 90%) (Pham et al. 1994). The rate of enthalpy change is influenced by the heat-transfer coefficient (which is decided by the material type and thickness used to pack the food product), the surface area of the package, the mass of the food product, and the temperature difference between the product and its environment. The change in enthalpy, ΔH [kJ/(kg•K)] is calculated by equation (3.1), which is based on a standard energy balance for a temperature difference, ΔT between environment and a package with the surface area A [m^2], the mass M [kg] and a heat transfer coefficient h [W/(m^2•K)]:

$$\Delta H \approx \frac{h \cdot A \cdot \Delta T}{M}. \qquad (3.1)$$

The approximation results from the fact that the enthalpy change is mainly related to the melting of ice.

In this hypothetical example, the period of thawing from –19°C to –9°C (ΔT_1) takes less than 2 hours (Δt_1) and the period of thawing from –4°C to –1°C (ΔT_2) which is around the range of super chilling takes more than 20 hours (Δt_2). In the figure on the left, this relates to the steep part of the curve. Here, a lot of energy is needed for the temperature increase to occur and the thawing process slows down accordingly, as most of the energy is used to melt ice to water, and not to increase the temperature of the product. This large thermal buffer creates an opportunity to distribute and store a food product after super chilling in the conventional cold chain without reaching too high temperature levels (Adler-Nissen and Zammit 2011).

Furthermore, due to the fact that most energy goes into the melting of ice, the increase in enthalpy related to time is nearly constant in the interval of super chilling (–4°C to –1°C) and can therefore be approximated by a constant relationship, which is used in the modeling approach presented in this paper. The slope of this curve, or the rise in enthalpy per time unit (ΔH) can be used to calculate the expected enthalpy of food products after transportation and storage for given time intervals, given the packaging material, mass and surface area (Adler-Nissen and Zammit 2011). For instance, a larger surface area would lead to a steeper slope of the curve in Figure 3.1(b), just as less-insulating packaging material would.

These parameters and their relationship can be used as parameters in the planning model developed in section 3.3. For this purpose, a discrete scale is developed for the enthalpy level (i.e. fixed small increments), similar to the way product quality was modeled by Rong et al. (2011).

3.3 Modeling network planning

3.3.1 Problem description

Successful production and distribution management requires many decisions, which must be made to ensure the competitiveness of a supply chain. In the production and distribution network of super chilled food products, some specific examples are the delivery intervals to customers and the choice of packaging materials. The delivery intervals affect the transportation costs and the quality deterioration of the super chilled food products. If we would for instance choose to increase shipment volumes and decrease the number of shipments, we would reduce the transportation cost. On the other hand, the product quality would be negatively affected, as part of the shipment would have to be stored for a longer time, which would lead to quality degradation of the food product. However, the investigated distribution method with a reduced product enthalpy (and temperature) may create an opportunity for such efficiency improvements without having a large impact on quality. As for packaging materials, choosing polystyrene boxes would slow down the thawing process after super chilling, because of the better insulation of polystyrene boxes. On the other hand, the material is more expensive than regular cardboard.

Our modeling approach is based on a foodservice supply chain with one manufacturer which produces one kind of food product, with the possibility to super chill this product at different temperatures, i.e. enthalpy levels, and the possibility to use different packaging materials. This product is then supplied to several satellite kitchens. The whole amount of product produced on one day for one customer is packed in the same type of packages and has the same starting enthalpy level. The main process at the manufacturer considered here is the super chilling of the product, requiring a certain processing time on the freezing tunnel, meaning that the manufacturing and cooling capacity of the production site is considered to be limited. According to the classical version of Plank's freezing formula (see e.g. Maroulis and Saravacos 2003), freezing time is proportional to the enthalpy removed. As a consequence, cooling down to lower enthalpy levels leads to higher production cost. The packaging costs are determined by the packaging material used and the quantity that is packed.

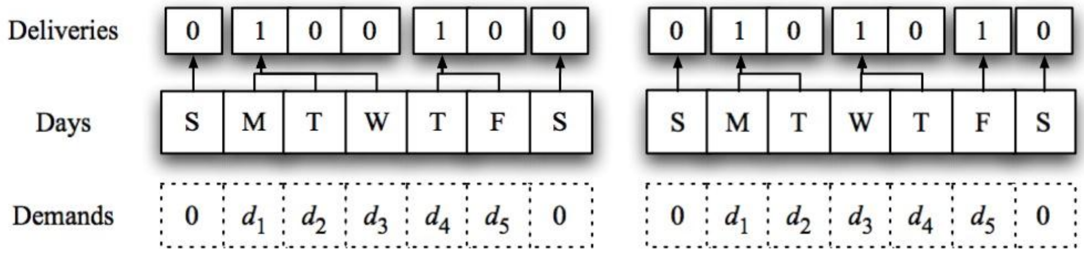

Figure 3.2 Two examples of assigning delivery chunks to a week's demand.

Customers are satellite kitchens whose demands are given and have to be met before the due dates. We also assume the demand to be integral multiples of the volume of the package box. Products can be delivered to customer sites before the due date and then be stored there until they are used. There are however limited storage capacities at the customer sites. All transportation is performed in the conventional cold chain, and transportation costs are proportional to the number of shipments and their length. We assume that all the deliveries can be performed in less than a day's time. When the product is used at a customer site (possibly after a certain storage time), it must still be below a given enthalpy level, i.e. be still partially frozen (cf. section 3.2).

The objective in production and distribution planning is to minimize the sum of production, transportation, and packaging costs.

3.3.2 Choosing delivery chunks

In the distribution system, customers do not need to be served every day. A customer's demands of several days can be satisfied in one shipment. To model this, we introduce the concept of delivery chunks. Delivery chunks are related to a number of days of demand covered by a single shipment. Delivery chunk '1' means we satisfy demand for one day with a delivery on that day, '1 0', means we satisfy demand of 2 days by a shipment on the first day, etc. We also introduce delivery chunk '0', to denote that there is no demand and no shipment on a specific day. To decide on which day to serve a customer is to combine a sequence of delivery chunks.

In Figure 3.2, two examples are shown for a situation with a week of demand for a customer. In both cases, there is no demand in the weekend, leading to the single-zero delivery chunks for those days. In the first example, the demands during the week are covered with two shipments, one on Monday and one on Thursday. In the second example, three shipments are used to cover the demand: on Monday, Wednesday, and Friday. How these delivery chunks are assigned is a fairly complex decision problem, depending on customer requirements, capacity constraints, and enthalpy change of the product (during transport and in storage). It furthermore involves cost trade-offs between packaging material, initial enthalpy level, and shipping cost.

Essentially, choosing delivery chunks will determine delivery intervals for each customer. In the literature, some other modeling methods have been proposed for the determination of delivery frequencies. In periodic routing problems, as in our planning problem, different customers usually require different numbers of visits in a certain time horizon. How often each customer should be visited in a period depends on its product usage, available storage space, preference, and the contract between the customer and the distributor (Parthanadee and Logendran 2006). Delivery frequencies in periodic routing problems are usually modeled with allowable visit combinations. For example, if customer 1 specifies a service frequency of 2 and a set of allowable combinations of visit days: {day 1, day 3} and {day 2, day 4}, then customer 1 must be visited twice in planning horizon and these visits should take place on day 1 and 3, or on day 2 and day 4 (e.g. Cordeau et al. 1997). Compared with this modeling approach, our approach of combining delivery chunks has more flexibility. No allowable visit combinations need to be defined first. Another modeling approach is setting up a variable stating how much products are actually delivered in period t which is an approach often used in standard network planning problems, for instance in Park (2005) and Ekşioğlu et al. (2007). Using this approach will add difficulties in tracking enthalpy changes because it is hard to tell how many days' demands are covered by the shipment on day t. This could be solved by adding an index of enthalpy to the decision variables, similar to how Rong et al. (2011) modeled when tracking quality changes, but this will increase the complexity of the model to a large extent. In our modeling approach, we still use discretization of enthalpy, but by defining delivery chunks beforehand, we are able to avoid the need to include an index of enthalpy and also the additional complexity.

3.3.3 Package stack patterns

As mentioned in section 3.2, the rate at which enthalpy changes is mainly decided by the mass of the product, the heat-transfer coefficient resulting from the packaging material, and the surface area related to the package stacking pattern. We assume a certain base area and package stack patterns (illustrated in Figure 3.3) to calculate corresponding surface areas. For more than 8 boxes, they will be stacked on higher layers in the same pattern as on the second layer. This means that for a customer demands with a specific delivery chunk, the package stack pattern of the demand is given. Hence, the surface area is given.

We realize it might be possible that the product is shipped or stored together with other products, or is stacked in kitchens' storage rooms in a pattern with only one layer in depth dimension, but this surface area calculation then provides an upper bound on the enthalpy change, as the other situations mentioned would lead to a surface area that is smaller than in the pattern we assume. For a similar reason, we only consider the last day's demand in tracking enthalpy changes. The products stored for the last day of a shipment have the largest enthalpy increase. By only considering the last day's shipments, and making sure that these boxes of product still fulfill quality requirement, we essentially analyze the worst case scenario. For instance, assume we have customer demand for three days of 10kg, 20kg, and 30kg to be delivered in one shipment and the volume of the packaging box is 10kg. The enthalpy changes of the last day's three boxes are tracked in our model in a stacking pattern as illustrated in Figure 3.3 for 3 boxes from the beginning of the delivery, disregarding of the other 3 boxes that cover the first two day's demand. Both of these factors lead to

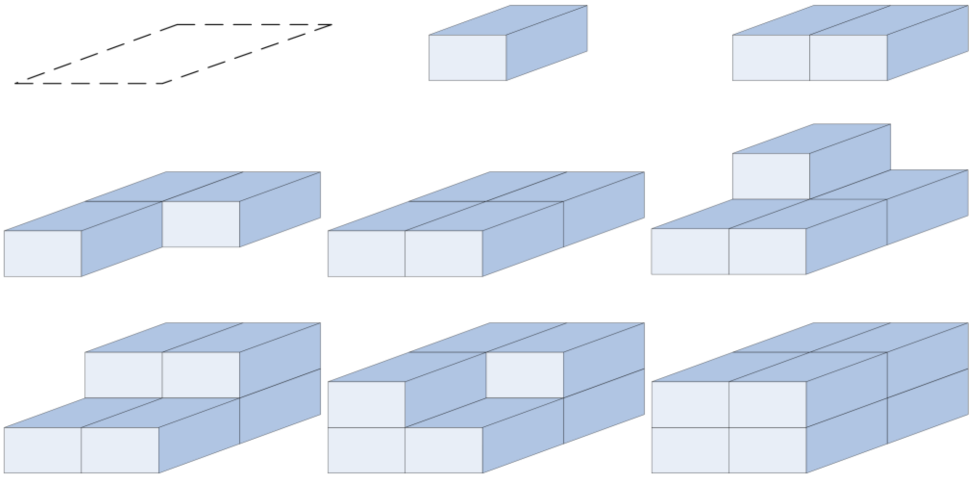

Figure 3.3 Possible package stack patterns for 1 to 8 boxes.

an overestimation of the enthalpy increase, which will guarantee that the product temperature stays below the initial freezing point of the food product.

3.3.4 Tracking enthalpy changes

All product flows are distinguished by their enthalpy level. We discretize the enthalpy in such a way that ΔH for storing at customer sites for one period can be expressed in integer values. As discussed in section 3.2, the enthalpy increase with temperature from –4°C to –1°C per time unit can be assumed constant, which means the enthalpy increase is only associated with the storage time using a given packaging material and package stack pattern regardless of the starting level of enthalpy, which reduces the complexity of the resulting model. We use maximum enthalpy levels $H_{\max}$ for customers in the supply chain. These are based on the maximum enthalpy level required by the customers, and are related to how far the thawing process is allowed to have progressed before the customer uses the food product. We assume the enthalpy level required by the customers will never be higher than the enthalpy at the initial freezing point of the food product, meaning that the product will always be partially frozen. The minimum enthalpy level of the product is denoted by $H_{\min}$ which is the minimum enthalpy level that super chilling can reach and the product can tolerate.

3.3.5 Problem formulation

Sets:

$f,f' \in F$ set of indices of delivery chunks {'0', '1', '1 0', '1 0 0', '1 0 0 0', '1 0 0 0 0'} where $F = \{1,...,6\}$ in this case. The set F is divided into two subsets:
$F_1 = \{1\}$ is index of delivery chunk '0' and
$F_2 = \{2,3,4,5,6\}$ is index of {'1', '1 0', '1 0 0', '1 0 0 0', '1 0 0 0 0'}
Note that the delivery chunk indexed by $f \in F_2$ covers exactly f–1 days of demand

$j \in J$ set of customers

$e \in H$	set of all enthalpy levels, $H = \{H_{\min},...,H_{\max}\}$
$t \in T$	set of days, $T = \{1,...,T_0\}$
$p \in P$	set of available packaging materials
$l \in L$	set of package stack patterns

Parameters:

w_e	cost for producing one unit of product with enthalpy level e
v_p	cost for packaging one unit of product using packaging material p
k_j	cost for transporting one shipment of product from the manufacturer to customer j
s_e	freezing time required to produce one unit of product with enthalpy level e
a_t	production time available at manufacturer on day t
g_j	storage capacity at customer j
ΔH_{pl}	enthalpy increase per day at customer sites with package loading methods l for package type p. If $l = 0$, we set ΔH_{pl} big enough to ensure that the day with no demand will not be the last day of any shipment.
d_{jt}	demand of customer j on day t
m	volume of packaging boxes
$H_{\min}$	minimum enthalpy level
$H_{\max}$	maximum enthalpy level allowed by customers
M	a relatively large number

Decision variables:

x_{jftpl}	binary variables indicating whether delivery chunk f is chosen and t is the start day of this delivery chunk for customer j using package stack pattern l and packaging material p
y_{jt}	binary variables indicating whether there is a shipment from the manufacturer to customer j on day t

Objective function:

$$\sum_{j\in J}\sum_{f\in F_2}\sum_{t\in T}\sum_{p\in P}\sum_{l\in L}(w_{H_{\max}-(f-2)\cdot\Delta H_{pl}}+v_p)\cdot\sum_{i=0}^{f-2}d_{j,t+i}\cdot x_{jftpl}+\sum_{j\in J}\sum_{t\in T}k_j\cdot y_{jt} \tag{3.2}$$

Subject to:

$$\sum_{j\in J}\sum_{f\in F_2}\sum_{p\in P}\sum_{l\in L}s_{H_{\max}-(f-2)\cdot\Delta H_{pl}}\cdot\sum_{i=0}^{f-2}d_{j,t+i}\cdot x_{jftpl}\le a_t \qquad \forall t\in T \tag{3.3}$$

$$\sum_{t\in T}\sum_{p\in P}\sum_{l\in L}x_{j1tpl}+\sum_{f\in F_2}\sum_{t\in T}\sum_{p\in P}\sum_{l\in L}(f-1)\cdot x_{jftpl}=T_0 \qquad \forall j\in J \tag{3.4}$$

$$d_{jt}\cdot\sum_{p\in P}\sum_{l\in L}x_{j1tpl}=0 \qquad \forall j\in J\ \ \forall t\in T \tag{3.5}$$

$$\sum_{f\in F}\sum_{p\in P}\sum_{l\in L}\sum_{i=1}^{f'-2}x_{j,f,t+i,p,l}\le M(1-\sum_{p\in P}\sum_{l\in L}x_{j,f',t,p,l}) \qquad \forall j\in J\ \ f'\in F_2\setminus\{2\}\ \forall t\in T \tag{3.6}$$

$$(t+f-2)\cdot x_{jftpl} \le T_0 \qquad \forall j \in J\ \forall f \in F\ \forall t \in T\ \forall p \in P\ \forall l \in L \tag{3.7}$$

$$\sum_{f\in F}\sum_{p\in P}\sum_{l\in L} x_{jftpl} \le 1 \qquad \forall j \in J\ \forall t \in T \tag{3.8}$$

$$\sum_{f\in F_2}\sum_{p\in P}\sum_{l\in L} x_{jftpl} = y_{jt} \qquad \forall j \in J\ \forall t \in T \tag{3.9}$$

$$\sum_{i=1}^{f-2} d_{j,t+i}\cdot x_{jftpl} \le g_j \qquad \forall j \in J\ \forall f \in F\ \forall t \in T\ \forall p \in P\ \forall l \in L \tag{3.10}$$

$$[H_{\max} - (f-2)\cdot \Delta H_{pl} - H_{\min}]\cdot x_{jftpl} \ge 0 \qquad \forall j \in J\ \forall f \in F_2\ \forall t \in T\ \forall p \in P\ \forall l \in L \tag{3.11}$$

$$x_{jftpl}\cdot\left(l - \frac{d_{j,t+f-2}}{m}\right) = 0 \qquad \forall j \in J\ \forall f \in F\ \forall t \in T\ \forall p \in P\ \forall l \in L \tag{3.12}$$

$$\sum_{p\in P}\sum_{l\in L} x_{jftpl} = \sum_{p\in P}\sum_{l\in L} x_{j,f,t+7,p,l} \qquad \forall j \in J\ \forall f \in F\ \forall t \in T: 1 \le t \le T_0 - 7 \tag{3.13}$$

$$x_{jftpl} \in \{0,1\} \qquad \forall j \in J\ \forall f \in F\ \forall t \in T\ \forall p \in P\ \forall l \in L \tag{3.14}$$

$$y_{jt} \in \{0,1\} \qquad \forall j \in J\ \forall t \in T \tag{3.15}$$

In the above formulation, the objective function (3.2) aims to minimize the total cost, consisting of production costs, packaging cost and transportation cost. Note that the production cost depends on how many days of demand are to be covered, and how the products are packaged and loaded, as this affects the required starting enthalpy level of the products. This is represented in the index for the production cost parameter, and calculated by $H_{\max} - (f - 2)\Delta H_{pl}$. Constraints (3.3) enforce the production capacity constraints where capacity use depends on the same enthalpy level as used in the objective. Constraints (3.4) make sure that the total number of days covered by delivery chunks equals the number of days in the planning horizon. Constraints (3.5) reflect that delivery chunk ‘0’ can only be chosen when the demand of that day equals to 0. Constraints (3.6) represent that there are no overlap delivery chunks, which means any two delivery chunks cannot cover a specific day’s demand together. Constraints (3.7) mean that the last delivery chunk chosen cannot be out of the range of the planning horizon. Constraints (3.8) enforce that exactly one packaging material and one package stack pattern are selected for the product produced on one day for one customer. Constraints (3.9) reflect that there should be shipments from production site to customers if we need to satisfy the customer’s demand on that day. Together, constraints (3.4) to (3.9) also guarantee that all the customers’ demand will be produced and distributed. Constraints (3.10) enforce the customers’ storage capacity constraints. Constraints (3.11) make sure that the enthalpy is within the range. Constraints (3.12) enforce the package stack pattern to use for a specific customer, on a specific day with a fixed delivery chunk. Constraints (3.13) represent those deliveries to a customer happening on the same days every week. In practice, such deliveries on the same days every week may be preferred, but without constraint (3.13), we can also allow deliveries to a customer on different days every week resulting in a more flexible solution. Finally, constraint (3.14) and (3.15) are binary variable constraints.

3.4 Experimental design

Typically, products are then distributed in a cold chain operating at a similar temperature as super chilling (e.g. Duy Bao et al. 2007; Dunn and Rustad 2007). However, this would require the operation of a special chain in addition to the existing cold chains and frost chains, including new, dedicated equipment. Our study therefore investigates whether the super chilled food products can be distributed in the conventional cold chain at +5°C. The super chilling process freezes a significant part of the water in the food product, and thereby creates a "thermal buffer" in the product, providing most of the aforementioned benefits without the need of a super-chilled chain. The challenge in the planning of production and distribution is then to make sure the product has not completely thawed before it is used by the satellite kitchens, as that would significantly increase the rate of quality degradation.

3.4.1 Distribution network

Here, we report our computational results for ten randomly generated networks of satellite kitchens which resemble our experiences with satellite kitchens in the greater Copenhagen area. In these networks, a single manufacturer produces pre-fried vegetables that can be packed either in cardboard boxes or in polystyrene boxes. There are 20 customers (institutional kitchens) served by this manufacturer in each network.

The distances from the kitchens to the manufacturer are generated according to two discrete uniform distributions $U[1,5]$ and $U[6,10]$ representing nearby kitchens and far away kitchens respectively. Every kitchen has 50% chance to be a far away kitchen or a nearby kitchen. For the sake of simplicity, we assume that all demands are multiples of 10kg. To reflect various types of the institutional kitchens, we divide them into large kitchens serving around 350 meals per day, where the daily demands for pre-fried vegetables are randomly selected from set $\Omega_1=\{60,70,80\}$, and small kitchens serving around 150 meals per day, where daily demands for pre-fried vegetables are randomly selected from set $\Omega_1=\{10,20,30,40,50\}$. Again, every kitchen has 50% chance of being either large or small. In reality, some institutional kitchens would not work on Saturdays or Sundays (schools, workplace canteens), which is also reflected in our experimental design. Large kitchens have 50% chance to work both on Saturdays and Sundays or work only on Saturdays, while small kitchens have 50% chance to work only on Saturdays or close during weekends. The planning horizon we consider is 6 weeks. Table 3.1 gives an overview of the customers in one of the datasets.

Table 3.1 General characteristics of customers (Y: there is demand on the day mentioned).

Customer	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Large or Small	S	S	L	L	S	L	L	L	L	L	S	S	S	S	S	S	S	L	S	L
Near or Far	N	N	N	N	F	F	F	N	F	F	N	N	F	F	N	F	N	F	F	N
Distance in units	2	1	3	2	7	7	7	2	9	8	1	4	9	9	5	7	1	8	10	1
Saturday	-	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	-	Y	Y	-	-	-	Y	Y	Y
Sunday	-	-	Y	-	-	Y	Y	-	-	Y	-	-	-	-	-	-	-	-	-	-

Table 3.2 Enthalpy changes (kJ/kg) per day for cardboard boxes and polystyrene boxes (ΔH_{pl}).

Number of boxes (l)		1	2	3	4	5	6	7	8
ΔH_{pl}	Cardboard box (p=1)	68	59	58	52	50	46	43	38
	Polystyrene box (p=2)	39	34	33	29	28	25	24	21

3.4.2 Cost considerations

In terms of production cost, we mainly focus on the freezing cost for super chilling the food products, referring to energy requirements for super chilling. Other costs, such as raw material costs would be the same and are therefore not considered in our model. In determining the super chilling costs, we have to take the thermal characteristics of freezing processes into account. As mentioned in section 3.3.1, the processing time is proportional to the change in enthalpy. Hence, freezing time could be calculated for a specific enthalpy level. The super chilling cost is then assumed to be proportional to this freezing time, as we are utilizing our processing equipment for a given time.

We have two packaging material choices: cardboard and polystyrene. The cost of polystyrene boxes is much higher than that of cardboard boxes, but it might be reused. Therefore, we assume the polystyrene box is only 10% more expensive than the cardboard box.

Aggregated transportation costs are based on straight-line distances in the distribution network.

3.4.3 Enthalpy changes

Parameter values in relation to the thermodynamic aspects of super chilled food products are based on the spreadsheet model described in and provided by Adler-Nissen and Zammit (2011). The basic data we use to illustrate the planning model presented in this paper are as follows. The dimensions of packaging boxes are 0.38m×0.28m×0.20m containing 10kg pre-fried vegetable and the thickness of cardboard box is 0.003m and polystyrene box is 0.010m. The corresponding surface area of one box is 0.477m^2. In our experiment, we define the base area based on the dimensions of typical roll containers used in the food service industry to be 0.6m×0.8m. Based on the package stack patterns introduced in section 3.3.3, the box surface areas, and typical enthalpy values for a super-chilled product, we can calculate the daily enthalpy changes for 1 to 8 boxes stacked together – for both cardboard boxes and polystyrene boxes. The results are shown in Table 3.2 and are used in the model as parameters.

3.5 Experimental results

The experiments were performed on a computer with an Intel Core 2 Duo T8300 CPU and 4GB RAM. The models were implemented using ILOG's OPL Studio 6.0 as a modeling environment and its incorporated standard optimization software CPLEX 11.1. The model without constraints (3.13) (flexible deliveries to customers) could be solved within 2 minutes for all ten datasets where the average running time is 73 seconds. With constraints (3.13), the average running time for the ten datasets is 15 minutes and the longest running time is 70 minutes, which would still be acceptable for planning problems with this time horizon.

3.5.1 General results

To illustrate the results generated by the model, we first solve the model without constraints (3.13). The resulting deliveries to two of the customers from one dataset are shown in Table 3.3 and Table 3.4. From the tables we see that polystyrene boxes are used three times by customer 1 which is a small and nearby customer. Because the demands are less and the number of deliveries is low, the polystyrene box is a better choice, as it allows for a longer storage time. Customer 6 is a large and far away customer, and because of the higher demand per day, several cardboard boxes stacked together seem enough to slow down the thawing process.

Table 3.3 Delivery chunks for customer 1 from dataset 1.
(C: cardboard box; P: polystyrene box; weekends marked in gray)

Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Delivery and Package	C	C	-	-	-	-	-	P	-	-	-	-	-	-
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	P	-	-	-	-	-	-	C	-	C	-	-	-	-
	29	30	31	32	33	34	35	36	37	38	39	40	41	42
	P	-	-	-	-	-	-	C	-	C	-	-	-	-

Table 3.4 Delivery chunks for customer 6 from dataset 1.
(C: cardboard box; P: polystyrene box; weekends marked in gray)

Days	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Delivery and Package	C	-	-	C	-	-	-	C	-	-	-	C	-	-
	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	-	C	-	-	-	C	-	-	-	C	-	-	-	C
	29	30	31	32	33	34	35	36	37	38	39	40	41	42
	-	-	-	-	C	-	-	-	-	C	-	-	-	-

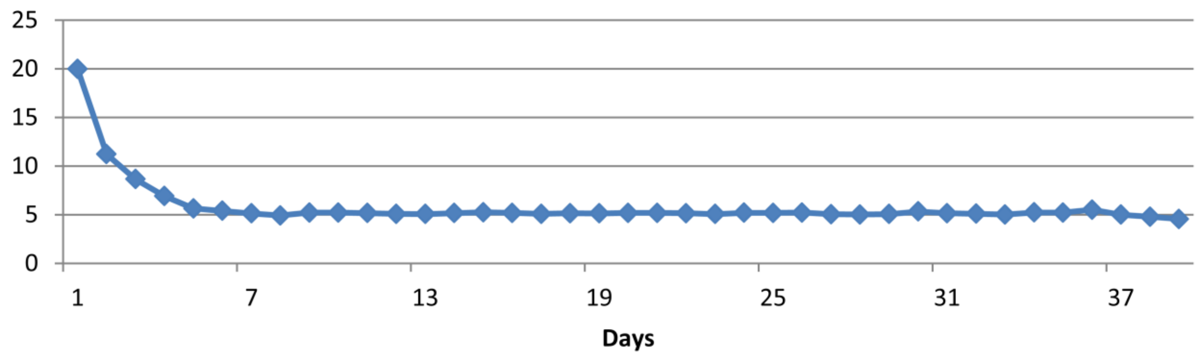

Figure 3.4 Moving averages for numbers of deliveries per day for 10 datasets.

It should be noted that the model starts on day one with an empty system which means there is not any stock at the kitchens before the planning started. This leads to deliveries to all the customers on the first day and more frequent small deliveries at the beginning of the planning horizon. In practice, there is always some stock when we start a planning. For further analysis, we would like to study the system in a steady state. To determine when the system turns into a steady state, we adopted the commonly used Welch's procedure from simulation methodology to decide on a warm-up period (cf. Law 2007). The resulting moving averages for numbers of deliveries per day for all 10 datasets are shown in Figure 3.4.

After the first week, the moving averages for numbers of deliveries per day are stable. For the remaining analysis, we therefore neglect the first week. Similarly, the last week is neglected because the plan will again result in an empty system. This means that, for the discussion below, a six-week period was considered, where the first and sixth week were neglected in the analysis.

3.5.2 Effect of fixed delivery pattern on starting enthalpy and delivery interval

In the following experiments, two scenarios are tested. A flexible delivery pattern in which we allow the deliveries to a customer in one week to be on different days than in other weeks, and fixed delivery pattern in which we enforces deliveries should to be on the same days in every week for a customer. For instance, the deliveries to customer 1 from dataset 1 with fixed delivery pattern are shown in Table 3.5.

Table 3.5 Delivery chunks for customer 1 from dataset 1 from week 2 to week 4 using fixed delivery pattern. (C: cardboard box; P: polystyrene box; weekends marked in gray)

Days	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Delivery and Package	C	-	-	C	-	-	-	C	-	-	C	-	-	-

22	23	24	25	26	27	28	29	30	31	32	33	34	35
C	-	-	C	-	-	-	C	-	-	C	-	-	-

The deliveries are on Monday and Thursday of every week. There are two deliveries per week instead of the (on average) 1.25 deliveries per week found in the solution for the flexible delivery pattern (Table 3.3). All the deliveries are using cardboard boxes instead of some polystyrene boxes in the previous solution. The reason is that, compared with the flexible delivery pattern, the fixed delivery pattern requires more frequent deliveries which means fewer days between two deliveries. In turn, this means that additional investment in more insulating packaging is not required. In total, the average number of deliveries to all the customers in the fixed delivery pattern is 18.28% more than that in the flexible delivery pattern. On the other hand, because there are fewer days between two deliveries, the average starting enthalpy of the food product of all the ten datasets is in general higher in a fixed delivery pattern, which is 268.38 kJ/kg in our experiment, compared with 241.04 kJ/kg in a flexible delivery pattern. This reflects a higher product temperature, and thus a saving in terms of production cost due to reduced super chilling costs.

3.5.3 Effect of enthalpy tracking approach

In case the enthalpy change is not tracked during production and distribution, we cannot plan our production and distribution network according to enthalpy restrictions and have to work with rough temperature estimates. To illustrate the value of using the enthalpy information, we compared the model with enthalpy tracking with a model without enthalpy tracking. We assume that all the food products are super chilled for an average time at manufacturing site down to −2°C. In case the product is packed in one cardboard box, according to the ΔH_{pl} calculations in section 3.4.3, it takes 2.1 days for the temperature of the food product to increase from −2°C to −1°C. Hence we assume the product can only be stored at most two days which is a conservative estimation at customer sites to guarantee the food quality. Since one box standing alone for several days rarely happens, and this likely overestimates the temperature increases, another scenario is also considered here that allows the product to be stored at most three days at customer sites. The comparison results are shown in Table 3.6.

The average utilization levels of the freezing tunnel without enthalpy tracking are around 15.50% higher than the utilization level of the model with enthalpy tracking. This implies significantly higher production efficiency in the case of enthalpy tracking, freeing up production capacity that can be used for other products. As for total cost, both models without enthalpy tracking have much

Table 3.6 Average relative changes (in %) to the model with enthalpy tracking for all ten instances.

	Model without enthalpy tracking					
	at most 2 days storage			at most 3 days storage		
	Highest	Average	Lowest	Highest	Average	Lowest
Number of deliveries per week	+80.29%	**+73.49%**	+61.44%	+24.82%	**+20.50%**	+11.76%
Production capacity utilization	+25.37%	**+15.78%**	+6.77%	+24.73%	**+15.33%**	+6.04%
Total cost	+20.66%	**+19.20%**	+15.34%	+8.91%	**+7.31%**	+4.65%

higher cost, especially the model with conservative estimation, which is on average 19.20% higher than that of the model with enthalpy tracking. In relation to the number of deliveries per week, both models without enthalpy information require more deliveries to customers. With conservative estimation, the average deliveries are 73.49% more than that of the model with enthalpy tracking. The results are consistent across all ten problem instances. These results illustrate that the model with enthalpy tracking provides significantly more detailed information which helps to reduce production cost and the number of deliveries.

3.5.4 Effect of super chilling approach

As this paper investigates a new way of distributing food products, it is useful to compare the resulting delivery intervals with the delivery intervals that would be used in the typical distribution method used in practice. For food products, this is often chilled distribution, where the products are only chilled at the manufacturing site before distribution in the cold chain at +5°C. We furthermore assume three different scenarios in which all the products can only be stored at most one, two, and three days respectively. We should be aware that the storage time limits assumption here is different from that of the super chilling approach introduced before. In super chilling, the storage time is the time limit within which the product is still in partially frozen state, which means the product still has some time before it becomes unacceptable from a sensory, nutritional or safety perspective. In the chilling approach, the temperature of product will never be lower than 0°C, so the storage assumption here is more like the time period estimation for the product to become unacceptable.

Since chilling does not require the freezing tunnel, we only compare the solutions based on the number of deliveries. The chilling approaches provide optimal solutions for the ten instances with on average 5.9, 3.1, and 2.2 deliveries to one customer per week with at most 1, 2, and 3 days storage at customer sites respectively. It was expected that, using super chilling, the deliveries could be reduced because of the longer shelf life. These results demonstrate that the number of deliveries is actually reduced by one third compared with the conventional chilling approach with at most two days storage.

For all the results presented above, it should be noted that a reduction of the number of deliveries does not necessarily lead to equally-sized reductions in transportation costs. As multiple deliveries are combined in one or more delivery runs, the actual savings in transportation costs also depend on the combination of customers in efficient routes. However, the resulting vehicle routing problem is beyond the scope of this paper.

3.6 Conclusions and future research

This paper presents a modeling approach for the production and distribution planning of super chilled food products by integrating the thermodynamic behavior of super chilled food products into supply chain planning. A mathematical model to support decision making focused on several important planning decisions is proposed. These include the production quantities, the enthalpy level of the produced product, the packaging material, and the delivery intervals to the satellite kitchens. The model has been used to gain insight into the complex interactions between these decisions, and contributes to efficient supply chain planning for high-quality food products in the foodservice sector.

Delivering super chilled food products in the conventional cold chain prolongs the shelf life of the products (compared to chilled distribution). Next to demonstrating the superiority of supply chain planning based on enthalpy tracking, the numerical results also illustrate that production and distribution of super chilled food products is feasible and realistic. As such, super chilling provides the kind of technological development that Karaesmen et al. (2011) envision in relation to improving supply chain efficiency for perishable products. Furthermore, it is also expected to reduce product waste, which is a large problem in the foodservice sector (Darlington and Rahimifard 2006).

In the model presented in this paper, the worst-case scenario of enthalpy increase is considered (i.e. the largest possible increase), meaning that the tracking of enthalpy changes could be more precise. However, the major part of the enthalpy change occurs at the customers. Therefore, a conservative estimation is better, as it allows for possible disturbances at the satellite kitchens. Another limitation of our study is that only a local distribution network is considered, which means we assume that transportation from manufacturer to satellite kitchens can be performed on a single day. A future research direction is the expansion of the distribution network to a more complex network, including long-distance transportation through distribution centers. Then, the enthalpy changes during transportation and product handling at distribution centers also need to be considered.

The modeling efforts presented in this paper are mainly focused on the economic performance (through traditional cost minimization), whereas the overall objective in production and distribution networks might be an improvement of the overall sustainability of the network. Environmental performance is to some extent built into the new concept through the expected reduction of waste and the reduction in external cooling energy during transportation, but in future research, one could also focus on integrating environmental objectives in supply chain planning, so as to be able to illustrate the trade-offs between different performance measures, and hereby quantify the cost of environmental friendliness.

Chapter 4. Supply-chain-planning-based sustainability assessment

This chapter is based on the following research paper:
Wang, Y., Birkved, M., Akkerman, R., and Grunow, M. (2012) *Supply-chain-planning-based sustainability assessment: General framework and illustration for super chilled food products*.

Abstract

In this article, we present a framework integrating supply chain planning in sustainability assessment, illustrating how supply chain planning tools can be applied in the assessment of production and distribution operations. We use life cycle assessment for the modeling and quantification of the environmental impacts of supply chain planning results. Our proposed approach supplies consistent scenarios of the future and realistic parameter values, especially when an environmental assessment of future technologies is done, where it can be difficult to estimate production and distribution parameters for yet to establish supply chains. More specifically, we have used this framework to assess the sustainability of super chilled food products produced on industrial scale which is a new concept in food engineering. For several important production and distribution planning decisions such as temperature treatments and packaging materials, we evaluate the environmental impacts, hereby demonstrating the benefits of our integrated framework. Among others, trade-offs between the energy invested in the food products and the expected waste are investigated. We confirm that distributing super chilled food products in the conventional cold chain improves the sustainability of the supply chain mainly by reducing food waste.

4.1 Introduction

As discussed in Frischknecht et al. (2009), when doing environmental assessment of future technologies, challenges are the definition of consistent scenarios of the future and the data availability. We propose here that supply chain planning (SCP) can be used to generate valid scenarios and to provide parameters we cannot obtain empirically. The framework presented in this article allows us to compare the new concept with traditional production methods from an environmental perspective.

Traditionally, SCP is driven by minimizing costs or maximizing service-related measures. In recent years, researchers have also started to integrate environmental considerations in planning approaches, for example by adding environmental constraints to their models (e.g. Rădulescu et al. 2009; Subramanian et al. 2010), by developing multi-objective approaches taking into account both economic and environmental impacts (e.g. Quariguasi Frota Neto et al. 2008; 2009), or by using methods like simulation to evaluate trade-offs between economic and environmental performance in SCP (e.g. Van der Vorst et al. 2009; Akkerman and van Donk 2010). In order to evaluate the sustainability of supply chains, environmental assessment methods and tools have to be included. A commonly used environmental assessment method is life cycle assessment (LCA).

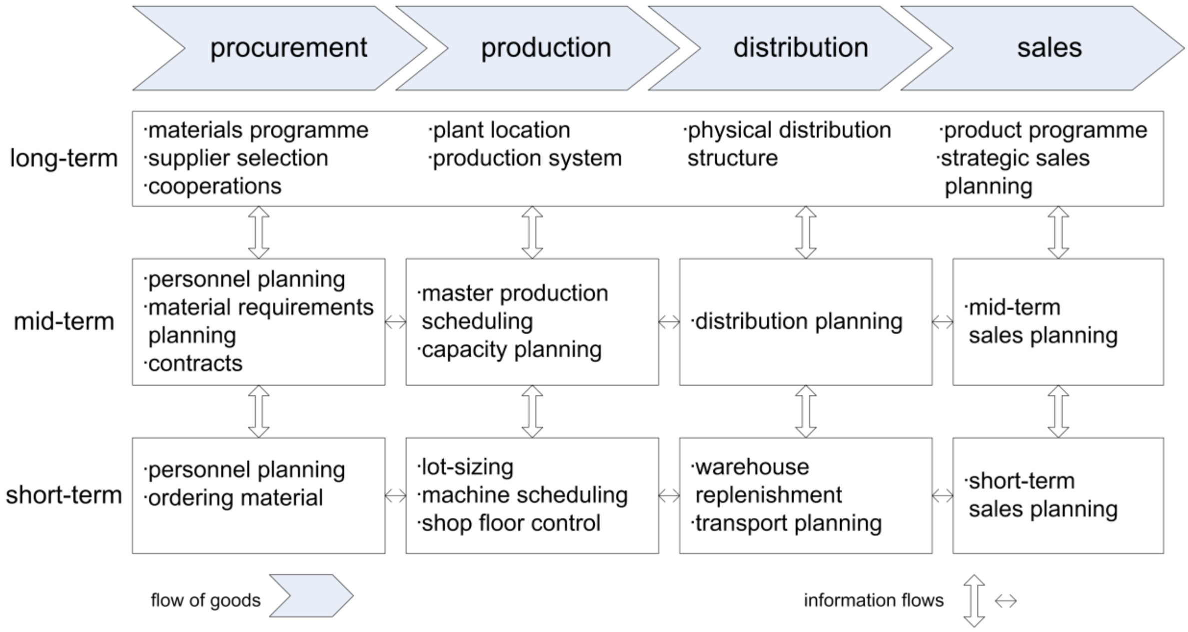

Figure 4.1 The supply chain planning matrix (Fleischmann et al. 2008).

Even though a considerable number of SCP approaches have started to include environmental aspects, the level of integration between the different research disciplines is still low. The main contributions of this article lie in (*i*) the development of a structured framework for SCP-based sustainability assessment, (*ii*) the illustration of this framework for super chilled food products, and (*iii*) the determination of the sustainability improvement obtained through the new technology in the food service supply chain.

After presenting our framework in the second section, we briefly describe our illustration for super chilled food products in the third section. The LCA results from the illustrative application of our framework are subsequently presented in the fourth section followed by a discussion and conclusions in the last section.

4.2 SCP-based sustainability assessment

4.2.1 Supply chain planning tasks

SCP coordinates the operations in a supply chain. According to the length of the planning horizon and the importance of the decisions to be made, SCP is usually classified into three different planning levels as shown in Figure 4.1. They range from long-term strategic decisions to short-term operational decisions. Long-term planning decisions create the prerequisites for the development of an enterprise/supply chain in the future. Mid-term planning decisions determine the outline of the regular operations, in particular rough quantities and timing for the product flows and resource usage in the given supply chain. Finally, short-term planning specifies all activities as detailed instructions for immediate execution and control of production and distribution operations (Fleischmann et al. 2008). These decisions are interrelated and require a variety of information flows between them. They influence both the economic and environmental performance of the supply chain.

4.2.2 Integrated framework

The framework applied in this article contains two main elements: an SCP model and an LCA model. LCA is a tool for evaluating the environmental impact associated with a product, process or activity during its life cycle (Berlin 2003). SCP and LCA have some similarities: both of them normally involve all the parties from raw material production to end customers and relate to assessing the way in which a customer request is fulfilled. Both models rely upon similar model parameters. For example, in a food production system, processing times, temperatures and production yields are required as inputs. These parameters affect both the operations in the supply chain and the result of the environmental assessment.

For LCA, data collection is a resource-demanding step. Some model parameters can be measured directly (e.g. distance, cargo weight) whereas other parameters are obtained from alternative sources like unit process databases. We propose here that when doing an LCA for a supply chain, parameters that depend on how production and distribution operations are planned should be derived from an SCP model. Several reasons for this exist. First, the outcome of the planning tasks shown in Figure 4.1 has a major impact on the environmental performance assessed in an LCA. For example, the plant location and physical distribution structure will affect the evaluation of the energy consumption during production as the energy mix will usually be different for different locations. Additionally, the fuel usage for transporting products from production sites to end customers is affected. Second, all planning decisions are interrelated and should therefore be considered in a comprehensive manner in order to define consistent scenarios. Supply network planning decides for example on the way products are produced, stored, and transported throughout the supply chain, directly affecting the waste during production, the energy use during storage, the fuel consumption during transportation, and so on. By fixing some of the supply chain decisions, for example the choice of the production technology at the production site, different consistent supply chain scenarios can be defined. Using an SCP modeling approach, we can determine the production and distribution options in the different scenarios, leading to realistic parameter values on, for example, the number of deliveries and the amount of product in storage, which can in turn be used as input parameters in the LCA model. Finally, as mentioned earlier, when doing environmental assessment of future technologies, an SCP model can help us to obtain parameters that we cannot obtain empirically. The proposed framework is illustrated in Figure 4.2 where the dashed boxes contain examples of relevant parameters.

Figure 4.2 also contains a line going back from the sustainability assessment to the SCP model. This illustrates that the assessment results can be used as environmental parameters in the SCP model, next to the typical economic parameters. Feeding back the LCA results into SCP has several

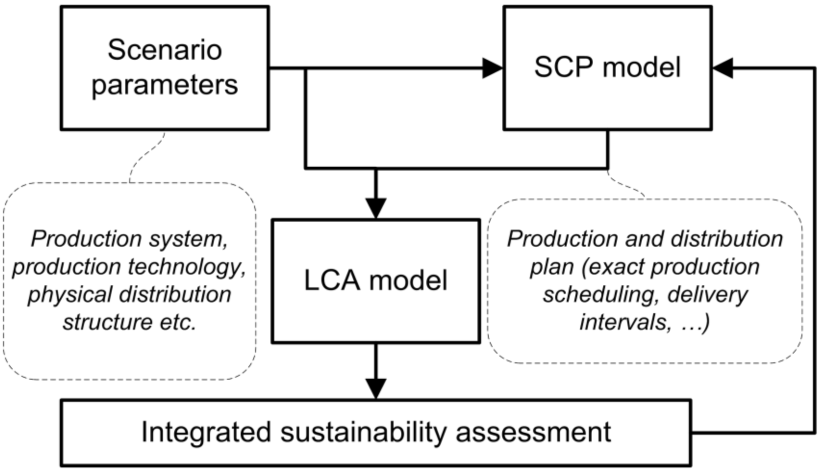

Figure 4.2 Supply-chain-planning-based sustainability assessment, including parameter examples.

advantages. First, doing an LCA of the whole supply chain helps us to obtain sustainability data of good quality, which can be used as parameter inputs to the SCP model. This would extend the focus of SCP beyond only costs, and enable multi-criteria decision making. Second, from the LCA results, we have a clear picture of the environmental impact of the individual activities along the supply chain. This knowledge can help us in identifying and focusing on the more impact-heavy activities, which is useful in keeping the complexity of the SCP model at a manageable level. Finally, LCA also provides information on the level of different impact categories, which supports the decision making on the importance weighting of the various environmental impact categories in multi-criteria decision making.

As such, this framework results in an iterative approach. The new SCP model includes environmental considerations in a new production and distribution plan, which might again lead to improved environmental performance and possibly updated environmental parameters. The iterative aspect of this framework combines well with the traditional LCA approach, which is also iterative in nature (Hauschild et al. 2005). In general, this framework can help decision makers better evaluate the supply chain, not only from an economical and service-level perspective but also from an environmental perspective. To illustrate the framework, we applied it to a foodservice supply chain. The results presented below illustrate the first stage of the first iteration: the use of SCP results in the LCA.

4.3 Illustration of SCP-based sustainability assessment

Sustainability is one of the main challenges in today's food supply chains (Akkerman et al. 2010). Integrating sustainability in food supply chain management requires multidisciplinary research efforts – combining for example management approaches, production technology, food engineering, and environmental studies. LCA studies have also been performed relatively widely (Roy et al.

2009). Only very limited research is however done on food service products. Two recent exceptions can be found in Zufia and Arana (2008) and Baldwin et al. (2011).

To illustrate the framework described in the previous section, we show how a well-known LCA tool such as the product system modeling platform GaBi (PE 2010) can be used to quantify the environmental impacts related to specific production and distribution decisions resulting from SCP in an example supply chain. Furthermore, the case investigated in this article is based on a new food engineering concept for the food service industry which has not yet been implemented in today's practices.

The production and distribution concept used as an illustrative case in this article aims at improving the overall sustainability of the supply chain for meals produced in large-scale production units such as hospital kitchens or nursing homes. Meal elements are produced industrially and distributed to these kitchens, where the kitchen staff can combine them into complete meals. Examples are pre-fried meat pieces and frozen or pre-processed vegetables.

To preserve the quality of food products and extend their shelf life, two treatments are typically applied. One is freezing, which implies that the pre-processed products are frozen to around –30°C and stored at around –25°C before distribution. The other one is chilling, using a temperature around +2°C to +5°C to chill the pre-processed products followed by distribution in the cold chain at a similar temperature. The latter is increasingly used in today's retail and foodservice industries and therefore used in our analysis as a baseline scenario. In the production and distribution concept evaluated here, the main idea is to super chill food products at production, meaning freezing the product to a temperature slightly below its initial freezing point (which, for instance, for vegetables, is around –1°C) and to subsequently distribute them in the conventional cold chain at +2°C or +5°C. As opposed to chilling, super chilling freezes part of the internal water which then acts as a refrigeration reservoir and leads to prolonged product shelf life (see also Adler-Nissen et al. 2012; Jensen et al. 2010; Wang et al. 2012b). This is expected to lead to a decrease in wasted product and to a more sustainable distribution system.

4.3.1 SCP model for super chilled food products

In the production and distribution of food products, the choice of temperature treatments (here: chilling or super chilling), the determination of delivery intervals and the choice of packaging materials are the main mid-term SCP decisions. The delivery intervals will affect the transportation costs and the quality deterioration of the food products. If we would for instance choose to decrease the number of shipments and increase shipment volumes, we increase the transportation efficiency; however, part of the shipments would have to be stored at the customers, leading to quality degradation of the food products. It should be noted that the storage capacity at customers is often limited, potentially limiting the increases in shipment size. Yet, if super chilling is able to reduce quality degradation, an opportunity to improve economic performance without affecting product quality is created. As for packaging materials, choosing polystyrene boxes would slow down the

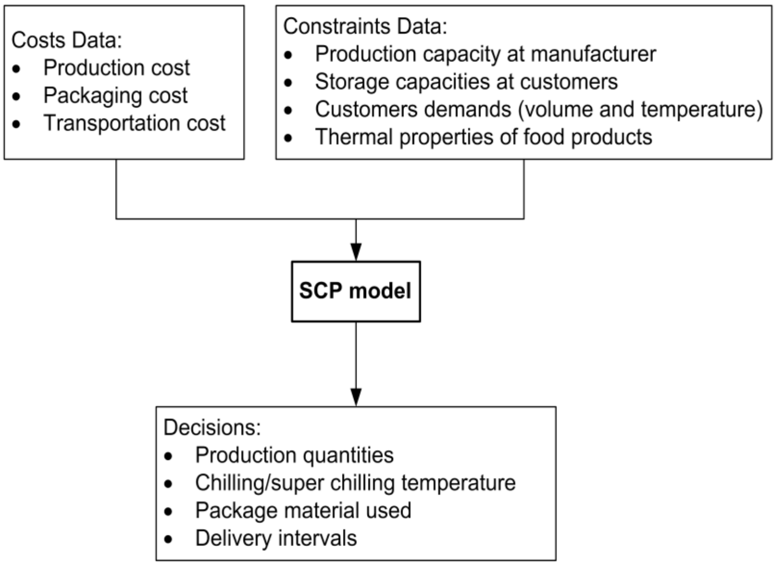

Figure 4.3 Schematic overview of the supply chain planning model.

temperature increase (and thereby quality degradation) after super chilling, due to better insulation. The material is on the other hand more expensive than ordinary cardboard, but the boxes can possibly be reused. Cardboard boxes, in contrast, cannot be reused after having been wetted by the thawing process of the food products.

In previous work, we have developed a mathematical programming approach to support decision-making on these decisions (Wang et al. 2012b). The structure of the supply chain planning model is illustrated in Figure 4.3. In the present article, we use this model to determine the cost-optimal production and distribution plan. We use the model to generate consistent supply chain scenarios based on different processing methods and different packaging materials, as the choice of these is expected to have a significant effect on the economic and environmental performance of the chain. Therefore, some of the decisions in relation to the choice of temperature treatments and packaging material are fixed before solving the model. For each of the scenarios, supply chain planning then leads to a set of supply chain parameters that will subsequently be used in the LCA model. For instance, one of the scenarios we consider in this article makes use of cardboard as a packaging material and uses chilling as a temperature treatment. By solving the SCP model, we obtain a cost-optimal solution that can be translated into input parameters required for the LCA model, that is the number of deliveries to customers, the amount and time the products need to be stored at customers' sites, and the shelf life of the products. In total, there are four supply chain scenarios considered in this article: (i) cardboard packaging and chilling (Card/C), (ii) polystyrene packaging and chilling (Poly/C), (iii) cardboard packaging and super chilling (Card/SC), and (iv) polystyrene packaging and super chilling (Poly/SC). The four scenarios yield different input parameters for the LCA model.

4.3.2 LCA model for super chilled food products

To quantify the impact potentials of a food product supply chain over its entire life cycle, a product system model was developed for the case of pre-processed vegetables. The presented product system model was modeled in GaBi 4 (PE 2010) applying data both from the GaBi professional database (PE 2010) and the EcoInvent 2.0 database (SCLCI 2007) and is illustrated in Figure 4.4.

The model consists of two parts: a processing part and a distribution part. Before processing, raw materials are transported directly from the farmers to the processing site. The raw materials are hereafter treated in three stages. In the first stage the raw materials are prepared (for example peeled or cut) and cooked followed by a chilling to +5°C or a super chilling to –1.5°C. In the second stage the products are bagged in polypropylene bags. In the third stage the bags containing the products are packed in either cardboard boxes or polystyrene boxes. The combination of the different processing methods at the first and third meal processing stages (dashed edge boxes in Figure 4.4) yields the different supply chain scenarios. The boxes containing the products are then distributed to the customers; in this case the institutional kitchens. Here, the products are put in cold storage and are unpacked and prepared for consumption when needed. The parameters in relation to distribution and storage at customers are mainly derived from the solution of the SCP model (shown in Figure 4.4 as boxes with bold edges). Based on the solution of the SCP model, we know the daily distribution plan, containing the customers that are served on each day. We assume that these customers are served in an optimized, pre-defined sequence. Based on this information, we can calculate the amount of food products distributed to every customer and the storage amount and duration at customers before use. At the customers, 4 types of waste are included in the model: food waste, cardboard, polystyrene and polypropylene. Except for the polystyrene, all waste is discarded at the customers and incinerated at municipal incineration plants with (material-specific) energy recovery. The polystyrene boxes are collected by the distributing trucks and transported back to the processing plant, where the reusable boxes are cleaned and those boxes not suited for reuse are discarded and also incinerated at municipal incineration plants with energy recovery.

One important assumption made in the product system model is the average waste rate of food products at customer sites. Different scenarios have different waste rates because the shelf life of the food products after either chilling or super chilling, and packaging in either cardboard boxes or polystyrene boxes, are different. Scenario Card/C, which is current industrial practice, has 5% as the average waste rate (Banks and Collison 1983; Collison and Colwill 1987). Food products in scenario Poly/C have the same shelf life as in scenario Card/C, because for both scenarios the product temperature is identical to the temperature in the storage environment; hence we assume the products in scenario Poly/C have the same average waste rate as in scenario Card/C. In scenario Card/SC, super chilling down to −1.5°C extends the shelf life of the products. It takes more than 1.5 days for one cardboard box of vegetable product standing alone to thaw to the same temperature as chilling (for thawing process calculations, we refer to Wang et al. 2012b). Due to the shelf life prolongation, storage capacity at the customer often replaces shelf life as a limiting factor for shipment size in the SCP model. Hence we assume the average waste rate is reduced to 2%, as in

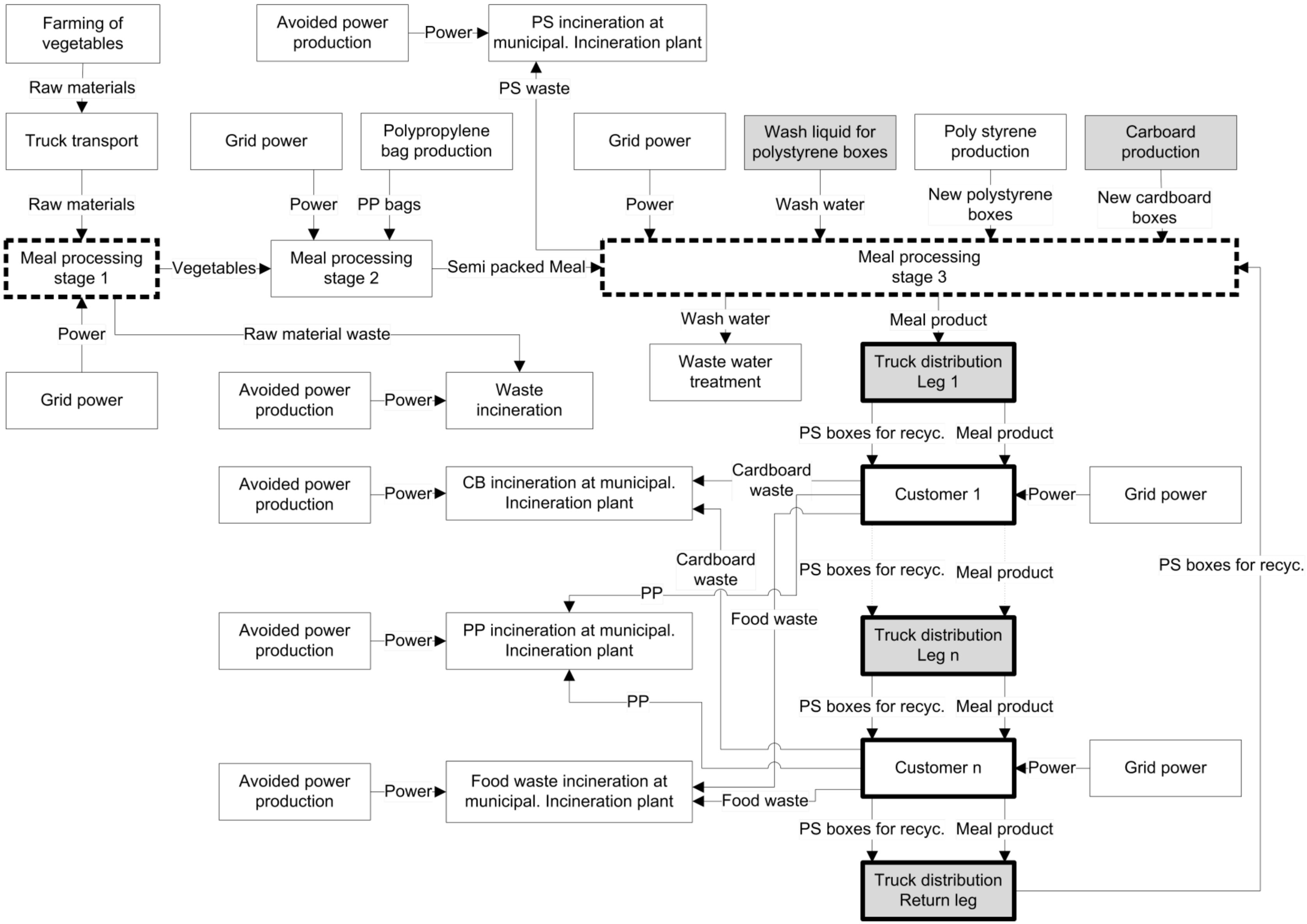

Figure 4.4 Overview of the product system model. (White boxes are standard and tailored unit processes, and grey boxes are case specific tailor-made sub-models. CB=cardboard, PP=polypropylene, PS=polystyrene.)

most cases, products will be used at the customers and stocks are replenished long before shelf life becomes an issue. The same principles apply to the Poly/SC scenario. Here, by using better insulating packaging material, the thawing process of vegetable product takes even longer than when using cardboard packaging. Waste due to expired shelf life hence becomes even less significant (1%). It is important to realize that wasted products leads to a larger required volume of raw materials.

The LCA model has a number of limitations. First of all, it has not been possible to include the water consumed and hence the waste water generated in the product preparation; it has however been possible to include water used for cleaning of the reused polystyrene boxes. Secondly the transport needed for the packaging material (from packaging material producer to vegetable processing site) is not included due to lack of information on the origin of the packaging material. Thirdly only raw material waste generated in the first processing stage and the food waste generated in the receiving kitchens preparing the products for consumption has been included, the uneaten part (consumption waste) of the final meals is not included. The waste ratios generated in the receiving kitchens in the four scenarios are mainly derived from comparisons between the shelf life of the meal elements and the storage capacities of the kitchens. These limitations are however not expected to influence the final and relative results to any noticeable extent.

4.4 LCA Results

4.4.1 General results for the four supply chain scenarios

The Life Cycle Impact Assessment (LCIA) of the product system presented in Figure 4.4 was carried out by applying the EDIP methodology (Hauschild and Wenzel 1998), and the EDIP 1997 characterization factors, normalization references and weighting factors for the impact assessment (Wenzel et al. 1997; Hauschild and Wenzel 1998). The functional unit was 'distribution of 23,000 kg of pre-processed vegetable food products'. This unit was chosen as it represents a monthly distribution volume to 20 institutional kitchens, which was considered to be a reasonably sized network for the introduction of the new technology.

The normalized and weighted results of the LCIA are grouped in three impact category groups, and are presented in Table 4.1 for all considered scenarios (for detailed LCIA results, please refer to Table S1.1-S1.4 in the supporting information). The 'environmental impact evaluation' is the aggregated impact of the acidification, global warming, nutrient enrichment, ozone depletion and

Table 4.1 Overall LCIA results for all considered scenarios.

	Scenarios			
Impact group	*Card/C*	*Poly/C*	*Card/SC*	*Poly/SC*
EDIP 1997, Env. imp. eval. (Unit:PET W, EU 2004)	24.43	24.18	23.36	22.59
EDIP 1997, Toxicity eval. (Unit:PET EU 2004)	74.44	69.15	71.63	65.27
EDIP 1997, Res. eval. (Unit:PR W 2004)	1.81	1.71	1.75	1.64

photochemical oxidation potentials. The 'toxicity evaluation' consists of six aggregated toxicological impact potentials covering chronic soil ecotoxicity, acute and chronic ecotoxicity in water and human toxicity by exposure through water, soil and air. The 'resource evaluation' consists of the resource depletion potentials of 32 metals and fuels.

Table 4.1 indicates that the Poly/SC scenario has the most desirable environmental impact profile (lowest impact in all the 3 included impact category groups), and the Card/C scenario has the least desirable impact profile (highest impact in all the 3 included impact category groups). When comparing super chilling scenarios with chilling scenarios, both Poly/SC and Card/SC have improvements on sustainability aspects. For cardboard packaging, super chilling reduces the environmental impacts with around 4%. For polystyrene, the figure is close to 7%. This confirms that the new concept of distributing super chilled food products in the conventional cold chain does improve the sustainability of the whole chain.

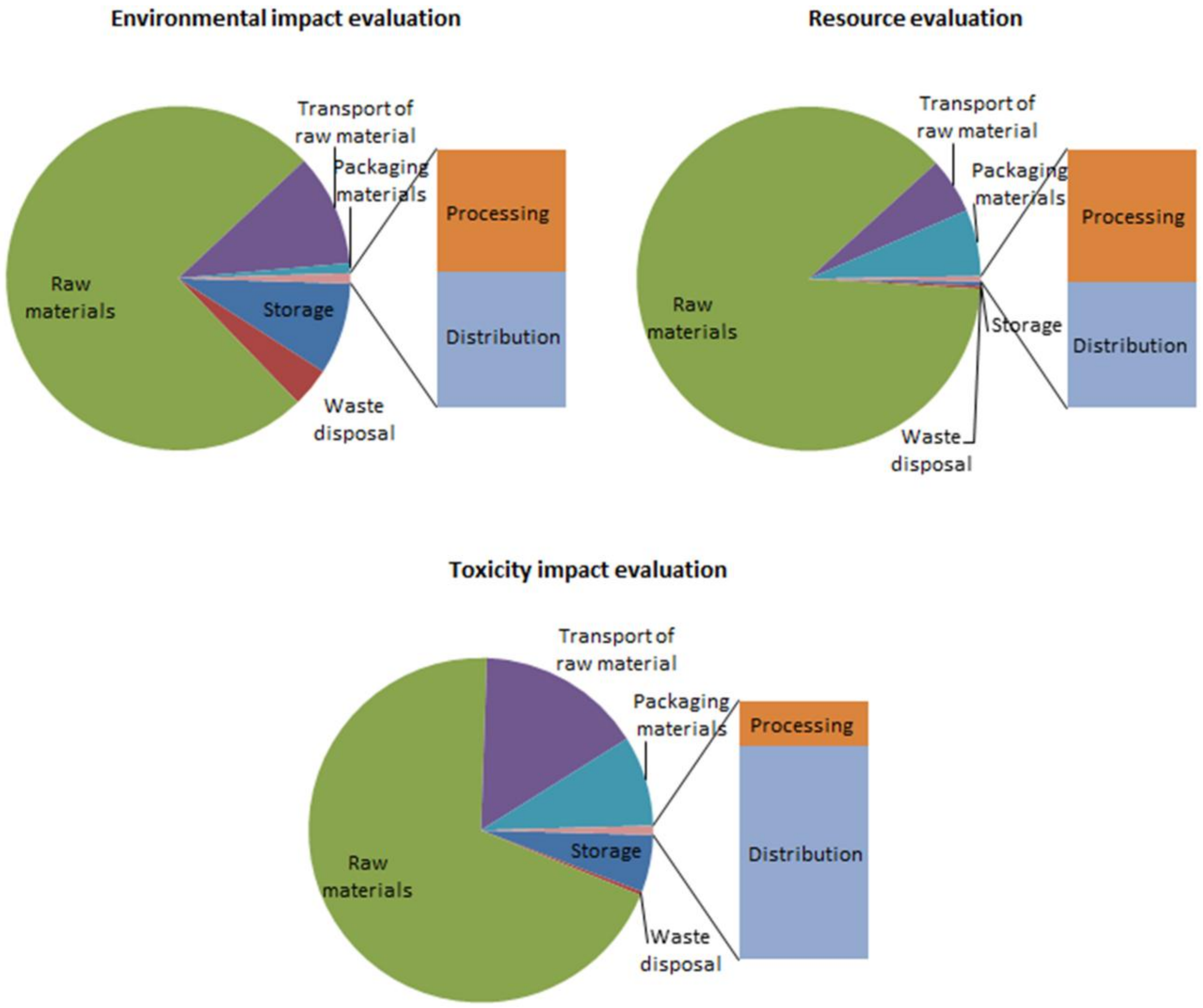

Figure 4.5 Relative LCIA contributions of the different activity types for scenario Card/C (for all impact categories).

To illustrate how the different supply chain activities contribute to the LCA results, Figure 4.5 shows the relative contributions of the different activities for scenario Card/C (the other scenarios show similar patterns). It is clear that raw material production and the transport from farms contribute the most to all impact category groups. Accordingly, the improvements obtained in the super chilling scenarios are mainly due to reduction of food waste by prolonged shelf life which reduces the 'environmental burden' of raw materials production and transportation. As production and transport of raw materials plays such a dominant role, the scenario which shows the least waste of raw material has the most desirable impact profile. The reduction of wasted raw material due to shelf life prolongation leads to situations where the storage capacity at the kitchens replaces shelf life as a limiting factor in the SCP model. Hence, the products more often get used before they expire.

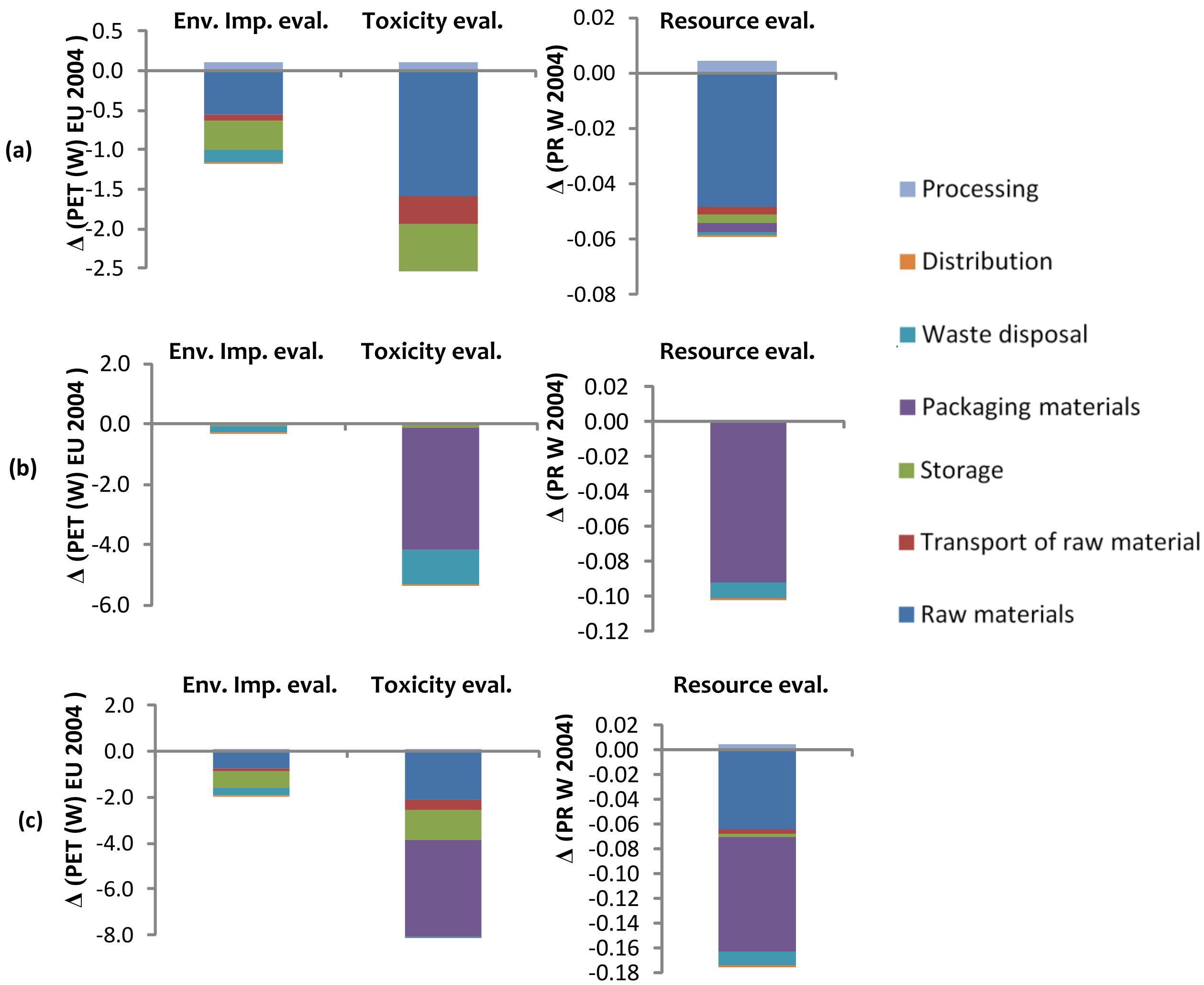

Figure 4.6 Results of the Δ-LCA for (a) scenario Card/SC, (b) scenario Poly/C, and (c) scenario Poly/SC (with Card/C as the reference scenario).

This is further illustrated in Figure 4.6, which shows the results of a Δ-LCA for scenarios Card/SC, Poly/C and Poly/SC. A Δ-LCA only includes the differences with a reference case, and is useful in assessing new technologies (Wenzel et al. 1997). As reference case, we used scenario Card/C, as this is the current industry practice. These Δ-LCA results allow us to study the effects of packaging material and temperature treatment separately. From the results for Card/SC in Figure 4.6(a), we can see that the additional impacts in processing due to the more extensive temperature treatment in super chilling compared to chilling are more than compensated for by reduced impacts related to raw materials and their transport. The Δ-LCA results for Poly/C, as seen in Figure 4.6(b), show that polystyrene is contributing considerably less than cardboard, partly due to a larger consumption of cardboard compared to polystyrene, because cardboard is heavier and not recyclable (contrary to polystyrene boxes). The impacts related to the combustion of used cardboard are mainly emission of greenhouse gases (CO_2 and CO) and various toxic compounds (e.g. dioxins, PAHs) created during the combustion process. From the results for Poly/SC in Figure 4.6(c), we can see that the improvement in terms of sustainability gained in the Poly/SC scenario is a combination of the individual effects of the choice of temperature treatment and packaging material.

In the interpretation of the LCIA results it is essential to realize that a large part of the impacts are the same for all scenarios (e.g. most of the raw material impact is for products that are actually consumed). This part of the impacts is therefore fixed; however, in the way the food is provided the relative difference in the impacts are actually large. Considering the size of the foodservice sector, the cumulated reductions could be substantial.

4.4.2 Sensitivity analysis

The waste rate of food products and the recycling rate of polystyrene boxes play an important role in the final LCA results. Therefore, a sensitivity analysis is carried out for these two parameters. Figure 4.7(a) shows the Δ-LCA results for Card/SC based on varying average waste rates of raw material at the institutional kitchens with the darker columns representing the results of the current waste rate as 2% for the Card/SC scenario. The reductions of all the three impact category groups have a linear relationship with the average waste rates. When the waste rate is equal to or higher than 5% (which is the waste rate for Card/C scenario), the Card/SC scenario has a less desirable resource evaluation profile compared to Card/C scenario, but still has minor reductions on environmental impact evaluation and toxicity evaluation due to the relatively larger savings in storage than the increase in processing. This further confirms that the new concept of distributing super chilled food products in the conventional cold chain actually improves the sustainability of the whole chain.

The sensitivity analysis results obtained by varying the recycling rates of polystyrene boxes are presented in Figure 4.7(b), again with the darker columns representing the results of our initially estimated recycling rate of 1/2 (which means that 50% of the polystyrene boxes are recycled). The reductions of the contribution to all the three impact category groups again have a nearly linear relationship with the recycling rates of polystyrene boxes. Even when the polystyrene boxes are not

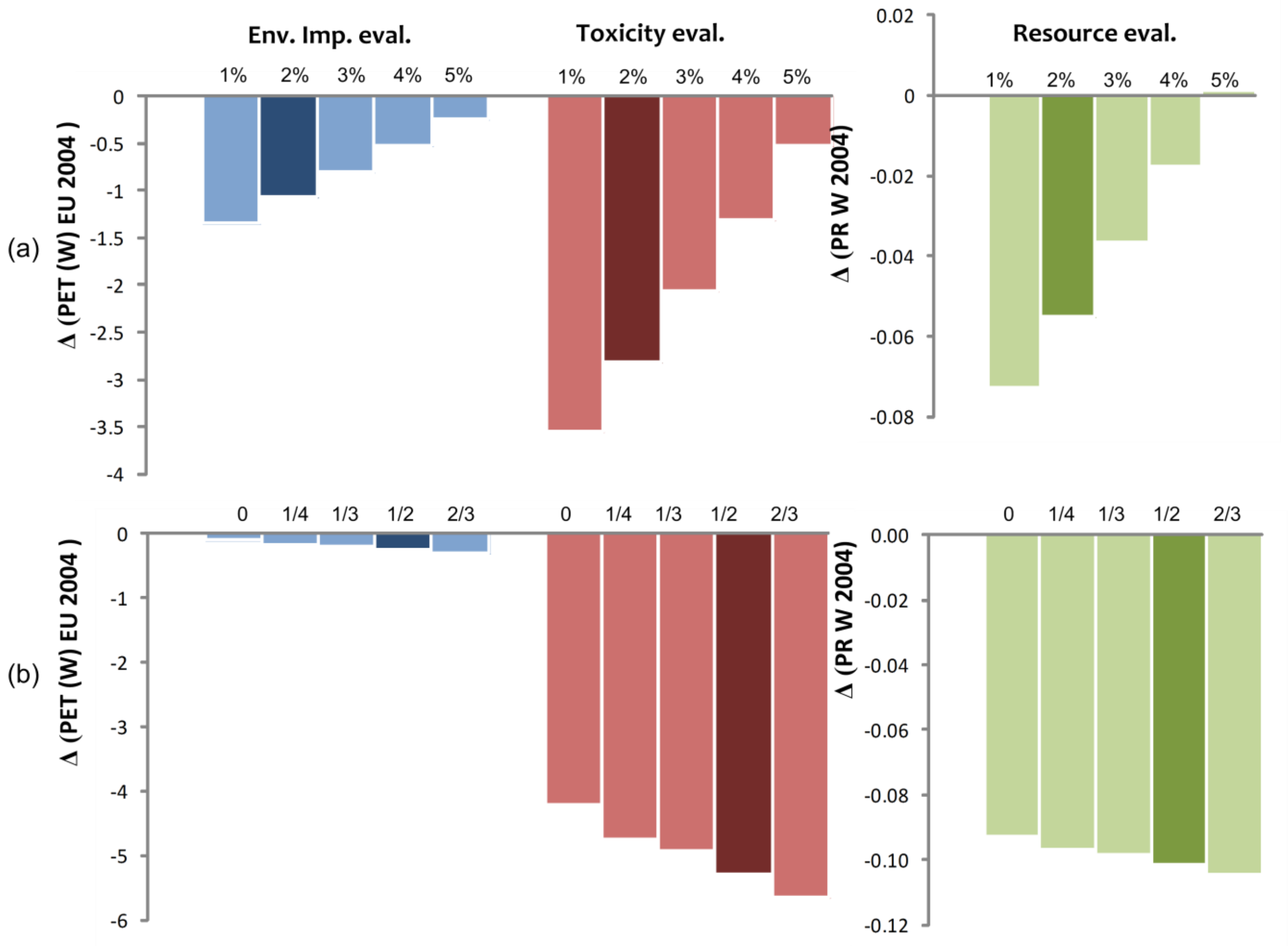

Figure 4.7 Results of a sensitivity analysis of the Δ-LCA for (a) scenario Card/SC for varying average raw material waste ratios, ranging from 1-5%, and (b) scenario Poly/C for varying recycling rates of polystyrene boxes, ranging from no recycling to a recycling rate equal to reuse of 2 out of 3 boxes. Card/C has again been used as the reference scenario and the darker columns represent the results of the current parameter setting.

recycled, the scenario Poly/C has a better impact profile compared to scenario Card/C. This is due to the much lower density of polystyrene material compared to cardboard; we use considerable less mass of polystyrene material than cardboard in order to package the same amount of food products.

4.4.3 Integrating SCP in LCA

Focusing specifically on the distribution of the food products and their storage at the customer sites, we observe relatively large changes. Super chilling reduces the impacts in all the three impact categories with around 17.5% for distribution. The improvements during distribution are due to the increased shelf life of food products, which allow for an increase in the delivery intervals to customers. With regards to storage, for cardboard packaging, super chilling reduces the environmental impacts, resource evaluation and toxicity evaluation with 17%, 39%, and 16% respectively. For polystyrene box packaging, the corresponding numbers are 32%, 39%, and 32%.

From Figure 4.6 (a), we can identify that the saving in scenario Card/SC compared with Card/C on storage contributes more than 23% of the total savings for environmental impact and toxicity evaluation. Super chilling creates a thermal buffer in the food products, lowering the energy consumption in storage rooms, because the product temperatures are lower than the temperatures of the storage room. Together with the reduction of waste, this reduces the environmental impact of storage operations.

Without the integration of the SCP model, it would have been impossible to evaluate the impacts in relation to distribution in different supply chain scenarios. Furthermore, the distribution in our study is assumed to take place at the municipal level. If the scale of the supply chain is expanded, as is expected in further industrialized supply chains, there are actually more improvements to gain. The quantification of these improvements will depend even more strongly on the availability of high-quality LCA parameter input from an SCP model.

4.5 Conclusions and further research

We have presented a framework integrating supply chain planning in sustainability assessment, and applied it to a case involving the distribution of super chilled food products. Using SCP results in LCA proved to work well, supplying realistic parameter settings for the implications of the use of a new technology. In our framework there is also a feedback in which environmental impacts from the LCA are again used in SCP. Further study of the feedback from LCA to SCP will be the next step in our research. Questions relating to how to determine the preferred solution(s) balancing environmental and business concerns, how to evaluate Pareto efficiency (Bao and Mordukhovich 2010), how to improve the understanding of the trade-offs between economic performance and environmental perspective (Quariguasi Frota Neto et al. 2008), and how to finally develop and solve an according decision support SCP model are all interesting and challenging research topics which are relevant for the expansion of research presented in this article.

Regarding the case study, we were able to confirm that distributing super chilled food products in the conventional cold chain improves the sustainability of the supply chain. The main reason for this is that super chilling can prolong shelf life of the food products, reducing waste at institutional kitchens. With reduced waste, fewer raw materials need to be produced and transported, which reduces the activities causing the largest environmental impacts along the supply chain. It should be noted that the included case considers vegetable food products. Production of meat is known to have larger environmental impact potentials than vegetable production (Davis et al. 2010). If meat was included in the supply chain the impact potential dominance of the raw material production would increase further, and super chilling would lead to even larger improvements. As waste is often negatively contributing to both economic and environmental performance, a reduction leads to a win-win situation as long as the reduction efforts are not overly expensive. Currently, institutions within the foodservice industry already focus on reducing waste (McCaffree 2009); our research confirms that by reducing food waste throughout the supply chain, a lot can be obtained, not only from an economic perspective but also from an environmental perspective.

Even though we only discussed one case example in this article, we strongly believe that our framework is widely applicable and leads to an improved sustainability assessment. We used the case to show that the framework is especially beneficial in the planning of supply chains for new technologies or product concepts. Here, the SCP model allows for the determination of consistent scenarios and realistic production and distribution parameters in the absence of real-life values.

Chapter 5. Multi-objective supply chain planning

This chapter is based on the following research paper:
Wang, Y., Akkerman, R., Birkved, M., and Grunow, M. (2012) *Supply chain planning with sustainability considerations: an integrative framework.*

Abstract

This paper proposes a modeling framework for combining supply chain planning and sustainability assessment, illustrating how sustainability assessments of logistic activities can be improved by supply chain planning input, and especially that supply chain planning can in turn make use of the results from sustainability assessments. We use mathematical programming for the supply chain planning and life cycle assessment for the modeling and quantification of the environmental impacts. We illustrate the benefits of our integrated framework for a case of production, distribution and storage of food products produced on industrial scale, studying several important planning decisions like temperature treatments and choice of packaging materials.

5.1 Introduction

Sustainable management of the environment and its resources is an issue of vital importance in our societies. The European Union formulated the three pillars of sustainability at its Copenhagen Summit and with the Treaty of Amsterdam of 1997. Often referred to as the "three-pillar model of sustainability" or the "triple bottom line", the principle states that sustainability not only comprises the environmental heritage we pass on to the next generation but also the economic performance and social impacts of our actions. Sustainable development thus rests on an environmental, an economic, and a social pillar (Corbett and Kleindorfer 2003; Kleindorfer et al. 2005; Dey et al. 2011).

In sustainability studies, in assessing environmental sustainability, the Life Cycle Assessment (LCA) methodology has proven to be one of the most effective tools. However, the wide variability and complexity of possible scenarios often lead to a large amount of configurations to be investigated, which require considerable computational time and resources. From the other side, operations management and supply chain management (SCM) researchers and practitioners were traditionally focusing on the economic perspective of sustainability and are now facing new challenges in integrating the other two dimensions of sustainability in their traditional areas of interest (Kleindorfer et al. 2005; Srivastava 2007).

A recent review paper (Liu et al. 2011) discusses the challenges, perspectives and recent advances in support of sustainable production operations. The authors conclude that integrated sustainability analysis, which tackles the sustainability issues from both life cycle and multi-criteria perspectives, can provide more efficient and effective support to complex decision-making in sustainable production operations. In order to achieve this, and to cover the multiple dimensions of sustainability, multi-criteria analysis is required. There is a growing body of literature on sustainable or green SCM that tries to do this, and LCA researchers started to investigate the application of multi-criteria analysis techniques to reduce the number of chain configurations to be investigated by means of LCA (Recchia et al. 2011). But despite the efforts from both the LCA and SCM fields, the application of multi-criteria analysis techniques in sustainability analysis is still at an early stage. Scoring and weighting are often used while the integration of more advanced techniques of multi-criteria analysis still needs to be investigated.

In this paper, we propose a framework integrating supply chain planning and life cycle assessment. We outline how environmental assessments can be improved by supply chain planning input, and specifically focus on how supply chain planning can in turn make use of the results from sustainability assessments by applying multi-objective modeling approach. The presented framework will enable decision makers to better evaluate supply chain performance, not only from the traditional economic or service-level perspectives but also from an environmental perspective. Also, it aims to advance the level of integration in multi-objective sustainability analysis beyond the common scoring and weighting approaches.

5.2 Related literature

Quantitative model-based research, which is based on a set of variables that vary over a specific domain, while quantitative and causal relationships have been defined between these variables, has been the basis of most of the initial research in operations (Bertrand and Fransoo 2002). When we look at recent quantitative modeling approaches, there are three main trends towards sustainable supply chain management.

The first is by applying single-objective optimization models, which mainly contains two subcategories. One subcategory focuses on supply chains in which sustainability is a built-in concept, such as reverse logistics, which is concerned with establishing an infrastructure to manage the reverse flow of products in production systems or supply chains (see e.g. Akçalı et al. 2009; Fleischmann et al. 1997) or closed-loop supply chains in which forward and reverse supply chain activities are integrated (see e.g. Akçalı et al. 2009; Guide and Van Wassenhove 2009; Paksoy et al. 2010). The primary objective of closed-loop supply chains is to improve the maximum economic benefit from end-of-use products. The literature within this stream of research advocates that closing the loop also helps to mitigate the undesirable environmental footprint of supply chains (Quariguasi Frota Neto et al. 2010). Normally, a single-objective model is developed, such as in Paksoy et al. (2010), to minimize the total cost. For example, in Hasani et al. (2012) specific decision-making environment of food industries as well as high-tech electronics manufacturing industries are considered. The authors develop a mathematical model for robust closed-loop supply chain network design. The other subcategory includes environmental constraints in planning models. For instance, dos Santos et al. (2010) developed a linear formulation for an agricultural production problem respecting ecologically based constraints such as the interdiction of certain crop successions, and the regular insertion of fallows and green manures. In Subramanian et al. (2010), a nonlinear mathematical programming model was developed from a profit-maximizing perspective, taking into account environmental constraints such as voluntarily specified emission limits and fuel mileage of the engine.

The second trend is the development of multi-objective models. Most of the researchers that develop these models consider both economic and environmental objectives. Other methodologies can be integrated with multi-objective optimization instead of using an approach that focuses solely on optimization models (e.g. Sheu et al. 2005, Wang et al. 2011). For instance, in Zhou et al. (2000), goal programming (GP) and the analytic hierarchy process (AHP) are integrated to address sustainable supply chain optimization in continuous process industries. In Mele et al. (2011), Bojarski et al. (2009), and Azapagic and Clift (1999), LCA was used to get the sustainability parameters for the multi-objective model. Furthermore in Azapagic and Clift (1999), multi-criteria decision-analysis has also been applied, which enables systematic analysis and modeling of preferences to multiple objectives. Quariguasi Frota Neto et al. (2008) introduced a technique, based on the commonalities between data envelopment analysis and multi-objective programming, to evaluate the efficiency of existing logistics networks. In Quariguasi Frota Neto et al. (2009), the authors subsequently focused on how to obtain a good approximation for the efficient frontier and how to obtain a good visual representation of the efficient frontier.

A third and final trend is the development of simulation approaches that include the trade-offs between environmental and economic performance. Van der Vorst et al. (2009) proposed a new integrated approach towards logistics, sustainability and food quality analysis, and implemented the approach by introducing a new simulation environment. Akkerman and van Donk (2010) explored the economic and environmental process design using a scenario-based simulation approach. Harris et al. (2011) argued that the traffic level and associated energy consumption are influenced by supply chain structure and different freight vehicle utilization and use a simulation model to assess the impact of the traditional cost optimization approach to strategic modeling on overall logistics costs and CO_2 emissions.

Despite the increasing interest in the literature both from the sustainability side and the SCM side, the level of integration between SCM and sustainability efforts is still relatively low (Liu et al. 2011; de Brito and van der Laan 2010; Wu and Pagell 2011). One of the reasons for this is that integrating sustainability into SCM (or the other way around) requires a multidisciplinary research effort – combining areas like operations management, production engineering, and environmental management (de Brito and van der Laan 2010; Kleindorfer et al. 2005). Therefore, in this paper, we develop a framework in which we integrate supply chain planning (SCP) with sustainability assessment (using LCA). The framework builds on the idea that SCP decisions have a significant effect on the sustainability of supply chains, and should also be performed with sustainability in mind.

5.3 Integrated SCP and LCA framework

The framework proposed in this paper is presented in Figure 5.1 and contains two main elements: an SCP model and an LCA model.

5.3.1 Supply chain planning

To model the supply chain activities, typical quantitative operations management approaches such as mathematical programming and simulation can be used. These approaches focus on quantitative and causal relationships between variables (Bertrand and Fransoo 2002) and as such provide a major fraction of the numerical values for the parameters needed in the LCA model. SCP includes the whole range of decisions on the design and operation of the supply chain, from long-term location decisions to mid-term coordination decisions and short-term scheduling processes (see e.g. Fleischmann and Meyr 2003). In order to solve SCP models, optimization software and model solvers are typically used.

5.3.2 Life cycle assessment

To assess the environmental performance of a supply chain, LCA has become one of the main methodologies, as it defines and quantifies the service provided by a product, identifying and quantifying the environmental exchanges and their potential impacts to the service (Wenzel et al. 1997). The International Standards Organization (ISO) has also set up standards for the application of LCA (Guinée 2002) and various software tools exist to assist in modeling the characteristics of a product and its supply chain. In addition, numerous data sources exist containing impact data for different products and processes, such as the CO_2 emissions for different transport options or the resource consumption of various types of packaging material.

5.3.3 The framework

The framework starts from a single-objective SCP model aiming to minimize the total cost of the supply chain. The first stage of the framework focuses on the data flow from the SCP model to the LCA model. After solving the SCP model by optimization software, cost-optimal production and distribution plans can be obtained. These plans contain parameters which represent the planning of activities throughout the supply chain, directly influence the environmental performance, and therefore should be considered in the LCA model. For LCA, data collection is typically a resource demanding step. Some parameters can be measured (e.g. distance, cargo weight) and some are obtained from alternative sources like unit process databases. As demonstrated in previous work (Wang et al. 2012c), logistic parameters that depend on how supply chain operations are planned should be derived from an SCP model. Using an SCP modeling approach, we can determine how to perform the production and distribution for relevant scenarios, leading to realistic parameter settings for LCA, especially for LCA of future technologies.

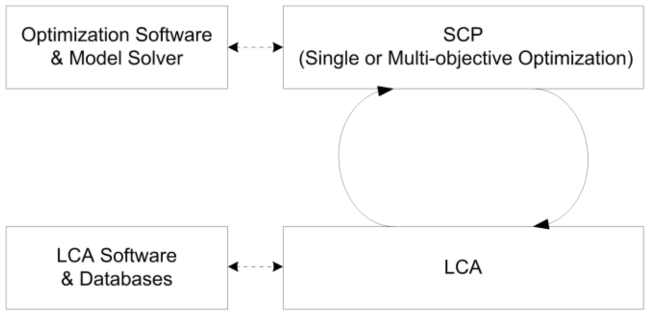

Figure 5.1 Integrated framework combining SCP and LCA.

The second stage of the framework contains information and parameters flowing from the LCA model to the SCP model, in such a way that a decision model including both economic objective and environmental objectives can be developed. This has several advantages:

(1) Performing an LCA of the whole supply chain enables us to get sustainability data of good quality, which are the parameter inputs to the environmental part of the SCP model.
(2) From the LCA results, we have quantified impacts potential of the individual activities along the supply chain. This knowledge could be used to identify and focus on the more impact heavy activities, which can help to keep the complexity of the SCP model at a manageable level.

In the second stage, multi-attribute decision-making methodologies could be applied. It helps decision makers to evaluate different solutions of the multi-objective model. Based on the information provided by the analysis, an LCA study can be carried out again in the third stage.

Furthermore, the interpretation of the SCP solution and LCA results may lead to recommendation of reviewing and possibly revising the goal and scope of the LCA study and the SCP model, the collection of data for the inventory or the impact assessment and the logistics parameters. As such, this framework results in an iterative approach and each iteration contains two stages. The new SCP model takes environmental aspect into considerations to generate a new production and distribution plan, which might again lead to improved environmental performance and possibly updated environmental parameters. The iterative aspect of this framework combines well with the traditional LCA approach, which is also iterative in nature (Hauschild et al. 2005). This framework can help decision makers better evaluate the supply chain, not only from an economical and service-level perspective but also an environmental perspective.

Compared with other multi-objective research, such as Mele et al. (2011), Bojarski et al. (2009), and Azapagic and Clift (1999), the improvements of this framework lie in a more structural approach combining SCP and LCA and an iterative nature.

In this paper, we only focus on the second and third stage, i.e. from LCA to SCP and back from SCP to LCA again.

5.4 Illustrative case study

5.4.1 Introduction

The production and distribution system used as an illustrative case in this paper concerns a supply chain for meal elements produced in large-scale production units such as hospital kitchens or nursing homes. As sustainability is one of the main challenges in today's food supply chains (Akkerman et al. 2010), the need to integrate sustainability considerations in supply chain planning is essential in these environments. Meal elements are produced industrially and distributed to institutional kitchens, where the kitchen staff can combine them into complete meals. Examples are pre-fried meat pieces, portions of frozen fish or pre-processed vegetables.

In the production and distribution system evaluated here, a new distribution principle is applied, in which the main idea is to super chill food products at production (i.e. freezing the product to a temperature slightly below its initial freezing point, which for instance, for vegetables, is around −1°C) and to subsequently distribute them in the conventional cold chain at +2°C or +5°C. As opposed to chilling, by super chilling part of the internal water is frozen and acts as a refrigeration reservoir, which leads to prolonged product shelf life, and is therefore expected to lead to a decrease in wasted product and a more sustainable distribution system (see also Adler-Nissen et al. 2012).

5.4.2 Application of the framework

5.4.2.1 SCP model

In planning the production and distribution, the choice of temperature treatments (chilling or super chilling), the determination of delivery frequencies, and the choice of packaging materials are the most important SCP decisions. The delivery frequency will affect the transportation costs and the quality deterioration of the food products. If we for instance choose to decrease the number of shipments and increase shipment volumes, we increase the transportation efficiency. However, part of the shipments would have to be stored at the customers, leading to quality degradation of the food product. However, if super chilling is able to reduce quality degradation, an opportunity to improve the economic performance without affecting product quality is created. As for packaging materials, choosing polystyrene boxes would slow down the temperature increase (and thereby quality degradation) after super chilling, due to better insulation. The material is more expensive than ordinary cardboard, but undamaged polystyrene boxes can most likely be reused after appropriate cleaning. Cardboard boxes on the other hand cannot be reused as they have been wetted by the thawing process of the meal elements.

In previous work, we have developed a mathematical programming approach to support decision-making on e.g. chilling/super chilling detailed temperatures, what types of packaging material should be used and how often to deliver to customers (Wang et al. 2012b). With minor adjustments, we apply the model to the scenario-based study in this paper.

The main modifications are found in (*i*) the use of two different processing choices instead of a range of possible temperature treatments, as we don't need an extensive scale due to the fact that we only look at limited number of scenarios. (*ii*) the inclusion of different waste ratios due to different processing methods and packaging material. This is an extension of the original model since we would like to go from a single parameter to a different one for each of the scenarios.

In the first stage of the framework, we apply this model to get the cost optimal solution for different supply chain scenarios: (i) cardboard packaging and chilling (Card/C), which makes use of cardboard as a packaging material and relies on chilling as a temperature treatment at manufacturing, (ii) polystyrene boxes packaging and chilling (Poly/C), (iii) cardboard packaging and super chilling (Card/SC), and (iv) polystyrene boxes packaging and super chilling (Poly/SC) (Wang et al. 2012c). For each of the scenarios, this then leads to a set of logistic parameters that can subsequently be used in the LCA model. By solving the SCP model, we get an economically optimized solution for each supply chain scenario that can be translated into several distribution and storage parameters in the LCA model concerning the number of deliveries to customers, the amount and time the products need to be stored at customers' sites, and the estimated shelf life of the products.

5.4.2.2 Life cycle assessment model

To quantify the impact potentials of the supply chain over the entire product life cycle a product system model was developed in GaBi 4 (PE 2010) applying data from both the GaBi professional database (PE 2010) and the EcoInvent 2.0 database (SCLCI 2007). The Life Cycle Impact Assessment (LCIA) of the product system presented was carried out by applying the EDIP methodology (Hauschild and Wenzel 1998), and the EDIP 1997 characterization factors, normalization references and weighting factors for the impact assessment (Wenzel et al. 1997; Hauschild and Wenzel 1998). More details on the LCA model can be found in Wang et al. (2012c).

The normalized and weighted results of the LCIA are grouped in three impact category groups, and are presented in Table 5.1 for all considered scenarios and supply chain activities. The 'environmental impact evaluation' is the aggregated impact of the acidification, global warming, nutrient enrichment, ozone depletion and photochemical oxidation potentials. The 'toxicity evaluation' consists of six aggregated toxicological impact potentials covering chronic soil ecotoxicity, acute and chronic ecotoxicity in water and human toxicity by exposure through water, soil and air. The 'resource evaluation' consists of the resource depletion potentials of 32 metals and fuels.

Table 5.1 LCIA results for all considered supply chain scenarios.

	Env. imp. eval. (PET W, EU 2004)				Res. eval. (PR W 2004)				Toxicity eval. (PET EU 2004)			
Activities	Card/C	Card/SC	Poly/C	Poly/SC	Card/C	Card/SC	Poly/C	Poly/SC	Card/C	Card/SC	Poly/C	Poly/SC
Distribution	0.125	0.102	0.126	0.104	0.004	0.004	0.004	0.004	0.532	0.435	0.535	0.444
Packaging materials	0.225	0.218	0.247	0.237	0.113	0.110	0.021	0.020	6.315	6.121	2.237	2.146
Processing	0.113	0.225	0.113	0.222	0.005	0.009	0.005	0.009	0.111	0.221	0.111	0.219
Raw materials	18.382	17.819	18.382	17.639	1.578	1.530	1.578	1.514	51.665	50.083	51.665	49.577
Storage	2.104	1.738	2.049	1.393	0.007	0.005	0.007	0.004	3.989	3.336	3.883	2.652
Transport	2.579	2.500	2.579	2.475	0.095	0.092	0.095	0.091	11.561	11.207	11.561	11.094
Waste disp.	0.900	0.757	0.686	0.520	0.005	0.004	−0.004	−0.005	0.271	0.223	−0.846	−0.862

Based on the results of the LCA for different activities throughout the supply chain, we could get sustainability parameters of all the activities by unit weight of the food products throughout the supply chain of good quality and integrate them back into the SCP.

5.4.2.3 Modified SCP model

When taking sustainability aspects into consideration, we should include the sustainability aspects of all the supply chain activities which are from raw material production and transportation to the waste disposal. This enables us to get a clear idea on how much impact the manufacturer's decision making has on the sustainability of the whole chain.

Integrating the sustainability aspects into the SCP model results in a model similar to the one presented in Wang et al. (2012b), but with both economic objective and sustainability objective.

The cost objective of the resulting model covers the supply chain from meal elements production to the institutional kitchens using the meal elements, while the sustainability objective covers the supply chain from raw material production to the waste disposal after the cooking activities at the institutional kitchens. Normally SCP models have a focus determined by a decision maker, who has influence over a certain part of the chain and the SCP model provides decision support for this decision maker. On the other hand, LCA models are often independent of decision makers while trying to measure an impact over the whole chain. Focusing only on the decisions relevant for a single decision maker would not have to be a problem, as with the more extensive coverage in the environmental part, we are also trying to include the effect of the decision maker's decision upstream and downstream from his area of influence, for instance by including the emissions in the agricultural stage. This means we should keep in mind that we could extend the SCP to the whole chain, which requires supports from different parties of the chain and results in further revising the scope of the SCP study which is out of scope of the current study.

Economic minimization SCP model

The full details of the SCP model can be found in Wang et al. (2012b). Here, we will suffice with a description of some of its main characteristics. The key decision variables in the model are:

x_{jftph} binary variables indicating whether delivery chunk f is chosen and t is the start day of this delivery chunk for customer j using temperature treatment h and packaging material p.

The concept of delivery chunk relates to how many days are covered by one shipment, in this case, the total amount produced and distributed would cover $f-1$ days of demand.

y_{jtph} binary variables indicating whether there is a shipment from the manufacturer to customer j on day t by applying temperature treatment h and packaging material p.

Related to these variables, the following parameters and objective function are defined for the model:

w_h cost for producing one kilogram of product with temperature treatment h (either chilling or super chilling)

v_p cost for packaging one kilogram of product using packaging material p (either cardboard or polystyrene box)

k_{jhp} cost for transporting a shipment of product produced by applying temperature treatment h and packaged with packaging material p from the manufacturer to customer j

r_{ph} waste ratio by applying temperature treatment h and packaging material p

d_{jt} demand of customer j on day t

$$\text{Min} \sum_{j\in J}\sum_{f\in F_2}\sum_{t\in T}\sum_{p\in P}\sum_{h\in H}\left(\frac{w_h+v_p}{1-r_{ph}}\right)\cdot\sum_{i=0}^{f-2} d_{j,t+i}\cdot x_{jftph}+\sum_{h\in H}\sum_{j\in J}\sum_{t\in T} k_{jhp}y_{jthp} \qquad (5.1)$$

The objective function in (5.1) aims to minimize the total cost, consisting of the production cost of food products, packaging cost and transportation cost, which also takes the waste rates of using different processing methods (chilling or super chilling) and the different packaging materials into account. Constraints in the model concern production capacity, customers' storage capacity, product shelf life, etc.

Sustainable considerations

By studying the LCA results we found that all the three sustainability impact categories (i.e. environmental impact evaluation, resource evaluation and toxicity evaluation) have trade-offs with cost aspect, which can also be verified by the results later in this section. The three impact categories have the same trend in this trade-off. For simplicity of the SCP model and to be able to graphically illustrate the results, we include only resource depletion objective into the multi-objective model. Since resource depletion and cost can demonstrate the trade-off, we assume the efficient solutions of these two objectives are also efficient solutions in four dimensions, which taking into consideration of the cost and all the three sustainability assessment categories. Technically, the method could be applied on as many dimensions as we would like.

The following additional parameters are then defined for the SCP model:

r ratio of raw materials wasted at the manufacturer (due to e.g. cutting or pealing).

b resource depletion potentials for producing and transportation of one unit of raw material.

s_p resource depletion potentials per kilogram of product using packaging material p.

c_h resource depletion potentials per kilogram of product using processing method h.

a_{jhp} resource depletion potentials for one shipment transportation of meal elements using processing method h and packaging material p to customer j.

n_{ph} resource depletion potentials per kilogram of product stored at customer site using packaging material p and processing method h.

The values of these parameters are obtained from LCA results. For instance, the resource depletion potentials of storage by using cardboard boxes as packaging material and chilling as processing method to distribute 24,495 kg meal elements is 0.007, hence we can calculate n_{ph} of cardboard boxes packaging and chilling processing dividing 0.007 by 24,495.

Using these, an alternative objective function can be defined:

$$\text{Min} \sum_{j\in J}\sum_{f\in F_2}\sum_{t\in T}\sum_{p\in P}\sum_{h\in H}\left[\frac{b}{(1-r_{ph})(1-r)}+\frac{c_h+s_p+n_{ph}}{1-r_{ph}}\right]\cdot\sum_{i=0}^{f-2} d_{j,t+i}\cdot x_{jftph}+\sum_{h\in H}\sum_{j\in J}\sum_{t\in T} a_{jhp}y_{jthp} \qquad (5.2)$$

The objective function in (5.2) aims to minimize the total resource depletion, from the raw material production to the end-use of meal elements and waste disposal. When we combine this with the economic objective, we have a multi-objective supply chain planning model with objectives (5.1) and (5.2), which takes into consideration of both cost aspect and resource depletion aspect.

Efficient solutions

We apply the ε-constraint method (Deb 2005), which is a classical multi-objective optimization method, to find a range of efficient solutions for the optimization model with both economic and resource objectives.

The experiments were performed on a computer with an Intel Core 2 Duo CPU and 4GB RAM. The models were implemented using ILOG's OPL Studio 6.0 as a modeling environment and its incorporated standard optimization software CPLEX 11.1. The models are run for a randomly generated network of 20 kitchens, for which a single manufacturer produces products that are packed either in cardboard boxes or in polystyrene boxes. As stated in Wang et al. (2012b), it should be noted that the model starts with an empty system which means there is no stock at the kitchens before the planning started. Similarly, the end of the planning horizon also contains a disturbance due to the minimization of remaining stock levels. Hence, similar to the experiments shown in Wang et al. (2012b), a six-week period was considered, where the first and sixth week were neglected in the analysis to focus on a period of normal operation since in practice, planning seldom starts from an empty system. The 100 efficient solutions obtained taking into account both economic and environmental perspectives for the middle 4 weeks are shown in Figure 5.2. We should keep in mind that the most efficient solution for 6 weeks may not be efficient for 4 weeks, which has the drawback that we see a cloud of solutions, instead of points that all lay on an efficient frontier.

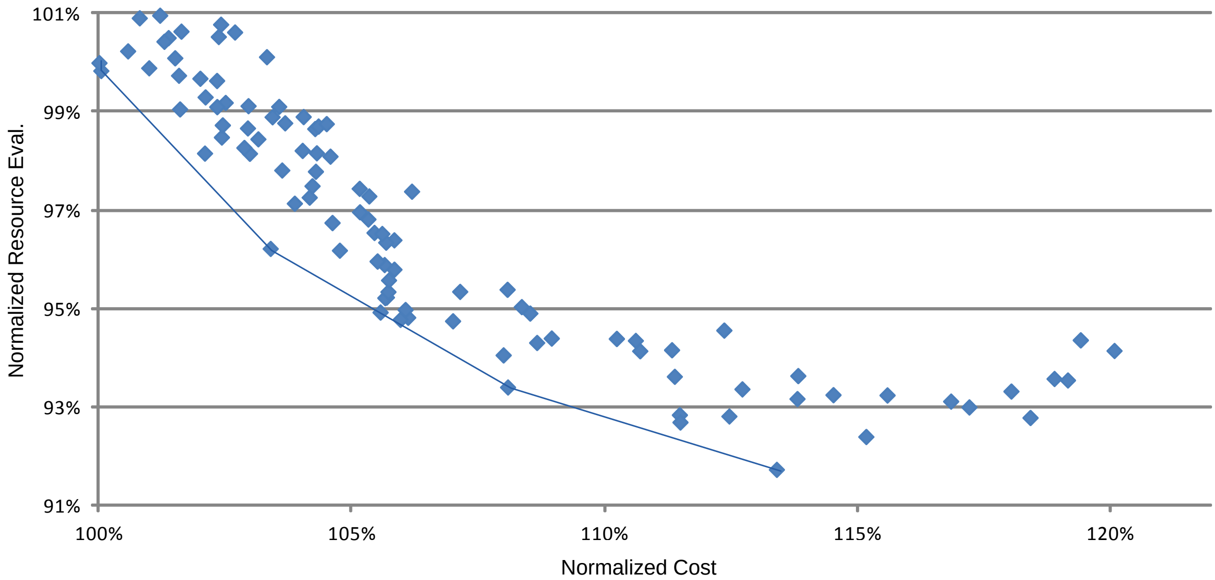

Figure 5.2 A set of 100 efficient solutions obtained after normalization relative to cost minimum solution.

The figures on the axes are the normalization results relative to the minimum cost solution for these 100 solutions.

According to the solutions obtained, the solution minimizing the total resource evaluation values uses only polystyrene boxes along the supply chain but uses the production methods combining both chilling and super chilling. This solution gives a total cost of approximately 113.40% of the cost for the configuration with minimum cost. On the other hand, the resource evaluation impact for the supply chain with minimum resource evaluation value is 8.26% lower than that of the minimum cost solution.

The minimization of cost gives a total cost of approximately 88.68% of the cost for the configuration with minimum resource depletion. In this solution, both polystyrene and cardboard boxes are used, and super chilling and chilling processing methods are also used in combination. On the other hand, the resource evaluation impact for the supply chain with minimum cost is 8.42% higher than the minimum feasible resource evaluation.

5.4.2.4 Modified LCA model

For the 100 solutions, we decided to further study the five efficient solutions as shown in Figure 5.2 connected by a line. The percentage usage of cardboard boxes and polystyrene boxes and the percentage of chilling and super chilling processing methods for the five efficient solutions are shown in Figure 5.3 and Figure 5.4. A similar pattern holds for the non-efficient solutions, when moving to the lower right part of the solution cloud. The last two solutions are mainly using polystyrene boxes and all the five efficient solutions are using combination processing methods,

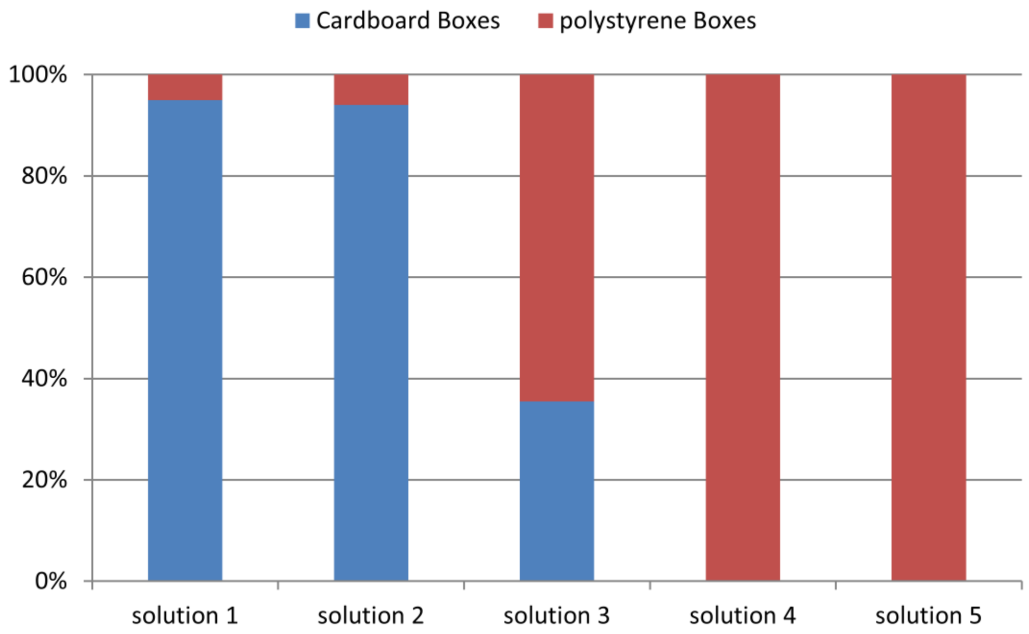

Figure 5.3 Percentage usages of cardboard box and polystyrene box for the five efficient solutions.

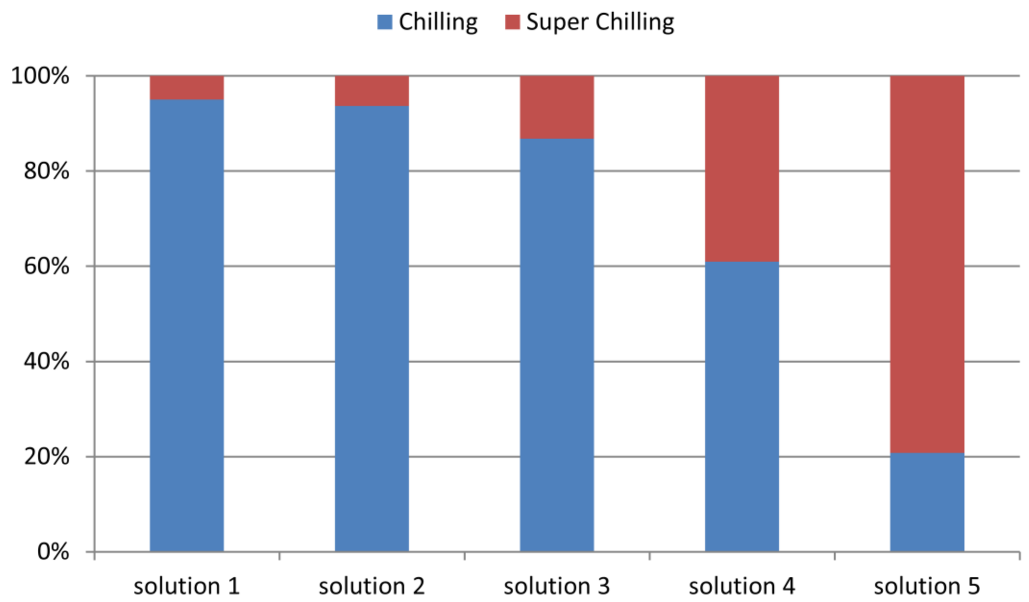

Figure 5.4 Percentage usages of chilling and super chilling for the five efficient solutions.

both chilling and super chilling. Polystyrene and super chilling are however increasingly used in solutions that are more focused on the minimization of resource depletion.

Table 5.2 Overall LCIA results and relative cost for all the five solutions.

Impact group and Relative Cost	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5
EDIP 1997, Toxicity eval. (Unit:PET EU 2004)	74.20	74.24	69.35	65.88	65.83
EDIP 1997, Res. eval. (Unit:PR W 2004)	1.80	1.80	1.73	1.67	1.64
EDIP 1997, Env. imp. eval. (Unit:PET W, EU 2004)	24.46	24.52	23.71	23.05	23.19
Relative cost	88.19%	88.22%	91.17%	95.31%	100%

The SCP results are translated into LCA parameters and the LCA model is run for the five supply chain scenarios again to get more precise sustainability aspects evaluation as shown in Table 5.2. Since the multi-objective SCP model includes environmental considerations in a new production and distribution plan, which leads to updated environmental parameters, the LCA results, especially resource evaluation are slightly different from the previous resource evaluation figures calculated from SCP for these five solutions (higher by 2% for all the five solutions), which again illustrates the statement that the production and distribution planning solution generated from the SCP model could influence the parameter settings of the LCA model.

Solution 1 has the highest resource depletion but has the minimum cost. The trends of environmental impact and toxicity evaluation are almost the same as that of resource depletion. Figure 5.5 shows the relative values of all these four dimensions.

Compared with Figure 5.3 and Figure 5.4, when the percentage usage of cardboard boxes is increasing, the evaluation values of all the three LCIA impact groups are increasing, while the cost is decreasing. The opposite trends appear when the percentage usage of polystyrene boxes is increasing. Regarding to processing methods, when the percentage usage of super chilling is increasing, the cost is also increasing but the environmental impacts are decreasing.

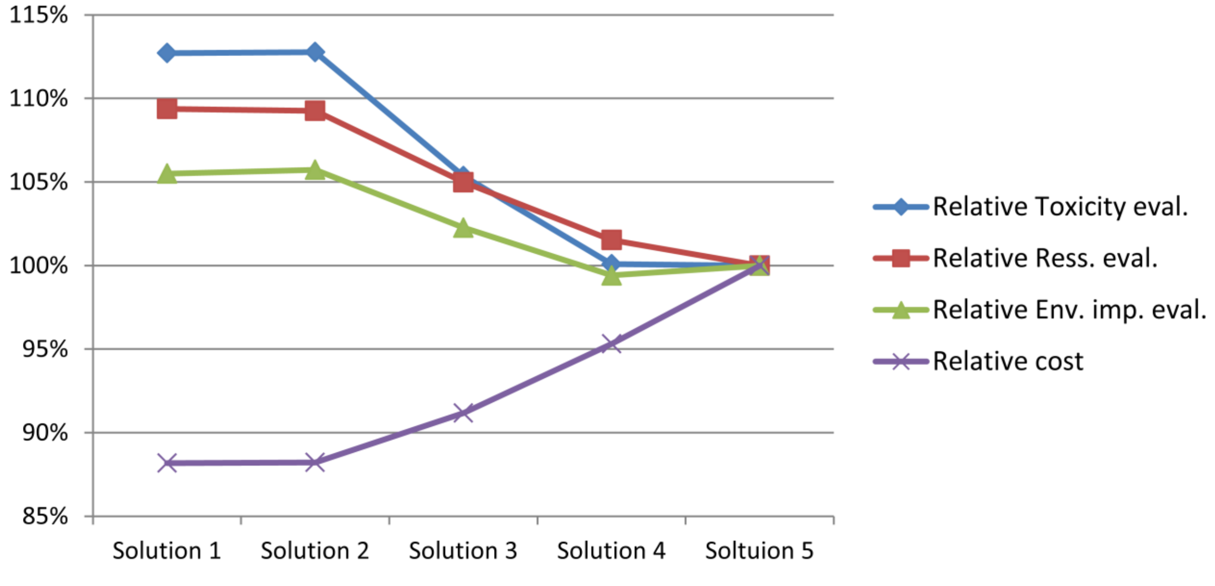

Figure 5.5 Relative values for all three impact categories and cost.

This gives us the implications that in order to improve the sustainability performance of the chain, economic perspective needs to be compromised. It is up to the decision makers to evaluate all the five solutions and select the one that best suits the supply chain.

5.5 Conclusions and further research

In summary, we propose a framework integrating supply chain planning with quantitative sustainability assessment by application of LCA, thereby contributing to the literature on decision support in balancing the economic and environmental performance of supply chains. We study how we can utilize the LCA methodology to allow SCP models to incorporate both economic and environmental aspects. At the same time we also show it is beneficial to apply a more advanced multi-criteria analysis technique in environmental sustainability analysis field. By analysing the resulting supply chain decisions, we are able to present a comprehensive overview of economic considerations and environmental impacts. The framework is widely applicable and leads to more comprehensive economic and environmental assessment of supply chains.

Regarding the case study presented, we were able to provide a supply planning solution minimizing the sustainability impact values for the middle 4 weeks of the planning horizon. But by allowing the sustainability impact values to increase, the total cost of the supply chain is decreased. There are trade-offs between sustainability aspect and economic aspect.

Even though we only discuss one case example in this paper, the framework presented is widely applicable and leads to a more comprehensive sustainability assessment. We used the case to show that our framework is especially beneficial in the design of supply chains, and the introduction of new technologies or product concepts. This experience with our framework could for instance also be extended to the introduction of reverse logistics or product-service systems.

Chapter 6. Conclusions and future research

This thesis has focused on the integration of food engineering knowledge and supply chain management approaches, and the integration of sustainability assessment technologies and supply chain planning methodologies. The production and distribution of super chilled meal elements from the foodservice industry is used as a case study throughout the thesis, and the possibilities and advantages of this case have also been investigated. In this chapter, we outline the results from the individual papers, look at the scope and limitations of these papers, and identify implications for future research.

6.1 Conclusions and discussion

This research starts in Chapter 2 by introducing the case study and identifying the scope of the supply chain for professionally prepared meals, identifying the important decisions and arranging them in decision hierarchy.

Based on Chapter 2, in Chapter 3, a decision support model based on mixed-integer linear programming is developed for the supply chain planning for professionally prepared meals. An integral part of the approach is a model of the thermodynamic behavior of the food products that is used to describe the thawing process. The model has been used to gain insight into the complex interactions between different decisions, such as packaging options and delivery intervals, and contributes to efficient supply chain planning for high-quality food products in the foodservice sector. Tracking a product's enthalpy content implicitly takes product quality wear and remaining shelf life into account. In general, experiments with the model show that the number of deliveries can be significantly decreased when the processing of meal elements changes from chilling to super chilling. The research approach in Chapter 3 combines food engineering knowledge and supply chain management modeling techniques. This integration approach shows its advantages which enable the tracking of food production thermodynamic behaviour and provides a better supply chain planning solution than the method with simply shelf-life limitation constraints.

The case applied here is the production and distribution of super chilled meal elements. As discussed in Chapter 3, most food products have similar enthalpy curves, as these relationships largely depend on the water content of a product, and products suitable for super chilling generally have a high water content (from 60% to 90%) (Pham et al. 1994). For individual products, only limited changes in parameter settings are required to make sure the correct enthalpy curve is included.

Even if we apply the integrated modeling approach here only to the supply chain planning for professionally prepared meals, we believe the methodology can also be applied to other foodservice supply chains with different food processing technologies. The central part is getting better understanding of the related food engineering knowledge and trying to find the concept which could be applied also in supply chain planning such as the enthalpy in this specific case.

Chapter 4 investigates how to integrate supply chain planning methodologies into sustainability field to improve the sustainability assessment for a supply chain. As a starting point, the chapter develops and illustrates a structured framework for combining supply chain planning and life cycle assessment and focuses on the data flow from supply chain planning to life cycle assessment. As discussed in the chapter, for life cycle assessment, data collection is a resource-demanding step and especially when doing environmental assessment of future technologies, there are challenges in the definition of consistent scenarios of the future and the data availability (Frischknecht et al. 2009). Supply chain planning provides a way to obtain supply chain data of good quality. In the numerical results, we show that using supply chain planning results in life cycle assessment proved to work well, supplying detailed parameter settings.

Chapter 5 continues with the study of the structured framework for combining supply chain planning and life cycle assessment and focuses on the data flow from life cycle assessment back to supply chain planning. Performing a life cycle assessment of a supply chain helps us to obtain sustainability data of good quality and allows supply chain planning models to incorporate both economic and environmental aspects. Meanwhile, multi-objective modeling approach provides a more advanced multi-criteria analysis techniques in sustainability assessment field.

Even if we only apply the framework for one case study in this thesis, the framework is generalizable when there is a supply chain planning activity happening especially when the supply chain planning decisions have big impacts on the sustainability assessment of the chain. The SCP model may sometimes be case specific, but the input from SCP to LCA has the same structure: details on how production and distribution is planned. On the other side, the sustainability objective can be easily defined based on the supply chain planning model with cost objective, which leads to a multi-objective model with both economic and sustainability objectives. The sustainability parameters in the multi-objective model are derived from the LCA results. Even if LCAs, like the SCP model, tend to be case specific, using them to provide environmental impacts related to the production and distribution should be general.

In summary, this thesis focuses on the integration of research methodologies applied to food supply chain planning. These integrated methodologies enable the combined study of quality, efficiency, and sustainability in the supply chain which contributes to the food supply chain planning research.

Regarding the case study presented, we are able to confirm that distributing super chilled meal elements in the conventional cold chain helps to increase the distribution efficiency and food quality.

More specific, compared with distributing super chilled meal elements in a super chilled chain, significant energy savings are achieved during distribution since the temperature applied is lower in the cold chain scenario. Compared with conventional chilling, super chilling the products increases the distribution efficiency and food quality. The comparison results in Chapter 3 show a decrease in the number of deliveries to customers. This would imply decreased distribution costs, and a decrease in the related environmental impact. Additional energy savings might be achieved from the fact that the super chilled products actually help keep the temperature in the delivery vehicles low, reducing the amount of energy used by the compressor. This further decrease in energy usage during distribution also leads to additional distribution cost savings.

In relation to a sustainability perspective, distributing super chilled food products in the conventional cold chain can be used to reduce the resource depletion, environmental impact and toxicity evaluation compared to the traditional chilling processing approach. The improvements are mainly due to the prolongation of the shelf life which results in the waste reduction in the super chilling scenario. Even if the waste percentage at the customer wouldn't decrease at all after the introduction of super chilling, there are still benefits due to the energy savings during storage and distribution, although they are then relatively minor.

Combined, our results show that super chilled distribution helps to increase the quality, efficiency and sustainability of foodservice supply chains.

6.2 Future researches

Based on the conclusions and three research papers, this section presents some ideas for future research. Farahani (2011) mentioned that looking into the literature only a few studies take an integrated approach towards operations planning in the food industry. The author proposed that more research needs to be done on developing appropriate modeling approaches and solution algorithms. As summed up in the previous section, in this thesis, basically two integrated approaches have been investigated: supply chain planning integrated with food engineering knowledge and supply chain planning with sustainability assessment methodologies. These are first steps toward the integrated research and more work still needs to be done in the future.

6.2.1 Integrating food engineering knowledge into food supply chain planning

Most of the relevant research has focused on tracking food quality changes by applying food engineering knowledge, but the integration is still at its infancy. Normally, food quality changes are estimated roughly. In Chapter 3, we investigate tracking the food product changes by a more detailed and accurate method and we believe there is still a long way to go in this research direction. For instance, in our research article, we introduce packing patterns and worst-case scenario analysis due to the extended complexity to track the product changes in more detail. In addition to this, due to the short transportation distance in the case study, we ignore the food product changes during distribution. If we extend the network and introduce long-distance transportation, the product changes during distribution also need to be take care of.
In summary, we believe, by the help of close cooperation between food engineers and supply chain researchers, more advanced food supply chain planning methods can be developed. Some examples are:

1. More accurate estimation or tracking of food quality changes during production, distribution and storage activities can be obtained.
2. Attributes of food product changes affected by other activities along the supply chain can be better tracked. Some examples could be the effects by opening and closing the temperature controlled compartments in the truck distributing food products and heat transfer happened between different food products at different temperatures when distributing food products by multi-compartments vehicles.
3. Food safety issue, which is highly related to food quality, can be better addressed. Food safety issues are not within the scope of this thesis, but we believe that by better understanding of the food engineering knowledge, supply chain researchers could be able to find more ways to improve the product safety tracking methods and include this important aspect into food supply chain planning.

In summary, integrating more and more food engineering knowledge into food supply chain planning could open up more research opportunities.

6.2.2 Integrating sustainable considerations into food supply chain planning

The food industry is one of the world's largest industrial sectors and hence is a large user of energy (Roy et al. 2009). It is a major contributor to both local and global environmental impact and resource use (Davis et al. 2010). Both in sustainability assessment and in supply chain planning, researchers have started to pay more attention to the food industry, but close cooperation is required. Farahani (2011) stated that so far, in food supply chain management, sustainability has mainly been associated with transportation, and particularly the travelling distance focusing on reducing the fuel consumption to lower the environmental pollution. While in other industries, there are more attempts towards sustainable production planning and scheduling (Rădulescu et al. 2009; Subramanian et al. 2010), which could be a good start point for food supply chain management. To summarise, the following points are believed to be promising future research directions:

1. Integrating sustainable considerations into food supply chain planning which covers broader activities along the supply chain, such as production planning and scheduling, packaging, and storage.
2. Developing better integration framework and methodologies integrating sustainable aspects into food supply chain planning. In supply chain planning, researchers are normally using methodologies that may not coordinate with sustainability assessment methodologies, for instance, life cycle assessment. The level of detail is not always the same in these two research fields and the understanding of parameters are sometimes different. Hence, better translations between these two research fields are required and can be a promising and important research direction.

6.2.3 Integrated research among food quality and all the three dimensions of sustainability

The interactions between food quality and profit have been touched in the past research and also the trade-offs between efficiency and environment. But the aspect of health and safety (the people dimension of sustainability) has not received similar attention in the past research. Future research could focus more on the aspect of people. In addition to that, studying the whole picture of food quality and all the three dimensions of sustainability would be a profitable research direction, leading to the development of multi-dimensional decision support systems.

Supporting information 1

This supporting information provides details of parameters used in the life cycle assessment (LCA) and detailed LCA and life cycle impact assessment (LCIA) results for the different impact categories in Chapter 4.

The document contains the following tables:

S1.1 – Parameter input for the LCA model
S1.2 – Detailed LCIA results - environmental impact evaluation
S1.3 – Detailed LCIA results - toxicity evaluation
S1.4 – Detailed LCIA results - resource evaluation

Table S1.1 Parameter input for the LCA model.

Parameters	Unit	Scenario				Comments
		Card/C	Poly/C	Card/SC	Poly/SC	
Cardboard boxes per mass meal needed	kg/kg	0.0386	0	0.0386	0	
Distance start - receiver 1 (primary leg)	km	15.00	15.00	15.00	15.00	
Distance between receivers	km	4.28	4.28	4.28	4.28	(1)
Distance receiver 10 - origin (return leg)	km	11.80	11.80	11.80	11.80	
Percentage (by mass) of cargo delivered to receiver 1	%	15.09	15.09	20.44	23.83	
Percentage (by mass) of cargo delivered to receiver 2	%	21.56	21.56	20.32	22.32	
Percentage (by mass) of cargo delivered to receiver 3	%	12.32	12.32	16.43	20.05	
Percentage (by mass) of cargo delivered to receiver 4	%	12.37	12.37	13.56	11.89	
Percentage (by mass) of cargo delivered to receiver 5	%	10.43	10.43	9.97	8.67	
Percentage (by mass) of cargo delivered to receiver 6	%	6.60	6.60	9.17	7.73	
Percentage (by mass) of cargo delivered to receiver 7	%	5.72	5.72	5.28	4.29	
Percentage (by mass) of cargo delivered to receiver 8	%	6.69	6.69	4.84	1.22	
Percentage (by mass) of cargo delivered to receiver 9	%	5.76	5.76	0	0	
Percentage (by mass) of cargo delivered to receiver 10	%	3.46	3.46	0	0	
Exploitation of max load capacity - leg 1	%	85.00	85.00	85.00	85.00	(2)
Exploitation of max load capacity - leg 2	%	72.17	72.17	67.62	64.75	
Exploitation of max load capacity - leg 3	%	53.84	53.84	50.36	45.77	
Exploitation of max load capacity - leg 4	%	43.37	43.37	36.39	38.73	
Exploitation of max load capacity - leg 5	%	32.86	32.86	24.87	18.63	
Exploitation of max load capacity - leg 6	%	23.99	23.99	16.39	11.26	
Exploitation of max load capacity - leg 7	%	18.38	18.38	8.60	4.69	
Exploitation of max load capacity - leg 8	%	13.52	13.52	4.12	1.04	
Exploitation of max load capacity - leg 9	%	7.83	7.83	0	0	
Exploitation of max load capacity - leg 10	%	2.93	2.93	0	0	
Exploitation of max load capacity - leg 11 (return run)	%	0	0	0	0	
Percentage of food waste at the kitchens	%	5	5	2	1	(3)
Percent additional fuel consumption due to cooling	%	20	20	20	20	(4)
Mass of packed meals to be distributed	kg	25465	24738	24685	23738	(5)
Percentage of distribution route on motorway	%	27	27	27	27	
Percentage of distribution route outside of town	%	43	43	43	43	(6)
Percentage of distribution route within town	%	30	30	30	30	
Fava beans in meals	%	40	40	40	40	
Maize in meals	%	10	10	10	10	
Potatoes in meals	%	40	40	40	40	
Wheat in meals	%	10	10	10	10	
Power needed for meal preparation	MJ/kg	0.11	0.11	0.23	0.23	(7)
Power consumption for meal storage at receivers	MJ/kg	0.077	0.079	0.007	0.031	(8)
Polypropylene bags per mass meal needed for packing	kg/kg	0.0010	0.0010	0.0010	0.0010	
Polystyrene boxes per mass meal needed for packing	kg/kg	0	0.0089	0	0.0089	
Raw materials turned in to wasted	%	10	10	10	10	
Average recycling efficiency of PS at receiver	%	0	50	0	50	
Selector for cooling setting on return run	-	uncooled	uncooled	uncooled	uncooled	
Distance farm to processing location	km	3000	3000	3000	3000	
Percentage of biogenic C in fuel - Farm -> processing plant	%	5	5	5	5	

Generally speaking, the parameter inputs for the LCA model were collected in four different ways:

1. Interviews with kitchen managers and staff in several professional kitchens in the greater Copenhagen area.
2. Data from a foodservice distribution company in the greater Copenhagen area.
3. Data from unit process database.
4. Output data from the relevant supply chain planning (SCP) model.

(1) *Distance data*

Distance data are mainly obtained from a foodservice distribution company in the greater Copenhagen area. The professional kitchens are located relatively close to one another, whereas the distribution company is located relatively far away.

(2) *Percentage of cargo delivered to each customer and exploitation of the maximum load on each leg*

By running the supply chain planning (SCP) model, we get the planning decisions on which customers are served on which days. As the customers are clustered and the SCP model is at a tactical level, we assume the daily route always follows the same optimized sequence from receiver 1 to receiver 10, but not including the customers that are not served on that day. For example, if on day 1, we visit customer 1, 2 and 5 and on day 2, we visit customer 3, 6 and 7, the percentage of cargo delivered to receiver 1 on these two days is the average cargo share of customer 1 on the first day and customer 3 on the second day. Using this data, we calculate the average percentage of cargo delivered to each customer for the whole month.

We assume that the company is using multi-compartment cooling trucks to distribute different kinds of food products together. Therefore, we further assume that when the truck starts from the distribution centre, the exploitation rate is 85% for all scenarios. When distributing less super chilled/chilled products in our study, the spare capacity of the trucks can be used for other kinds of products. The exploitation rates on other legs are then calculated according to how much capacity is assigned to the products in our study at the beginning of the trips.

(3) *Percentage of food waste at the kitchens*

Based on relevant data from Collison and Colwill (1987) and Banks and Collison (1983), we assume that the food waste rate for scenario Card/C is 5%. Food products in scenario Poly/C have the same shelf life as in scenario Card/C, which means that we assume it has the same average waste rate as Card/C. In scenario Card/SC, super chilling down to −1.5°C extends the shelf life of the products. It takes more than 1.5 days for one cardboard box of vegetable product standing alone to thaw to the same temperature as chilling (for thawing process calculations, we refer to Wang et al. 2012b). Due to the shelf life prolongation, storage capacity at the kitchens replaces shelf life as a limiting factor on the time between deliveries in the SCP model. Hence we assume the average waste rate is reduced to 2%, as in most cases, products will be used in the kitchens and stocks are replenished long before shelf life becomes an issue. The same principles are applied to Poly/SC scenario. In Poly/SC, by using better insulating packaging material, the thawing process of vegetable product takes even longer than when using cardboard packaging. The storage capacity replaces shelf life more often than in scenario Card/SC as the limiting factor.

(4) *Percent additional fuel consumption due to cooling*

According to McKinnon and Campbell (1998), the distribution of frozen food is around 1.7 times as energy-intensive as the distribution of groceries at ambient temperature. Because the cold chain is used in the distribution of super chilled food products instead of the frozen chain, we assume a percentage of additional fuel consumption lower than the frozen chain.

(5) *Mass of packed meals to be distributed*

The total monthly delivery demand of all the customers is around 23000 kg. Hence the weight of packed meals to be distributed is calculated by:

Monthly Demand/(1− *Fraction of Food Waste at the Kitchens*)+*Weight of Packaging Material*,

which means that the total weight of packed meals to be distributed is calculated by taking into consideration the food waste at the kitchens.

(6) *Percentage of distribution route on motorway, outside town or within town*

The distribution route information is collected from the same foodservice distribution company and afterwards the percentage data are estimated using Google Maps.

(7) *Power needed for meal preparation*

According to My Dieu (2009), the energy consumption of the initial preparation before freezing and cooling in an efficient food-processing environment is around 0.054 kwh/ton. We further add the energy consumption of cooling or freezing which is calculated by the energy extracted from the food products.

(8) *Power consumption for meal storage at receivers*

According to Evans (2007), there is very little published data on the energy consumption of cold storage systems for foods. Based on the cold storage data presented in Evans (2007), we assume storage rooms volume used to store super chilling/chilling food products in our experiments are $3m^3$ and $6m^3$ for small and large customers respectively and average unit power consumption is c = $75kwh/yr/m^3$. We calculate the total power consumption for all the customers and then used the average numbers in the life cycle assessment.

For the super chilling scenarios, the temperature of food products is lower than the temperature of the chilled storage rooms. Hence some energy will be saved. From the supply chain planning model, we obtain the storage time of the food products at customers. The energy saving is calculated by the energy released by the super chilled food product during their storage time.

Table S1.2 Detailed LCIA results of the environmental impact evaluation.

Impact category	Card/C	Poly/C	Card/SC	Poly/SC
EDIP 1997, Env. imp. eval. (PET W, EU 2004)	2.44E+01	2.41E+01	2.33E+01	2.25E+01
Acidification potential (AP)	7.44E+00	7.33E+00	7.03E+00	6.64E+00
Global warming potential (GWP 100 years)	9.72E–01	9.45E–01	8.42E–01	7.40E–01
Nutrient enrichment potential	1.42E+01	1.41E+01	1.37E+01	1.35E+01
Ozone depletion potential	1.04E+00	1.01E+00	9.98E–01	9.56E–01
Photochemical oxidant potential (high NOx)	4.06E–01	4.06E–01	3.92E–01	3.86E–01
Photochemical oxidant potential (low NOx)	3.49E–01	3.48E–01	3.37E–01	3.31E–01

Table S1.3 Detailed LCIA results of the toxicity evaluation.

Impact category	Card/C	Poly/C	Card/SC	Poly/SC
EDIP 1997, Toxicity eval. (PET EU 2004)	7.43E+01	6.90E+01	7.15E+01	6.51E+01
Ecotoxicity soil chronic	2.32E+00	2.32E+00	2.25E+00	2.22E+00
Ecotoxicity water acute	2.56E+01	2.27E+01	2.46E+01	2.14E+01
Ecotoxicity water chronic	1.97E+01	1.83E+01	1.89E+01	1.72E+01
Human toxicity air	8.43E–02	7.78E–02	8.05E–02	7.21E–02
Human toxicity soil	2.20E+01	2.11E+01	2.12E+01	2.01E+01
Human toxicity water	4.57E+00	4.43E+00	4.37E+00	4.11E+00

Table S1.4 Detailed LCIA results of the resource evaluation.

Impact category	Card/C	Poly/C	Card/SC	Poly/SC
EDIP 1997, Res. eval. (PR W 2004)	1.81E+00	1.70E+00	1.75E+00	1.64E+00
Aluminum	1.01E–02	7.92E–03	9.83E–03	7.61E–03
Antimony	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Beryllium	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cadmium	6.92E–02	6.68E–02	6.70E–02	6.41E–02
Chromium	7.87E–02	7.42E–02	7.64E–02	7.13E–02
Cobalt	5.61E–04	5.54E–04	5.42E–04	5.29E–04
Copper	4.60E–02	4.40E–02	4.46E–02	4.23E–02
Crude oil	1.10E–01	1.11E–01	1.06E–01	1.06E–01
Gold	1.41E–02	1.28E–02	1.37E–02	1.23E–02
Hard coal	7.11E–03	6.55E–03	7.95E–03	7.59E–03
Iron	1.86E–02	1.79E–02	1.81E–02	1.72E–02
Lead	5.06E–02	4.95E–02	4.91E–02	4.75E–02
Lignite	4.30E–02	3.27E–02	4.10E–02	3.05E–02
Manganese	4.40E–03	4.11E–03	4.28E–03	3.96E–03
Mercury	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Molybdenum	2.38E–01	2.23E–01	2.31E–01	2.14E–01
Natural gas	2.85E–02	2.91E–02	2.81E–02	2.81E–02
Nickel	1.00E+00	9.52E–01	9.73E–01	9.14E–01
Palladium	1.91E–03	1.76E–03	1.85E–03	1.69E–03
Platinum	5.17E–05	4.35E–05	5.01E–05	4.17E–05
Selenium	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Silver	5.84E–03	5.31E–03	5.66E–03	5.09E–03
Strontium	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tantalum	1.36E–02	1.23E–02	1.31E–02	1.18E–02
Thallium	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Tin	4.63E–03	4.16E–03	4.49E–03	3.99E–03
Tungsten	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Uranium	2.77E–05	2.35E–05	2.66E–05	2.19E–05
Vanadium	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Yttrium	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Zinc	5.75E–02	4.87E–02	5.58E–02	4.68E–02
Zirconium	2.82E–05	2.56E–05	2.73E–05	2.46E–05

Supporting information 2

This supporting information provides details of parameters used in the life cycle assessment (LCA) for the five efficient solutions in chapter 5. Please refer to Supporting information 1 for explanations of some parameters.

The document contains the following tables:
S2.1 – Parameter input of five efficient solutions for the LCA model

Table S2.1 Parameter input for the LCA model.

Parameters	Unit	Scenario				
		Solution1	**Solution2**	**Solution3**	**Solution4**	**Solution5**
Cardboard boxes per mass meal needed	kg/kg	0.0367	0.0363	0.0137	0	0
Distance start - receiver 1 (primary leg)	km	15.00	15.00	15.00	15.00	15.00
Distance between receivers	km	4.28	4.28	4.28	4.28	4.28
Distance receiver 10 - origin (return leg)	km	11.80	11.80	11.80	11.80	11.80
Percentage (by mass) of cargo delivered to receiver 1	%	13.22	15.38	14.12	18.95	22.10
Percentage (by mass) of cargo delivered to receiver 2	%	15.51	17.61	20.16	21.03	21.73
Percentage (by mass) of cargo delivered to receiver 3	%	13.09	15.40	16.08	15.33	16.93
Percentage (by mass) of cargo delivered to receiver 4	%	15.75	12.62	14.23	12.35	12.30
Percentage (by mass) of cargo delivered to receiver 5	%	10.40	8.70	9.52	7.42	8.09
Percentage (by mass) of cargo delivered to receiver 6	%	7.41	8.66	6.61	3.58	7.42
Percentage (by mass) of cargo delivered to receiver 7	%	6.04	6.29	4.84	4.05	5.89
Percentage (by mass) of cargo delivered to receiver 8	%	7.78	4.34	5.81	6.37	3.14
Percentage (by mass) of cargo delivered to receiver 9	%	4.41	5.50	5.91	6.22	2.40
Percentage (by mass) of cargo delivered to receiver 10	%	6.40	5.50	2.73	4.69	0
Exploitation of max load capacity - leg 1	%	85.00	85.00	85.00	85.00	85.00
Exploitation of max load capacity - leg 2	%	73.76	71.92	73.00	68.89	66.22
Exploitation of max load capacity - leg 3	%	60.58	56.96	55.86	51.02	47.74
Exploitation of max load capacity - leg 4	%	49.46	43.87	42.19	37.99	33.35
Exploitation of max load capacity - leg 5	%	36.07	33.15	30.10	27.49	22.90
Exploitation of max load capacity - leg 6	%	27.23	25.75	22.01	21.18	16.02
Exploitation of max load capacity - leg 7	%	20.93	18.38	16.39	18.14	9.72
Exploitation of max load capacity - leg 8	%	15.80	13.04	12.28	14.69	4.71
Exploitation of max load capacity - leg 9	%	9.19	9.35	7.34	9.28	2.04
Exploitation of max load capacity - leg 10	%	5.44	4.67	2.32	3.99	0
Exploitation of max load capacity - leg 11 (return run)	%	0	0	0	0	0
Percentage of food waste at the kitchens	%	4.80	4.75	4.47	3.44	1.83
Percent additional fuel consumption due to cooling	%	20	20	20	20	20
Mass of packed meals to be distributed	kg	253756	25354	24858	24337	23939
Percentage of distribution route on motorway	%	27	27	27	27	27
Percentage of distribution route outside of town	%	43	43	43	43	43
Percentage of distribution route within town	%	30	30	30	30	30
Fava beans in meals	%	40	40	40	40	40
Maize in meals	%	10	10	10	10	10
Potatoes in meals	%	40	40	40	40	40
Wheat in meals	%	10	10	10	10	10
Power needed for meal preparation	MJ/kg	0.12	0.12	0.13	0.16	0.20
Power consumption for meal storage at receivers	MJ/kg	0.074	0.074	0.073	0.065	0.050
Polypropylene bags per mass meal needed for packing	kg/kg	0.0010	0.0010	0.0010	0.0010	0.0010
Polystyrene boxes per mass meal needed for packing	kg/kg	0.0004	0.0005	0.0057	0.0089	0.0089
Raw materials turned in to wasted	%	10	10	10	10	10
Average recycling efficiency of PS at receiver	%	50	50	50	50	50
Selector for cooling setting on return run	-	uncooled	uncooled	uncooled	uncooled	uncooled
Distance farm to processing location	km	3000	3000	3000	3000	3000
Percentage of biogenic C in fuel - Farm -> processing plant	%	5	5	5	5	5

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List of abbreviations

AHP	Aanalytic Hierarchy Process
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
GP	Goal Programming
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
MILP	Mixed-Integer Linear Programming
SCLCI	Swiss Centre for Life Cycle Inventories
SCM	Supply Chain Management
SCP	Supply Chain Planning